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Sensitivity Study on Typical Parameters of Underwater Explosion Numerical Simulation

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Abstract. In the numerical simulation research for underwater explosion, the selection of simulation parameters has a great influence on the results of numerical calculation. Based on the one-dimensional spherical symmetry model, this paper systematically studies the influence of three factors: grid size, water state equation and artificial viscosity coefficient on the important physical parameters of water explosion when TNT explosive is exploded in water. The important physical parameters selected for the explosion in water are the shock wave intensity, the maximum radius of the bubble and the pulsation period of the bubble. A series of studies are carried out on underwater explosions with different grid sizes, so as to obtain the corresponding recommended grids that meet the calculation accuracy. The influence of different water state equations on the simulation results is discussed. The effect of artificial viscosity coefficient on the simulation results is analyzed. Finally, the similarity law of the model is studied to verify the universality of the model parameters.

1. Introduction

Water explosion has always been a key issue in the research of explosion mechanics in various countries. At present, the research methods of shock wave propagation law of water explosion at domestic and foreign basically focus on theoretical analysis, experimental research and numerical simulation.

In 1948, the United States conducted a systematic underwater explosion test on the abandoned ships left over from World War II, and Cole [1] summarized the relevant research results and published the book "Underwater Explosion", which discusses the physical effects of underwater explosions. In this book, a systematic exposition is made, the basic laws of water explosion, the experimental research methods of water explosion, etc. are introduced, and some semi-empirical formulas for calculation are put forward according to the test results, especially the calculation method of water explosion shock wave, which is still widely used. On the basis of Cole's research, Zamyshlyayew of the former Soviet Union conducted key research on free water surface effect, bottom effect, diffraction effect, cavitation effect and the interaction of shock wave and structure [2], and published the book "Dynamic loads in underwater explosion". With the application of advanced test equipment such as high-speed photography in underwater explosions, the research work on underwater explosion experiments has been further developed[3-4]. Benjamin et al. [5] for the first time photographed the bubble jet generated by the bubble near the rigid boundary and under the action of buoyancy through the high-speed photography, which proved the prediction of the previous researchers. Saito[6] used high-speed photography technology to study the law of shock wave sparse in porous thin plate.

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With the high-speed improvement of computer computing performance, the study of underwater explosion problem through numerical calculation has become one of the main research methods of today's researchers[7-8]. Through numerical simulation, not only can the experimental workload be reduced, but also the simulation analysis cannot be carried out. According to the environmental conditions achieved, data that cannot be measured by experiments can be obtained, so as to conduct more detailed analysis and research on underwater explosions. On the one hand, scholars independently developed underwater calculation programs based on calculation methods such as finite element method and SPH for simulation calculation. For example, Chan improved the accuracy of underwater explosion shock wave load calculation by improving the finite element mesh model [9], Swegle et al. [10] used the smooth particle meshless method SPH to numerically simulate the underwater explosion problem, but the calculation amount is too large and the calculation accuracy is low. Peng et al. [11] studied the structural damage subjected to the near-field underwater explosion, which is carried out by coupling the SPH and RKPM, and several numerical examples were studied to verify the robustness and accuracy of their numerical model. In addition, large commercial finite element programs such as ABAQUS, LS-DYNA, AUTODYN and MSC/DYTRAN integrate SPH and Eulerian algorithms, which can simulate the underwater explosion process and have been widely used by scholars. Brett used the two-dimensional method of LS-DYNA to study the numerical simulation of underwater explosion shock wave and bubble pulsation, and compared with the experimental results [12]. Based on the MSC.DYTRAN program, Chisum uses quasi-one-dimensional and quasi-two-dimensional methods to simulate the pulsation process of underwater explosion bubbles [13]. Fox et al. used the LS-DYNA/USA program to study the damage response of the cylindrical shell under the action of lateral underwater explosion, and compared the numerical calculation results with the experimental results [14].

