

Three Dimensional High Order Parallel Investigations on Underwater Explosion

†C. Wang, *J. X. Ding, W. J. Wang and T. Li

State Key Lab of Explosion Science and Technology, Beijing Institute of Technology,
Beijing, 100081, China

*Presenting author: dingjianxu@163.com

†Corresponding author: wangcheng@bit.edu.cn

Abstract

Based on the double shockwave approximation procedure and combining RGFM procedure with level-set method, a local Riemann problem for strong nonlinear equations of state such as JWL equation of state was constructed and then solved to suppress successfully the numerical oscillation caused by high-density ratio and high-pressure ratio across the explosion products and water interface. A fifth order finite difference WENO scheme and the third order TVD Runge-Kutta method were utilized for spatial discretization and time advance, respectively. A novel enclosed type MPI-based parallel methodology for RGFM procedure on uniform structured meshes was presented to realize the parallelization of the three dimensional RGFM-based code for underwater explosion, which had dramatically improved the practical scale of computing model. The overall process of three dimensional bubble pulsations generated by underwater explosion of both TNT and aluminized explosives was successfully simulated with high order numerical scheme. The peak overpressure at different locations of three dimensional underwater explosion for both explosives mentioned above was monitored and analyzed for revealing the influence of aluminum powder combustion on peak overpressure of explosion wave. The numerical results obtained indicated that the attenuation of explosion wave formed by aluminized explosives was slower than that caused by TNT. The influences of aluminum powder combustion on bubble pulsations were also investigated by comparing TNT with aluminized explosives.

Key words: Underwater explosion; WENO scheme; RGFM; Local Riemann solver; Parallel computation

Introduction

Underwater explosion is one of the typical multi-medium problems, in which explosion flow usually consists of detonation products and water. It is obvious that the sharp medium interface with high-density ratio and high-pressure ratio separates the detonation products from water. In the process of numerical simulation on underwater explosion problem, because of the abrupt change with density and pressure close to the interface, the unphysical numerical oscillation is very easy to occur in the neighborhood of the interface. Meanwhile, as the continuous upgrade of explosives, density ratio and pressure ratio increase constantly and greatly. Therefore, tracking and treating the strong discontinuous nonlinear interface of underwater explosion becomes a gradually popular topic and receives considerable attentions in this field.

As for interface tracking technique, many scholars had presented some efficient ways over the past few decades. With particle-in-cell [Amsden (1966)] approach based on the rectangular mesh, the numerical results for the flow field and sharp material interface were achieved by tracking the particle. MAC method [Harlow and Welch (1965)] was often used to track the interface movement and the flow field evolution.

Level-set method [Sethian (1996); Adalsteinsson and Sethian (1999)] used the Hamilton-Jacobi equations to describe the moving interface, which was tracked for later time as the zero level set of the smooth signed distance function instead of the explicit function. Thus, some cases with complex interface, such as crisscross, torsion and separation, can be easily treated.

Fedkiw [Fedkiw et al. (1999)] presented the Ghost Fluid Method (GFM), which can obtain excellent results in treating the interaction between the weak shock wave and interface. Under the condition of strong shock wave, it, however, may get fake physical solution. Liu [Liu et al. (2003)] had put forward the MGFM procedure and a local Riemann problem solver, where the states of ghost fluid across the interface for each phase were defined. Wang [Wang et al. (2006)] presented the RGFM procedure. According to the states of medium across the interface, a local Riemann problem was constructed at first. The solution obtained was then used to redefine the flow states for not only real fluid grids next to the interface but also ghost fluid grids. Thus fewer errors were introduced by RGFM procedure. Considering the impact of the explosion on the interface with high-density ratio and high-pressure ratio and different equations of state, Zhao [Zhao et al. (2013)] proposed a novel interface treatment by combining the original GFM with RGFM procedure.

It can be observed that, since the GFM, MGFM and RGFM were presented, the numerical simulations for multi-medium flow had been applied widely. Simulating the underwater explosion based on the GFM in the attainable literatures generally used the stiff-gas equation of state for explosion products and water, while the complex EOS like JWL was seldom used. Meanwhile, RGFM-based simulation by splitting a multi-medium problem into single medium flows, usually requires that the computer hardware configuration is extremely rigor to satisfy a large-scale calculation. In general, serial computation can't meet the needs of three dimensional large-scale engineering applications.

