Numerical simulation of two-phase flow field in underwater sealing device based on dynamic mesh

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Abstract: In order to speed underwater launch of minor-caliber weapons, a sealing device can be set in front of underwater muzzle to separate water, preventing the muzzle from water immersion. By establishing and simplifying the model of underwater weapon sealing device and unstructured mesh computing domain model based on computational fluid dynamics (CFD), dynamic mesh and user defined function (UDF), the N-S equation is solved and the numerical analysis and calculation of the complex two-phase flow inside the sealing device are carried out. The results show that the gas discharged from the sealing device is conducive to the formation of the projectile supercavity. When the projectile is launched at 5 m under water, the shock wave before and after the projectile has impact on the box body up to 100 MPa, therefore the sealing device must be strong enough. The research results have the vital significance to the design of underwater weapon sealing device and the formation of the projectile supercavitation.

Key words: two-phase flow; supercavitation; sealing device; computational fluid dynamics (CFD); dynamic mech

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As a result of the change of international situation, the water weapon has got rapid development. The density of water is about 850 times as dense as that of air, thus water resistance is too large for projectile weapons to hit the target at a distance. Therefore, how to increase the initial velocity and decrease the resistance of underwater weapon inevitably becomes the key of the research.

In recent years, many experts and scholars have done a lot of work in the numerical simulation of underwater jet and supercavity based on computational fluid dynamics (CFD). TANG, et al. [1] used volume of fluid (VOF) model to simulate the evolution of underwater gas jet. XU Jia-wei, et al. [2-3] used mixture model based on FLUENT software to study the unsteady evolution process of nozzle air-water two-phase flow field at different underwater depths in rocket ignition experiment. CHEN Huan-long, et al. [4-5] calculated the initial flow of underwater gas jet using axisymmetric, inviscid and compressible Euler equations, revealed the gas-water interaction and shock wave shape as well as the formation and evolution process of jet air bags at jet initial stage, and confirmed the similarity of near flow fields of the gas jet in the water and gas. ZHU Lin, et al. used the dynamic mesh technique and mixed multiple flow model to get the effect of thrusting force on production, variation and development processes of water cavity and natural cavity hydrodynamics of projectile bodies[6]. YI Wen-jun, et al. used mixed multi-phase flow model of Fluet6. 2 to conduct the simulation of resistance characteristics of underwater projectile[7]. Uhlman and Kinnas[8-10] and Fine used the velocity potential modified boundary element method to carry out nonlinear simulation on many cases of partial cavity flow. But the analysis of muzzle gas injecting sealed container is rare. This paper, using mixed multiple flow model and dynamic mesh technology, by solving N-S equations, carries numerical analysis and calculation for complex water-gas two-phase flow

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inside it and gets the distribution of the flow field inside the sealing device. Furthermore, the strength of the sealing device and bubble formation of supercavitation are analyzed.

1 Control equation and numerical method

1.1 Control equation

The basic laws of conservation in the element include the following equations.

Continuity equation

$$\frac{\partial \rho}{\partial t}+\nabla \cdot (\rho \boldsymbol{V}) = S_{\mathrm{m}}, \tag{1}$$

Momentum conservation theorem

$$\frac{\partial (\rho \boldsymbol{V})}{\partial t}+\nabla (\rho \boldsymbol{V}\boldsymbol{V}) = -\nabla p+\nabla (\boldsymbol{\tau})+\rho \boldsymbol{g}+\boldsymbol{F}, \tag{2}$$

Energy conservation equation

$$\frac{\partial (\rho E)}{\partial t}+\nabla (\boldsymbol{V}(\rho E+p)) = \nabla (k_{\mathrm{eff}}\nabla T-\sum_j h_j J_j+(\tau_{\mathrm{eff}}\cdot V))+S_{\mathrm{h}}, \tag{3}$$

where ρ stands for the density; t, the time; $\boldsymbol{V}$, the velocity vector; S_{m}, the mass added to the continuous phase; p, the pressure born on upon fluid micelle; $\boldsymbol{g}$ and $\boldsymbol{F}$ represent gravity and other external volume forces exerted on the infinitesimal; $\boldsymbol{\tau}$, the viscous stress tensor on infinitesimal surface due to molecular viscosity; E, the fluid micelle gross energy; T, the temperature; J_j, the diffusion flux of j; k_{eff}, effective thermal conductivity; and S_{h}, the other customized heat sources.