Scholars have carried out a certain degree of research on the underwater explosion problem, but the sensitivity of each parameter is not very clear when using the LS-DYNA commercial software to simulate the underwater explosion problem. In order to solve the above problems, this paper uses the one-dimensional TNT underwater explosion spherical symmetry model. the influence of three factors: grid size, water state equation and artificial viscosity coefficient on the simulation results of underwater explosion was systematically analyzed. Finally, the similarity rate of the model is discussed, which verifies the universality of the conclusion.

2. Theoretical model

In order to verify the results of the numerical simulation, empirical formulas are used for comparison. The calculation formulas of the underwater explosion shock wave are all based on the analysis of the explosion similarity law and the fitting of the underwater explosion test data. Depending on the method, the form and scope of the empirical formula are not consistent. Among them, Cole's empirical formula [1] is a relatively classic formula, so this paper uses the Cole's empirical formula to compare the simulation results, and its form is as follows.

The calculation formula of shock wave peak pressure is:

$$P_m = k\left(\frac{m_e^{\frac{1}{3}}}{R}\right)^{\alpha} \tag{1}$$

The calculation formula he maximum radius of the bubble is:

$$r_{\max} = \left(\frac{3E}{4\pi P_0}\right)^{\frac{1}{3}} \tag{2}$$

And the formula for calculating the pulsation period is:

$$T = 1.14\rho_0^{\frac{1}{2}} \frac{E^{\frac{1}{3}}}{P_0^{\frac{5}{6}}} \tag{3}$$

Where P_m, r_{max}, and T denote the peak pressure for shock wave, the maximum radius of the bubble, and the bubble pulsation period, respectively. m_e is the charge quality， R is the distance from the explosion center, k, α are the empirical coefficients, for TNT explosive, they takes 52.27, 1.13 respectively. E is the residual energy in the explosive product after shock wave radiation, this energy is about 41% of the total energy, which $E = 0.41WQ$. W is the quality of explosives. Q denotes the explosive heat of explosives, for TNT explosives it takes as 4.19×10^6. ρ_0 is the density of the explosive, P_0 is the hydrostatic pressure at the explosion depth.

3. Numerical method and material model

3.1. Numerical method

If the pressure gradient effect in water is not considered, the explosion problem of spherical explosives in infinite water can be simplified as a spherical symmetry problem for analysis. The one-dimensional spherical symmetry ALE algorithm in LS-DYNA is used to simulate, and the beam element is used to divide the mesh, which can significantly reduce the calculation scale and shorten the solution time. Since there is no effective method for imposing a non-reflection or pressure outflow boundary in the one-dimensional computational model, the general processing method is to increase the solution area (at the cost of increasing computational efficiency) and set the remote velocity to 0 boundary.

Taking the explosion of 1kg TNT spherical explosive at 5m underwater as a typical problem, the reference environmental pressure is set to 49000Pa. A tracer point is set at an interval of 1m from the center of the explosive to record the pressure time-history curve at different distances. An observation point that moves with the explosive material is set at the initial outer edge of the explosive to record the time-history curve of the bubble pulsation radius formed by the explosive product. A typical one-dimensional water burst calculation model is shown in figure 1.

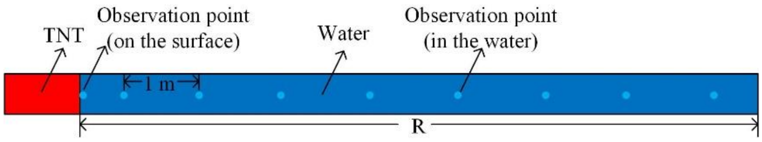


Figure 1. Computation setup.

3.2. Equation of state

In the investigation and calculation of the detonation performance of explosives, the selection of the equation of state of the detonation product is very important, which can be roughly divided into two categories according to the source route. The first type is pure theoretical form, that is, it starts from certain assumptions and does not depend on the explosive detonation test data. The typical state equations are multi-exponential state equations [15] and VLM state equations [16]. The other type mainly depends on experimental data and belongs to empirical or semi-theoretical semi-empirical forms, such as BKW equation of state [17], JWL equation of state [18] and so on. In this paper, the JWL equation of state is used to describe the relationship between the detonation pressure P, the internal energy per unit volume e and the relative volume V. The specific form is as follows:

$$p = A_1\left[1 - \frac{\omega}{R_1 V}\right]e^{-R_1 V} + B_1\left[1 - \frac{\omega}{R_2 V}\right]e^{-R_2 V} + \frac{\omega E}{V} \tag{4}$$