In this paper, based on double shockwave approximation procedure, we first presented in detail a technology to solve the local Riemann problem with the complex equations of state such as JWL equation of state used in underwater explosion simulations. It effectively avoided the unphysical oscillation occurring at the multi-medium interface in explosion flow field. Combining RGFM method formally transformed multi-medium flow field into pure flow fields with enclosed type parallelization module, the mechanism of three dimensional underwater explosion and the evolutionary laws of bubble pulsation were obtained by using the fifth order finite difference WENO scheme on uniform structured meshes.

1. Governing equations

The equations governing three dimensional underwater explosion can be written as

$$\frac{\partial U}{\partial t} + \frac{\partial F(U)}{\partial x} + \frac{\partial G(U)}{\partial y} + \frac{\partial H(U)}{\partial z} = S, \quad (1)$$

$$U = (\rho, \rho u, \rho v, \rho w, \rho E)^T,$$

$$F = (\rho u, \rho u^2 + p, \rho uv, \rho uw, (\rho E + p)u)^T,$$

$$G = (\rho v, \rho uv, \rho v^2 + p, \rho vw, (\rho E + p)v)^T,$$

$$H = (\rho w, \rho uw, \rho vw, \rho w^2 + p, (\rho E + p)w)^T,$$

$$S = (0, 0, 0, 0, 0)^T,$$

where ρ , p denote the density and pressure, respectively. u , v and w are the velocity components, and E is the total energy per unit mass.

The total energy generally consists of internal energy and kinetic energy as follows

$$E = \frac{1}{2}(u^2 + v^2 + w^2) + e, \quad (2)$$

here e means the internal energy.

To close the above governing equations, the corresponding equations of state for explosion products and water must be introduced.

The explosion products are usually described by the JWL equation of state, which can be expressed in the following form as

$$p = A(1 - \frac{\omega\rho}{R_1\rho_0})e^{-\frac{R_1\rho_0}{\rho}} + B(1 - \frac{\omega\rho}{R_2\rho_0})e^{-\frac{R_2\rho_0}{\rho}} + \omega\rho e, \quad (3)$$

where the parameters A , B , R_1 , R_2 , ω and ρ_0 are material constants of detonation products, which are specifically shown in the following table.

Table 1. JWL EOS parameters for explosion products

$\rho_0(\text{kg/m}^3)$	$A(\text{MPa})$	$B(\text{MPa})$	$C(\text{MPa})$	R_1	R_2	ω
1630.0	373800.0	3747.0	734.0	4.15	0.9	0.35

The compressible water enclosing the explosion product is also our focus. So the stiff-gas equations of state must be required and could be written as

$$p = (\gamma - 1)\rho e - \gamma B, \quad (4)$$

where γ and B shown in Table 2 are constants.

Table 2. Stiff-gas EOS parameters for water

γ	$B(\text{MPa})$
7.15	331.0

For aluminized explosives, Miller mathematical model describing the combustion of aluminum powder can be written as

$$\frac{d\lambda}{dt} = a(1 - \lambda)^{\frac{1}{2}} p^{\frac{1}{2}}, \quad (5)$$

where λ is the reaction process variable characterizing the aluminum powder reaction degree in the process of aluminum powder combustion and a is a material constant.

2. The local Riemann problem for underwater explosion

After confirming the specific locations of the explosion products and water interface by advancing implicit Level-set function, RGFM-based multi-medium interface treatment should be utilized to change a multi-medium problem into two single medium problems. A local Riemann problem is constructed first at the interface and then solved. In the RGFM method, the predicted interface states solved by Riemann problem are assigned to the real fluid nodes just close to the interface in the real fluid. Then normal constant extrapolation by solving extension equation is used to acquire the values of three ghost fluid nodes required for high order WENO scheme. Next, the particular solution to local Riemann problem in underwater explosion will be described briefly.

Taking one dimensional case as an example, with the help of mass conservation equation and momentum conservation equation, the relationship between the velocity and pressure of the interface can be achieved as follows

$$u_* = F_1(p_*) = u_L - \sqrt{(P_* - P_L) \left(\frac{1}{\rho_L} - \frac{1}{\rho_{*L}} \right)}, \quad (6)$$

$$u_* = F_2(p_*) = u_R + \sqrt{(P_* - P_R) \left(\frac{1}{\rho_R} - \frac{1}{\rho_{*R}} \right)}, \quad (7)$$

here ρ_{*L} and ρ_{*R} are the densities of both sides of interface, which are unknown quantities for the time being and also need to be solved.