1.2 Cavitation model

Regardless of the influence of the latent heat of evaporation, it is done in the isothermal process. Considering the pressure and bubble volume, Rayleigh-Plesset equation is written as

$$R\frac{\mathrm{d}^2R}{\mathrm{d}t^2}+\frac{3}{2}\left(\frac{\mathrm{d}R}{\mathrm{d}t}\right)^2 = \frac{p_{\mathrm{B}}-p}{\rho_{\mathrm{l}}}-\frac{2\sigma}{\rho_{\mathrm{l}}R}-4\frac{\mu_{\mathrm{l}}}{\rho_{\mathrm{l}}R}\frac{\mathrm{d}R}{\mathrm{d}t}, \tag{4}$$

where p_{B} is the pressure inside the cavity, which is the sum of steam pressure p_{v} and noncondensable gas partial pressure p; σ is coefficient of surface tension. Simulation calculation functions for growth and rupture process of cavitation are given by

$$\frac{\mathrm{d}R}{\mathrm{d}t} = \begin{cases} \sqrt{\dfrac{2(p_{\mathrm{B}}-p)}{3\rho_{\mathrm{l}}}} & p_{\mathrm{v}} > p, \\ -\sqrt{\dfrac{2(p_{\mathrm{B}}-p)}{3\rho_{\mathrm{l}}}} & p_{\mathrm{v}} < p. \end{cases} \tag{5}$$

2 Dynamic meshing theory and computation model

2.1 Dynamic mesh updating method

FLUENT provides three methods of dynamic meshing movement to update the mesh after deformation, including spring smoothing method (smoothing), dynamic layer method (layering) and local mesh reconstruction method (remeshing). Spring smoothing method is to idealize the meshes between the nodes as a spring system. The movement of boundary nodes produces spring force between the nodes, and the force spreads along the downstream nodes in turn and eventually produces a new spring system. Dynamic layer method is that whether to increase or to decrease the mesh layer number is determined by the height of mesh layer close to the moving object surface. In FLUENT, when the mesh cell layer near the border increases or reduces to a certain extent, the mesh automatically splits or merges. Local mesh reconstruction method refers to the interpolation reconstruction method for distorted mesh because the movement of boundary may result in serious quality decline, even negative volume, which increases the difficultly for next solution. The methods adopted in this article to control mesh deformation are the spring smoothing method and the local mesh reconstruction method.

2.2 Establishment of computation model

A 3D model profile of a sealing device is shown in Fig. 1. The whole sealing device is put under water at a depth of 5 m whose inside pressure and water pressure are equal before firing. The valve (unshown in Fig. 1) of the sealing device under the water pressure acts as a seal. Mesh partition method is used for the calculation region, and mesh refinement is processed within the tube and sealing device. The farther from the tank, the sparser the mesh is. Boundary conditions include pressure export, pressure inlet and the solid wall boundary. The related parameters of pressure export and the depth of water are the same, and the pressure inlet parametes are defined based on field function. At the same time, FLUENT UDF is used to control projectile motion parameters. The initial velocity of the projectile is 890 m/s.

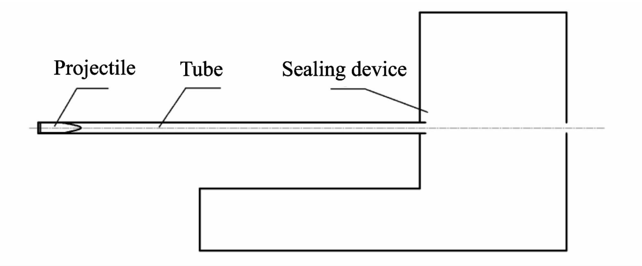


Fig. 1 Sealing device with a tube

Fig. 2 exhibits the computation mesh in flow field of the sealing device with a tube.

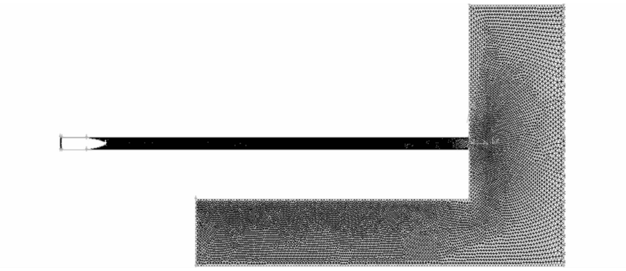


Fig. 2 Computation mesh in flow field of sealing device with a tube

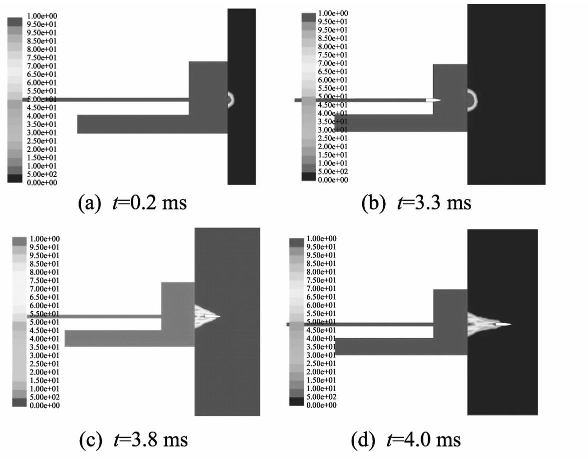
In the process of the projectile entering into the water, air, vapor and liquid water are allowed to interpenetrate each other and move at different speeds. VOF model is not applicable, mixture model should be shosen.