Where p is the detonation pressure, V is the ratio of the volume of the detonation product to the initial volume of the explosive, E is the initial internal energy of the explosive, A_1, B_1, R_1, R_2, ω are characteristic parameters. The values of each parameter are as follows: $A_1 = 3.738 \times 10^{11}$, $B_1 = 3.747 \times 10^{11}$, $R_1 = 4.15$, $R_2 = 0.9$, $\omega = 0.35$, $E = 5.999 \times 10^9$.

When the explosive explodes in water, a high-temperature and high-pressure detonation product is formed in the charge, its pressure is far greater than the static pressure of the surrounding water medium, and water shock waves and bubble pulsation will be generated in the water medium. The state equation of water has a great influence on the calculation results. In comparison, there are mainly two types of state equations: Mie-Grüneisen state equation and Linear polynomial state equation. The Mie-Grüneisen state equation is in the form of:

$$\begin{cases} p = \dfrac{\rho_0 C_0^2 \mu \left[1 + \left(1 - \dfrac{\gamma_0}{2} \right) \mu - \dfrac{a}{2} \mu^2 \right]}{\left[1 - (S_1 - 1)\mu - S_2 \dfrac{\mu^2}{\mu + 1} - S_3 \dfrac{\mu^2}{(\mu+1)^2} \right]} + (\gamma_0 + a\mu) e & \mu \geq 0 \\ p = \rho_0 C_0^2 \mu + (\gamma_0 + a\mu) e & \mu < 0 \end{cases} \tag{5}$$

Where μ is the compression ratio, as $\mu > 0$, water is compressed, as $\mu < 0$, water is expanding. C_0 is the speed of sound. γ_0 is the Mie-Grüneisen coefficient, a is the volume correction coefficient, S_1, S_2 and S_3 are the experimental fitting coefficients.

The Mie-Grüneisen equation of state is widely used in common commercial software such as LS-DYNA, ABAQUS and AUTODYN. According to its different simplified expressions, the SNL equation of state, the HULL equation of state and the LLNL equation of state can be obtained [19].

The Linear polynomial equation of state is also a commonly used equation of state for water. Some scholars [20] use this equation of state for numerical simulation of underwater explosions, and have achieved certain results. The specific form of the Autodyn polynomial equation of state is:

$$\begin{cases} p = A_1\mu + A_2\mu^2 + A_3\mu^3 + (B_0 + B_1\mu)\rho_0 E_M & \mu \geq 0 \\ p = T_1\mu + T_2\mu^2 + B_0\rho_0 E_M & \mu < 0 \end{cases} \tag{6}$$

Where A_1 is Bulk Modulus, A_2, A_3, B_0, B_1, T_1 and T_2 are the fitting coefficient.

In the subsequent research, this paper compares the calculation results of various state equations in detail. The LLNL form in the Mie-Grüneisen state equation is selected to study the remaining parameters.

4. Results and discussions

4.1. Grid size

Firstly, we investigate the effect of grid size on the calculation results. As we all know, the grid size has a great influence on the results of numerical simulation, and the grid independence is generally verified before numerical simulation. For the underwater explosion problem, it is difficult to achieve finer grid division when the computational domain is wide. In order to explore the reasonable grid size under different working conditions in the numerical simulation of underwater explosion, Zhang et al. [21] studied the grid size of explosives with different equivalents in infinite water, and proposed a grid division method based on the ratio of the explosive radius to the grid size. In order to quantitatively study the effect of explosive equivalent on the numerical simulation grid size effect, this paper uses this method, a dimensionless parameter η is introduced to describe the relationship between the explosive radius and the finite element grid size, where η is defined as:

$$\eta = r_0 / l \tag{7}$$

Where r_0 is the initial radius of the explosive, l is grid size.