The nonlinear function relationship on interfacial pressure is obtained by the above two equations, which can be written as

$$F(p_*) = F_1(p_*) - F_2(p_*) = 0. \quad (8)$$

Combining energy conservation equation with respective equations of state, the implicit function with respect to ρ_{*L} , ρ_{*R} and p_* can be deduced and then given as

$$e_L(p_L, \rho_L) - e_{*L}(p_*, \rho_{*L}) - \frac{1}{2}(p_L + p_*) \frac{\rho_L - \rho_{*L}}{\rho_L \rho_{*L}} = 0, \quad (9)$$

$$e_{*R}(p_*, \rho_{*R}) - e_R(p_R, \rho_R) - \frac{1}{2}(p_* + p_R) \frac{\rho_{*R} - \rho_R}{\rho_{*R} \rho_R} = 0. \quad (10)$$

For the local Riemann problem composing of JWL equations of state and Stiff-gas equations of state, the brief process of solving it by Newton iterative method is described below. It is supposed that, for one dimensional Riemann problem, gaseous

detonation products locate at the left hand side of the interface and the water is on the opposite side. Obviously, the Eq. (8-10) is now a closed nonlinear equation consisting of interfacial pressure and both sides of densities close to interface as unknown variables. The classical Newton iterative method is adopted to solve the problem of interest, and it can be written as

$$p_{*(n+1)} = p_{*(n)} - \frac{F_1(p_{*(n)}) - F_2(p_{*(n)})}{F_1'(p_{*(n)}) - F_2'(p_{*(n)})}. \quad (11)$$

The appropriate guess value of the interfacial pressure for (11) is necessary, and should be selected at first. If the value of $|p_{*(n+1)} - p_{*(n)}|$ is equal or less than a given threshold, Newton iteration will be stop automatically, and the final result $p_{*(n+1)}$ is the interfacial pressure p_* to be sought. Thus, the velocity and both sides of densities can be obtained by simultaneously solving the Eq. (6), (9) and (10). At this point, the solution of the local Riemann problem in underwater explosion has been deduced completely.

3. Parallelization for RGFM procedure

For a general difference scheme, it is only required to communicate data in current process with adjacent processes in the orthogonal directions, that is to say, the processes in the diagonal directions are not necessary. For the WENO scheme combining with RGFM for underwater explosion, it is slightly different. If the interface is very close to any corner of the current computational process, information such as pressure and density at some nodes of diagonal processes will be inevitably used in the construction of the local Riemann problem. Considering such special requirements for RGFM method to implement data communication, a novel fully enclosed type data communication mode is presented, in which the enclosed communication boundaries are built on the periphery of computational domain of any process.

Table 3. Parallelization for RGFM

Process number of receive buffer	Receive buffer number	Send buffer number	Process number of send buffer
n	1	4	n-x-1
n	2	3	n-x+1
n	3	2	n+x-1
n	4	1	n+x+1
n	5	6	n-1
n	6	5	n+1
n	7	8	n-x
n	8	7	n+x

The above table takes the two dimensional case as an example to illustrate the presented enclosed type parallel method. It is obvious that the method can be directly extended to three dimension underwater explosion, and has been implemented in this paper.

4. Numerical investigations on three dimensional underwater explosion

4.1 Validation

According to the one dimensional fluid unsteady motion theory, the law of bubble pulsation can be given as

$$R_b'' = \frac{27}{64} P_H \frac{r^9}{\rho R_b^{10}} - \frac{p_\infty}{\rho R_b} - \frac{3}{2} \frac{R_b'^2}{R_b}. \quad (12)$$