FLUENT simulation settings: ① Calculation is based on three-phase flow, whose major phase is water and minor phases are vapor and compressible gas; ② Realizable k-ε model is selected as turbulence model, PRESTO is as the pressure and velocity fields coupled mode; ③ Gravity effect should be considered, and the change curve of water pressure with depth is defined based on field function, Patch for repairing it in the computational domain; ④ Using the cavitation model is opened.

Making unsteady calculation according to the above settings, we can get better convergence by selecting the appropriate iteration step length and the relaxion factor.

3 Simulation and analysis

Fig. 3 is the nephogram of gas-liquid phase distribution at different times after projectile is out of the chamber. It can be seen that the moment the projectile firing, shock wave in front of projectile is generated by squeezing the air in front of projectile when the projectile moves at high speed in the tube. The gas expands rapidly after entering the sealing device, which results in pressure rising and part of the gas is pushed through the valve into the water forming bubbles. With the projectile velocity increasing, the shock waves in front of the projectile keep swelling and the gas inside the sealing device is constantly discharged into the water, and bubbles increase quickly. After 3.3 ms, gunpowder gas was totally released into the case and enough pressure is created to form a big bubble to wrap the projectile outside the sealing device. At 3.5 ms, the projectile moved throughout the sealing device into the big bubble in the water. At 3.8 ms, the projectile pierced the big bubble into the water, but was still wrapped by cavitation bubbles which are natural supercavitation. The bubbles in the valve in the seal device is helpful to provide the projectile with ventilated supercavitation. The device combines the ventilated supercavitation with natural supercavitation perfectly.



(a) t=0.2 ms (b) t=3.3 ms

(c) t=3.8 ms (d) t=4.0 ms

Fig. 3 Nephogram of gas-liquid phase distribution at different times after firing

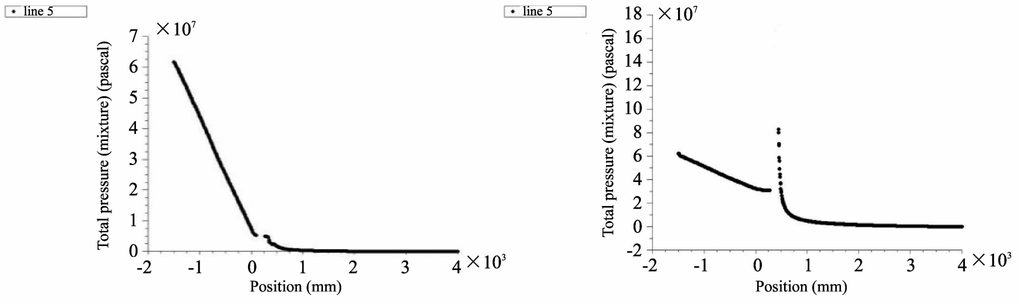
Fig. 4 is the pressure distribution curve in axial direction of gun when the projectile is fired out of muzzle and goes into the sealing device at different times.

It can be seen that at 3. 3 ms, warhead is just fired out of the tube. The pressure distribution behind the projectile is linear, but the pressure in front of the projectile is higher than atmospheric pressure. This is because the moving projectile in the tube pushes the air in the tube leaked behind the projectile as well as gunpowder gas into the sealing device.

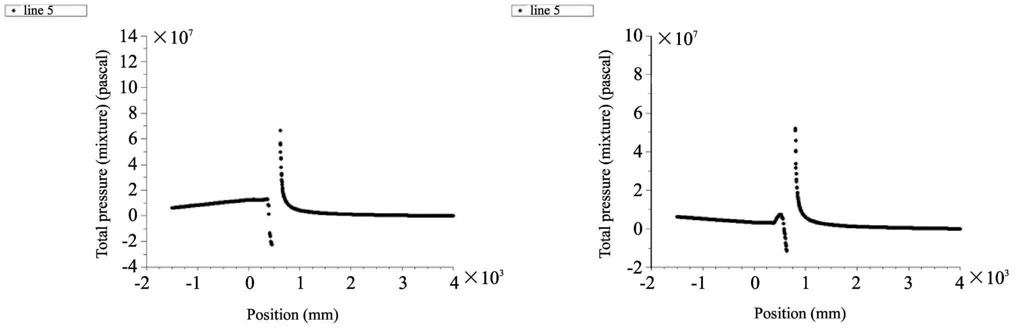
At 3. 5 ms, the projectile goes through the tube into the sealing device, the pressure behind the projectile spreads instantly in the sealing device. But unlike in the air, the pressure diffusion is restricted by the sealing device, resulting in high pressure in the sealing device. The projectile under high pressure continues to move forward and warhead appears in high pressure area. For high-speed projectile, it moves in the sealing device in a very short time, therefore, the effect on the projectile velocity can be neglected. At the time of 3. 8 ms, the projectile goes into the water and the end of the projectile appears in low pressure area, which is conducive to the formation of cavitation bubble.