In this paper, η is taken as 3, 5, 10, 15, 20, 25, and 30 for numerical calculation, and the shock wave pressure peaks at a distance of 1m to 8m from the explosive are monitored. The relationship between the required calculation time and η is shown in the figure 2.

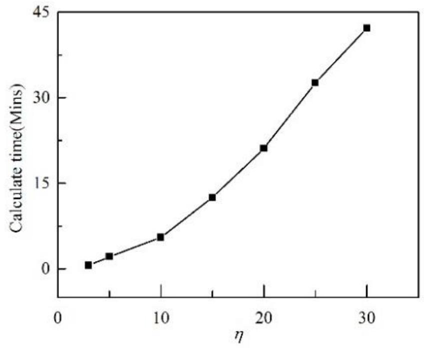
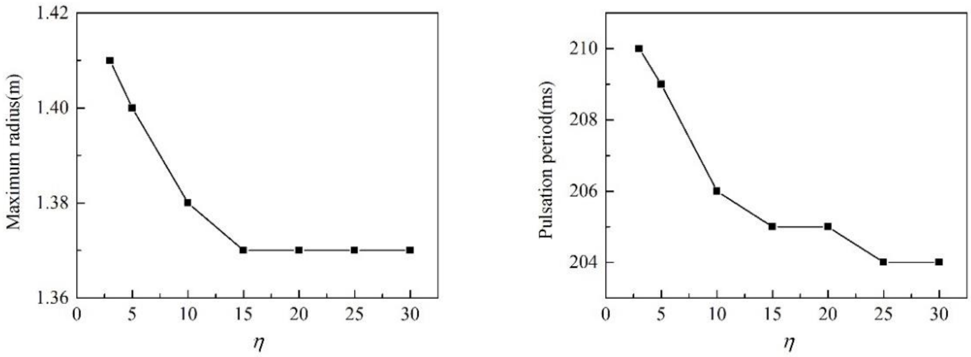


Figure 2. Calculate times diagram under different grid numbers.



(a) (b)

Figure 3. Typical bubble variable curves under different grid numbers (a) maximum radius of bubble; (b) bubble pulsation period.

It shows that with the increase of the number of grids within the unit explosive radius, the required calculation time increases exponentially. The change of Maximum radius of bubble and bubble pulsation period with respect to the η are plotted in figure 3. It is observed that, with the increase of the η, the maximum radius of bubble first decreases and then keeps constant, resulting in a converge value. The bubble pulsation period has the same relationship with η.

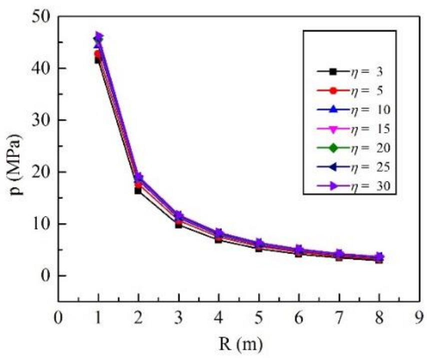


Figure 4. Shock wave peak pressure curve under different grid numbers.

We also plotted the relationship between shock wave peak pressure and η, which shown in figure 4. When the value of η is 3 to10, with the increase of n, the peak value of shock wave pressure increases obviously in the near field, but remains basically unchanged in the far field. However, when the value of η ranges from 10 to 30, the shock wave intensity does not change significantly in both the near field and the far field, indicating that the calculation has converged at this time. However, as shown in figure 2, it can be found that when the value of η ranges from 10 to 30, the calculation time increases linearly. Considering the calculation cost, η is selected as 15 for the subsequent calculation.

4.2. Equation of state for water

The state equation of water is used to define the functional relationship between the state parameters of water under different stress conditions. The selection of the state equation parameters is crucial to the calculation results. When simulating underwater explosion problems, the high pressure state equations of water used by various commercial programs or scientific research institutions are different, and the range of parameter selection varies greatly. Therefore, we use the more commonly used equations of state of water to compare and analyse their influence on the calculation results. The state equations of water mainly include the Mie-Grüneisen state equation and the Linear polynomial state equation. The main parameters are shown in Table 1 and Table 2.