The corresponding initial condition has the following form

$$\begin{cases} R_b|_{t=0} = r \\ R_b'|_{t=0} = 0 \end{cases}. \quad (13)$$

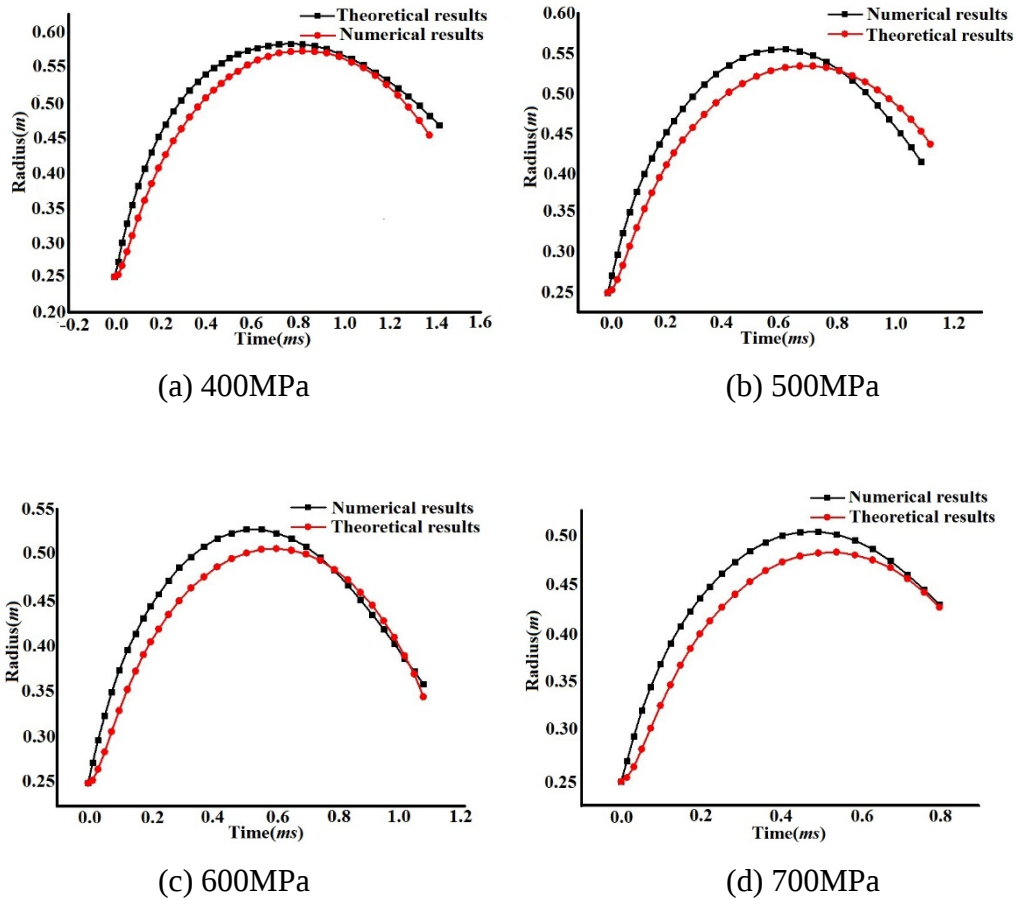


Figure 1. The comparisons of numerical results with theoretical results on bubble radius under different pressures

The numerical results of bubble pulsation using RGFM procedure are compared with the theoretical results, which is shown in Fig.1. The maximum bubble radius and its corresponding time are shown in Table 4 and Table 5, respectively. It is evident from Fig.1 and two tables that the numerical results obtained are consistent with the theoretical results, and that the errors of maximum bubble radius and its time don't exceed 10%. So, the RGFM-based high order procedure presented in this paper can exactly describe the whole process of bubble pulsation.

Table 4. The comparisons of numerical results of maximum bubble radius with theoretical results

Pressures	Theoretical results(m)	Numerical results(m)	Relative errors
400MPa	0.572	0.583	1.9%
500MPa	0.534	0.555	3.9%
600MPa	0.506	0.527	4.2%
700MPa	0.483	0.504	4.3%

Table 5. The comparisons of numerical results of the maximum radius time with theoretical results

Pressures	Theoretical results(m)	Numerical results(m)	Relative errors
400MPa	0.819	0.768	-6.2%
500MPa	0.668	0.618	-7.5%
600MPa	0.602	0.554	-8.0%
700MPa	0.541	0.495	-8.5%

4.2 Numerical investigations on bubble pulsation of TNT explosive

The TNT explosive is used with the radius of 0.25m for underwater explosion. Water pressure is 400MPa, 500MPa and 600 MPa, respectively. Apparently, the selected pressure exceeds the usual pressure of underwater explosion. The main purpose is to save the computing time without damaging the essential laws of bubble pulsation. The 64 processes are employed to compute this problem with up to 13.824 million grids. The size of grids is 0.02m×0.02m×0.02m, while the whole physical domain is 4.8m×4.8m×4.8m.