At 4. 0 ms, the pressure of gunpowder gas is still greater than the water pressure. It may be impossible for the gunpowder gas to be instantly released into the sealing device because of the small mouth of the valve, which means the water not going back to the sealing device under super-high firing frequency can be realized absolutely.

During the whole process, the gunpowder gas is kept in the sealing device and the maxium shock wave can reach up to 100 MPa generated by gunpowder gas at high temperature and high pressure, which requires strong strength capacity of the sealing device.



(a) t=3.3 ms (b) t=3.5 ms



(c) t=3.8 ms (d) t=4.0 ms

Fig. 4 Pressure distribution curves in axial direction of gun at different times after projectile is out of muzzle

4 Conclusion

The following conclusion can be drawn based on numerical simulation on the complex two-phase flow in the sealing device of underwater weapon by using FLUENT. When the underwater weapon with the sealing device is fired, gunpowder gas pressure distribution in the sealing device is extremely complex. The high pressure also requires strong strength of the sealing device. With high-speed movement, the gas in front of the projectile is extruded and shock wave is formed. The gas in front of the projectile and gunpowder gas leaked from the clearance between projectile and tube expand rapidly after entering sealing device, which results in pressure rising in the sealing device. With the increasing of pressure, the gas inside the sealing device is discharged into the water. As the projectile entering the water, the pressure inside the sealing device is strong enough to prevent the reverse flow of water. Under ultra-high frequency shooting, the pressure of the sealing device can ensure that the water will not flow back at the depth of 25 m under water; at the same time, the actuating pressure of the sealing device caused by the projectile shock wave reach up to 100 MPa. The research results may have some significance to the design of underwater weapon sealing device and the formation of the projectile supercavitation.

References

[1] Tang J N, Wang N F, Wei Shyy. Flow structure of gaseous jets injected into water for underwater propulsion. Acta Mechanica Sinica, 2011, 27(4): 461-472.

[2] CHEN Huan-long, WANG Ning, LIU Hua-ping, et al. Investigation of nozzle gas jet characteristics with different launch depth underwater. Chinese Journal of Hydrodynamics, 2012, 27(6): 659-664.

[3] XU Jia-wei. Numerical simulation of gas jet due to underwater missle of different ocean depths. Harbin: Harbin Institute of Technology, 2009: 33-89.

[4] HE Xiao-yan, MA Han-dong, JI Chu-qun. Numerical simulation of the underwater gas jets formed. Journal of Hydrodynamics A, 2004, 19(2): 207-212.

[5] HE Xiao-yan, MA Han-dong, WANG Qiang. Temporal instability of compressible 3D gas injected in liquids. Acta Aerodynamica Sinica, 2002, 20(1):78-83.

[6] ZHU lin, YUAN Xu-long, WANG Ya-dong. The influence of the thrusting force on the characters of the high speed flow field. Journal of Air Force Engineering University(Natural Science Edition), 2014, 15(1): 10-14.

[7] YI Wen-jun, WANG Zhong-yuan, XIONG Tian-hong, et al. Research on drag reduction characteristics of a underwater high-speed supercavitation projectile. Journal of Ballistics, 2008, 20(4): 1-4.

[8] Uhalman J S. The surface singularity method applied to partially cavitating hydofoils. Journal of Ship Research, 1987: 23-36.

[9] Uhalman J S. The surface singulaity or boundary integral method applied to supercavitating hydrofoils. Journal of ship Research, 1989, 31(1): 51-65.

[10] Kinnas S A, Fine N E. A numerical nonlinear analysis of the flow around two-and three-dimensional partially cavitating hydrofoils. Journal of Fluid Mechanics, 1993 (254): 151-181.

基于动网格的水下发射装置两相流研究

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摘　要： 为防止水下武器发射时水流浸没身管，提高小口径武器在水下发射的初速，水下武器膛口前需设计密封装置。建立水下武器密封装置模型的非结构网格计算域模型，利用计算流体动力学(CFD)、动网格和UDF等相关知识，通过求解N-S方程，对密封装置内复杂的两相流进行了数值分析计算。仿真结果表明，密封装置内排出的气体有利于射弹超空炮的形成；此外，在水下5 m发射时弹前激波和弹后激波对箱体冲击作用力峰值可达100 MPa，因此要求密封装置要有足够的强度。

关键词： 两相流；超空泡；密封装置；计算流体动力学；动网格

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