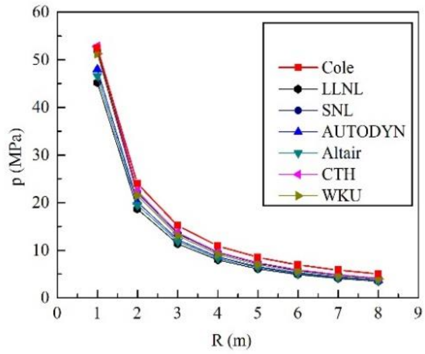
Table 1. Mie-Grüneisen equation of state parameters for water.

Model	C_0(cm•μs^{-1})	S_1	S_2	S_3	γ_0	γ_0	a
LLNL	0.148	2.56	-1.986	0.2268	0.5	0	0.148
SNL	0.1647	1.92	0	0	0	0	0.1647
AUTODYN	0.1483	1.75	0	0	0.28	0	0.1483
Altair	1.484	1.979	0	0	0.11	3	1.484
CTH&LSTC	0.1647	1.921	-0.096	0	0.35	0	0.1647
Kumamoto	0.1489	1.79	0	0	1.65	0	0.1489

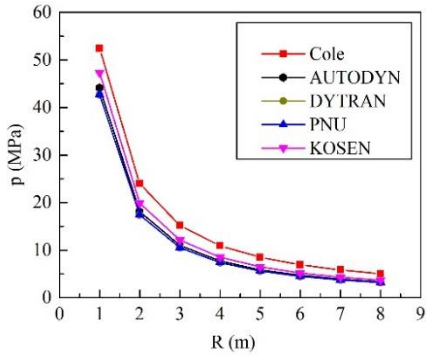
Table 2. Linear polynomial equation of state parameters for water.

Model	C_0(Mbar)	C_1Mbar	C_2(Mbar)	C_3(Mbar)	C_4	C_5	C_6
AUTODYN	0	0.022	0.0954	0.1460	0.28	0.28	0
DYTRAN	0	0.020	0.0922	0.0877	0.4394	1.3937	0
PNU	0	0.020	0.0844	0.0801	0.4394	1.3937	0
KOSEN	0	0.022	0.0535	0.0732	0	0	0

The numerical simulation results are shown in Figure 5. Figure 5 (a) and (b) are the simulation results of different forms of Mie-Grüneisen state equation and different forms of Linear polynomial state equation, respectively. It should be noted that the red grid line in the figure is the result calculated using Cole's empirical formula. Figure 5 (a) shows that regardless of the near field and far field, the results calculated by the Mie-Grüneisen state equation of different forms are lower than the results calculated by the Cole empirical formula.



(a)



(b)

Figure 5. Shock wave peak pressure curve under different water state equations, (a)Mie-Grüneisen; (b)Linear polynomial.

In addition, based on empirical formula values, the peak value of the shock wave calculated by the Linear polynomial state equation of different forms are also lower, which shown in Figure 5 (b). However, in comparison, the results calculated by the Mie-Grüneisen equation of state are closer to the results calculated by Cole's empirical formula. To sum up, we choose the LLNL form in the Mie-Grüneisen equation of state as the equation of state of water for the rest of the research.

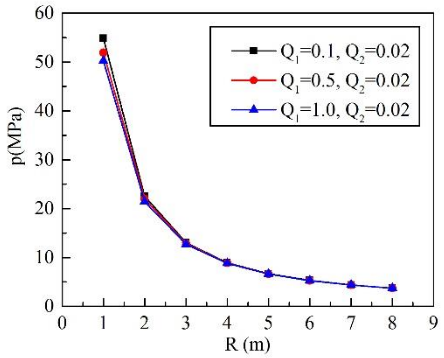
4.3. Artificial viscosity coefficient

There are discontinuities in physical quantities such as pressure at the shock wave front, which makes numerical solutions difficult. Usually, artificial viscosity terms are added to the numerical algorithm to suppress the numerical oscillations at the shock wave. Therefore, the calculation results are greatly affected by the value of the artificial viscosity coefficient. Due to the incompressibility of water, higher density and higher flow viscosity, the expansion speed of the detonation products in water is slower, the action intensity of the explosion shock wave is higher, and the action time is longer. Therefore, the viscosity coefficient has a more obvious effect on the shock wave pressure value of the explosion in water. In LS-DYNA, the artificial viscosity coefficient is expressed as follows:

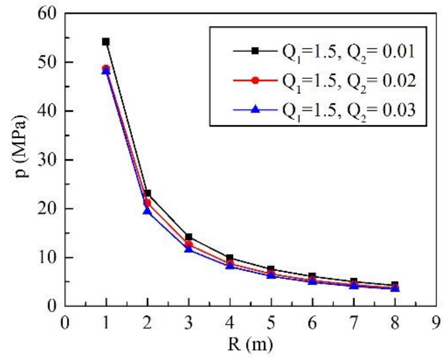
$$q = \begin{cases} \rho l\left(Q_1 l\varepsilon^2 - Q_2 a\varepsilon\right) & \varepsilon < 0 \\ 0 & \varepsilon \geq 0 \end{cases} \quad (8)$$

where Q_1 is quadratic viscosity coefficient, and $Q_2$is linear viscosity coefficient, ρ is the material density, l is a characteristic length, a is the local sound speed.

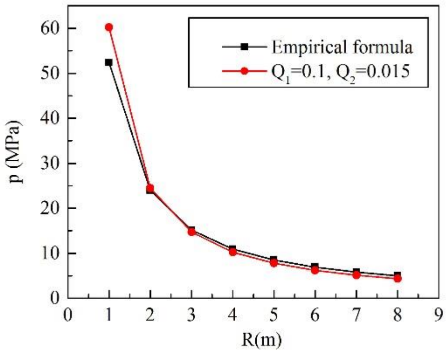
We plotted the shock wave peak pressure under different artificial viscosity coefficients, which is shown in figure 6. Figure 6 (a) shows the numerical calculation results when the quadratic viscosity coefficient Q_1 is changed. Q_1 is 0.1, 0.5 and 1.0, respectively. It is found that with the increase of Q_1, the peak value of shock wave pressure decreases in the near field, but remains basically unchanged in the far field. When changing Q_2, the simulation results are shown in Figure (b). The values of Q_2 are 0.01, 0.02 and 0.03, respectively, and Q_1 remains unchanged.



(a)



(b)



(c)

Figure 6. Shock wave peak pressure under different artificial viscosity coefficients, (a)different Q_1; (b) different Q_2; (c) simulation and empirical formula.

According to the above analysis conclusions, we choose Q_1 as 0.1 and Q_2 as 0.015 for simulation calculation, and compare the results with the calculation results of the classical Cole formula, which is shown in figure 6 (c).It is found that the simulation calculation results are slightly higher than the empirical formula at 1 m from the detonation point. However, as the distance from the detonation point increases, calculation results are basically equal to empirical results, which indicates that the numerical calculation model has a little error in the near field, but in the far field is more consistent. Therefore, we use the above value to study the model similarity law as follows.

4.4. Similarity Law

According to the above research conclusions, we selected reasonable grid size, water equation of state and parameters of artificial viscosity coefficient, then carried out numerical calculation of shock wave intensity, bubble pulsation period and maximum bubble radius under different charge qualities. The formula calculation results are compared. The charge weights were selected as 1kg, 4kg, 125kg, 512kg and 1000kg respectively. It is worth mentioning that, using the similarity theory and dimensional analysis method, through a series of changes, the similarity law formula of explosive explosion air shock wave explosion can be obtained [22]:

$$\Delta p = f\left(\frac{\sqrt[3]{m}}{r}\right) \tag{9}$$

where: Δp is the shock wave peak overpressure, m is the charge mass based on TNT explosive, r is the distance to the detonation point, the proportional distance r_s is defined, which the calculation formula is:

$$r_s = \frac{r}{\sqrt[3]{m}} \tag{10}$$

That is, the shock wave peak overpressure is only related to r_s. Therefore, in order to better verify the universality of the selected parameters, we recorded the shock wave intensities of different charges at the same proportional distance, and the result is shown in the figure 7.