The computational results at some typical moments are shown in Fig. 2-4. The contour of density and pressure are very symmetrical and fake nonphysical oscillation doesn't happen. The distribution of density and pressure in the underwater explosion field can be reflected precisely.

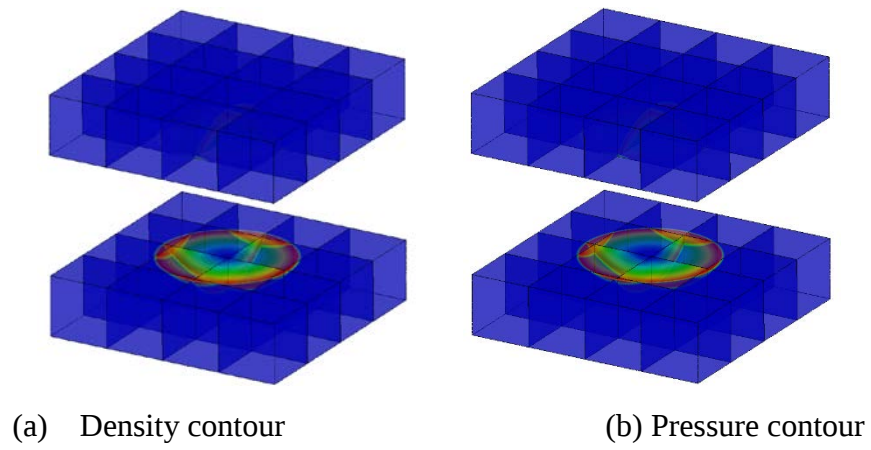


Figure 2. Numerical results at 0.531ms

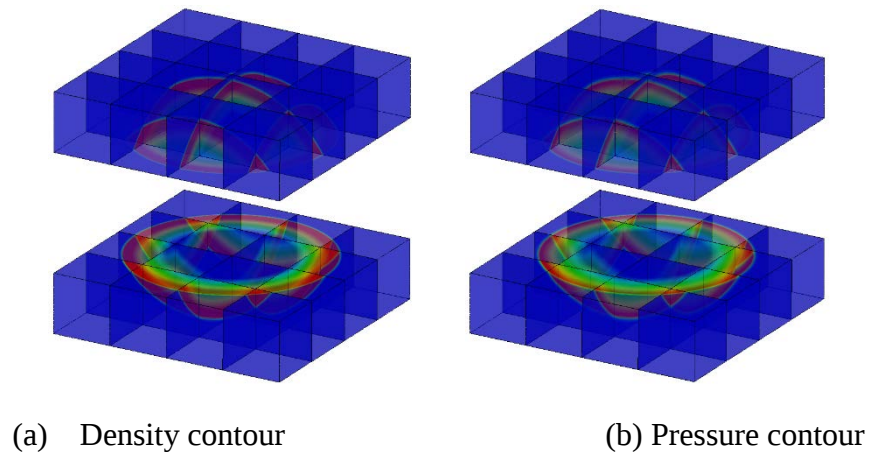


Figure 3. Numerical results at 0.744ms

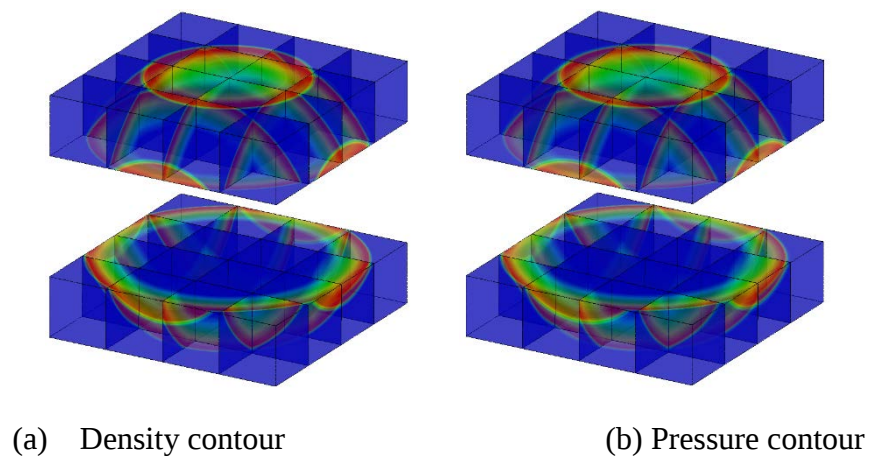


Figure 4. Numerical results at 0.962ms

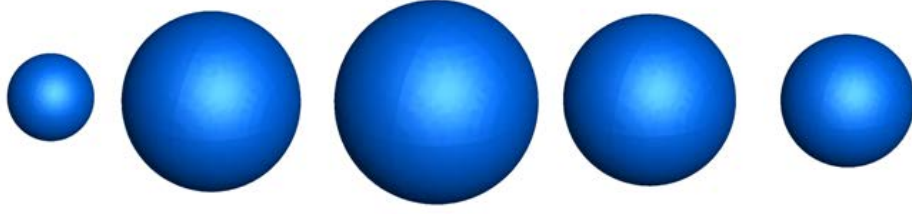


Figure 5. Numerical results on the evolution of bubble pulsation

The numerical results shown in Fig. 5 indicate that combining the local Riemann solver with RGFM procedure can exactly simulate the full process of underwater explosion and bubble pulsation, and the interface of the computed bubble consistently maintains smooth without any numerical oscillation.

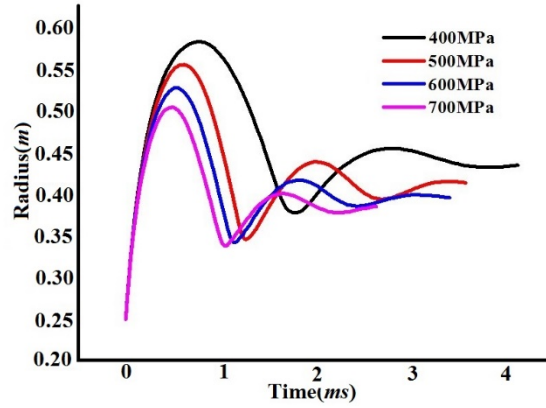


Figure 6. The evolution of bubble radius under the different pressure conditions

Fig. 6 shows that maximum bubble radius decreases with the increase of pressure. The maximum radius is 0.583m when water pressure is 400MPa. When its pressure is 700MPa, the maximum radius reduces by 13.6% and decreases to 0.504m. Bubble pulsation period also decreases with the increase of pressure. The pulsation period is 1.749ms when pressure is 400MPa. When pressure is 700MPa, the period reduces by 40.4% and reduce to 1.043ms. So, the influence of water pressure on bubble pulsation period is more obvious.

The numerical results reveal that the physical essence of expansion and contraction of the bubble interface is the movement of contact discontinuity for local Riemann problem at the interface, and the pressure, normal speed and density close to the interface determine the evolution of bubble interface. Thus, solving local Riemann problem is an effective way to quantitatively reveal the formation mechanism of bubble pulsation. Solving local Riemann problem can obtain accurate flow characteristics near the interface and the evolution of bubble interface in the flow field. The complete process of bubble pulsation is captured nicely. Therefore, the unique advantages based on RGFM procedure and local Riemann solver are obvious to simulate bubble pulsation in underwater explosion.

4.3 Numerical investigations on bubble pulsation of aluminized explosives

The aluminized explosives is simplified to gas detonation products containing unreacted aluminum powder. The stiff-gas equation of state is used for water. The initial pressure is 500 MPa, and the radius of explosive is 0.21m. The 64 processes are employed for this problem with 13.824 million grids, and the size of grids is 0.02m×0.02m×0.02m, while the whole physical domain is also 4.8m×4.8m×4.8m.

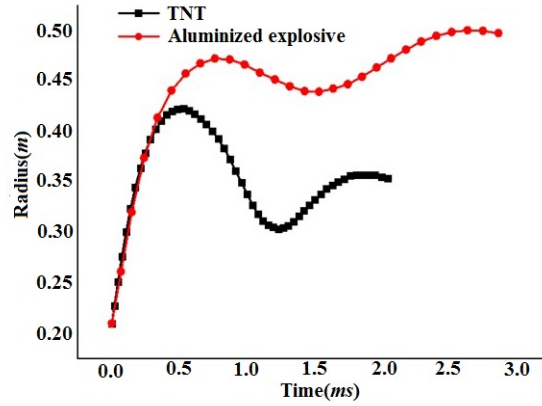


Figure 7. The comparison of aluminized explosive with TNT on bubble pulsation radius under 500 MPa water pressure

It is shown in Fig. 7 that the expansion processes of two kinds of explosive are almost the same at the initial stage and the radius-time curve is substantially coincident. But, at the late stage, the appearances of two kinds of explosives are very different. First, the maximum bubble radius and its evolutionary period of aluminized explosives are significantly greater than those of TNT. Second, because explosion wave propagation causes energy loss, the maximum radius for TNT at the later stage becomes small. For aluminized explosives, the maximum radius during the second period is even greater than that of the previous period due to the secondary energy release formed by the combustion of aluminum powder supplementing the energy losses to some extent.

Conclusions

Combining RGFM multi-medium interface treatment method with fifth order finite difference WENO scheme, the large scale underwater explosion parallel simulations are performed by the novel Riemann problem solver presented for complex nonlinear equations of state and MPI-based enclose type parallel module. The three dimensional whole physical processes of bubble pulsation in underwater explosion are numerically investigated. The important mechanism of underwater explosion is also revealed as follows:

- 1) Solving local Riemann problem defined by detonation products and water can essentially depicts the motion process of bubble surface caused by both sides of the flow field, by which the complete process of bubble pulsation is captured exactly. The

maximum radius and its corresponding time of bubble obtained by numerical simulations are agreed well with the theoretical results;

2) For bubble pulsation in underwater explosion, the physical essence of expansion and contraction of bubble surface is the propagation of contact discontinuity of local Riemann problem at the explosion products and water interface. The interfacial states including pressure and normal speed at the interface and density on both sides of the interface play a key role in determining the motion behavior of bubble surface;

3) For the same charge configuration, with the increase of water pressure, both maximum bubble radius and its pulsation period decrease. Nevertheless, the influence of water pressure on bubble pulsation period is more obvious than maximum bubble radius;

4) The secondary energy release for aluminized explosives can continuously add the energy loss caused by explosion wave propagation in water. So in the subsequent process of bubble pulsation, the radius and pulsation period for aluminized explosives are obviously larger than those of TNT charge. Maximum radius of aluminized explosive in the process of the second pulsation even exceeds the first pulsation process.

Acknowledgement

This work is supported by the National Natural Science Foundation of China under grant number 11325209 and 11272056, the Specialized Research Foundation for the Doctoral Program of Higher Education of China under grant 20121101110004, Beijing Natural Science Foundation (8132034)

References

- Amsden, A. A. (1966) The particle-in cell method for the calculations of the dynamics of compressible fluids, *Los Alamos Scientific Laboratory Report*, LA-3466.
- Harlow, F. H. and Welch, J. E. (1965) Numerical calculation of time dependent viscous incompressible flow of fluid with free surface, *Physics of Fluids* **8**, 2182-2189.
- Sethian, J. A. (1996) Theory, algorithms, and applications of level set methods for propagating interfaces, *Acta Numerica* **5**, 309-395.
- Adalsteinsson, D. and Sethian, J. A. (1999) The fast construction of extension velocities in level set methods, *Journal of Computational Physics* **148**, 2-22.
- Fedkiw, R. P., Aslam, T., Merriman, B. and Osher, S. (1999) A non-oscillatory Eulerian approach to interfaces in multimaterial flows (the ghost fluid method), *Journal of Computational Physics* **152**, 457-492.
- Liu, T. G., Khoo, B. C. and Yeo, K. S. (2003) Ghost fluid method for strong shock impacting on material interface, *Journal of Computational Physics* **190**, 651-681.
- Wang, C. W., Liu, T. G. and Khoo, B. C. (2006) A real ghost fluid method for the simulation of multimedium compressible flow, *Siam Journal on Scientific Computing* **28**, 278-302.
- Zhao, H. T. and Wang, C. (2013) High resolution numerical simulation of air explosion, *Acta Armamentarii* **34**, 1536-1546.