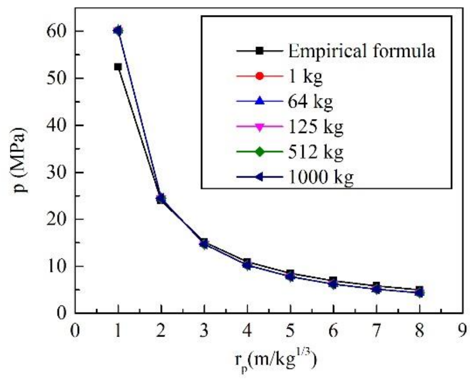
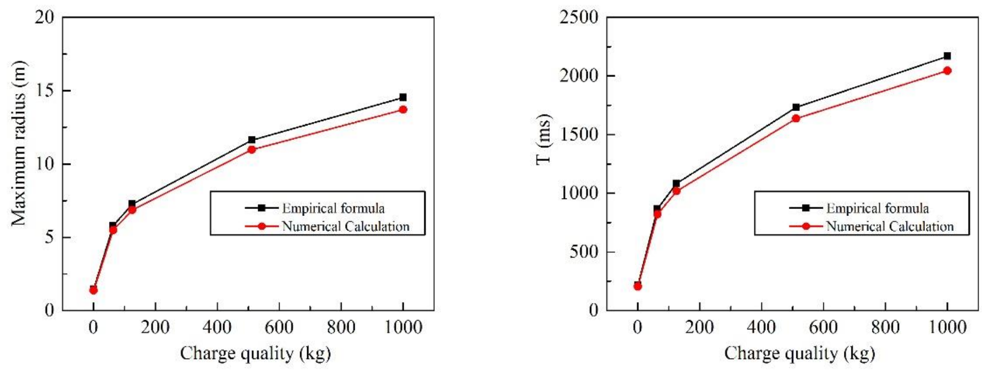


Figure 7. Shock wave peak pressure curve at different proportional distances

It is found that with the increase of the proportional distance, the peak pressure of the shock wave under different charges decreases. In addition, the simulation calculation results are basically consistent with the empirical formula calculation results. It is worth mentioning that the pressure peak curves under different charges coincide with the empirical formula curves. The typical bubble variables such as the maximum bubble radius and the bubble pulsation period are also analyzed, and the results are shown in the figure 8.



(a) (b)

Figure 8. Typical bubble variable curve under different charge quality (a) maximum radius of bubble; (b) bubble pulsation period.

The simulation results show that with the increase of the charge quality, the maximum radius of the bubble and the bubble pulsation period both increases, and the simulation results and the empirical formula calculation results have small errors under different charge masses, which proves that the parameters in the calculation model are selected. The universality of the value means that more accurate results can be calculated for different charges.

5. Conclusion

In this paper, the LS-DYNA software is used to carry out a systematic numerical simulation of the typical problem on the explosion of 1kg TNT spherical explosive at 5m underwater. Taking the peak pressure of shock wave, the maximum radius of the bubble and the pulsation period of the bubble as the check parameters, the simulation calculation results are compared with the results calculated by the empirical formula. The influence of the grid size, the state equation of water and the artificial viscosity coefficient on the numerical simulation calculation results is analyzed. Firstly, the underwater explosions with different grid sizes in 7 cases are studied, and it is found that when the value of η is greater than a certain value, the calculation results are basically unchanged, which means the calculation converges, as a result, the more suitable grid size is obtained. Secondly, the influence of different water state equations on the numerical calculation results is analyzed, focusing on the Mie-Grüneisen state equation and the Linear polynomial state equation. Thirdly, the effect of artificial viscosity coefficient is analyzed, the simulation results show that Q_2 has a greater influence on the numerical calculation results than Q_1. Finally, the similarity law of the model is discussed after selecting appropriate parameters. The results prove the universality of parameter values in the calculation model, which means more accurate results can be obtained for different charges.

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