INTRODUCTION

The submarine-launched missile is an advanced army weapon which can across the different media. This launching technology has advantages of good invisibility, large-scale maneuvering, strong viability and destructiveness. At present the gas-steam ejection dynamic system is usually employed by Submarine launched missile. The trajectory underwater includes tube-exit stage, free moving stage in water and water-exit stage. The stage of tube-exit is the most important stage for its complex mechanical environment. When the missile bottom leaves the tube outlet, the high pressure gas will move into water and forms cavity in missile bottom. With the missile moving and hydrostatic pressure impacting, the cavity will expand, shrink and break and its effects on trajectory of missile and loads on deck are presented. In addition, the natural cavitation of missile shoulder because of high speed movement of missile is analyzed.

A Study on the Tube-exit Cavity Surrounding Submarine-launched Missile

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ABSTRACT: The gas-steam ejection dynamic system is usually employed by submarine launched missile. In the separating process of missile tail and canister outlet, cavity formed by Interaction between gas and water has influence on the load of launch platform and missile trajectory. The mixture multiphase flow model, RNG k-ε turbulence model combined with the dynamic mesh model were adopted to simulate the tube-exit cavity and missile trajectory. The results show that in the process of missile bottom leaving tube, the high pressure gas pours out and forms cavity in missile bottom. With the missile moving and hydrostatic pressure impacting, the cavity will expand, shrink and break and its effects on trajectory of missile and loads on deck are presented. In addition, the natural cavitation of missile shoulder because of high speed movement of missile is analyzed.

Keywords: submarine-launched missile; multiphase flow; dynamic mesh technology; cavitation; trajectory

1 INTRODUCTION

The research mentioned above most didn’t consider the process of missile in tube. In the paper, the mixture multiphase model and dynamic mesh are adopted to simulate the whole process of submarine launch. What’s more, the interaction between gas and water in tube-exit process, the trajectory parameters of missile and loads in platform are analyzed.

2 MATHEMATICAL MODEL

2.1 Governing equations

The equation for the mass and momentum conservation were applied to simulate the tube-exit flow field. The equation for the mass conservation can be written as

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{V}) = 0$$

(1)

$$\frac{\partial (\rho f_i)}{\partial t} + \nabla \cdot (\rho f_i \vec{V}) = \dot{m}^i - \dot{m}^i$$

(2)

$$\frac{\partial (\rho g_f)}{\partial t} + \nabla \cdot (\rho g_f \vec{V}) = 0$$

(3)

In the equation, we defined the velocity vector $\vec{V}$, the phase density $\rho_i$, the phase volume fraction $a_i$, the phase mass fraction $f_i$, where the subscripts $i=1$, v, ng denote liquid, vapor and non-condensable phase respectively. where $(\dot{m}^i - \dot{m}^i)$ is the net phase change rate. $\dot{m}^i$ is the mass transfer rate from liquid to vapor

$$\dot{m}^i = c_e \frac{\sqrt{k}}{\sigma} \rho_i \rho_j \left( \frac{2}{3} \frac{p_v - p}{\rho_j} \right)^{1/2} \left( 1 - f_v - f_g \right)$$

(4)

$\dot{m}^i$ is the mass transfer rate from vapor to liquid

$$\dot{m}^i = c_e \frac{\sqrt{k}}{\sigma} \rho_i \rho_j \left( \frac{2}{3} \frac{p_v - p}{\rho_j} \right)^{1/2} f_v$$

(5)

where the values of empirical constant $c_e$ and $c_e$, which regulate the rate of evaporation and condensation of phases respectively, are 0.02 and 0.01, surface tension $\sigma$ to 0.717N/m.

The equation for momentum conservation can be written as

$$\frac{\partial (\rho \vec{V})}{\partial t} + \nabla \cdot (\rho \vec{V} \vec{V}) = \nabla \left( \frac{p + \frac{2}{3} \mu \nabla \cdot \vec{V}}{\rho} \right)$$

(6)

Where $\vec{S}$ is the rate of deformation tensor, $p$ is the dynamic pressure, $g$ is the gravitational acceleration and $\mu_e$ is the effective viscosity.

2.2 Cavitation model

In the current research, Zwart-Gerber-Belamri model\cite{9} is taken to simulate cavitation. It can be expressed as

$$\frac{\partial}{\partial t} (\alpha_v \rho_v) + \frac{\partial}{\partial x_j} (\alpha_v \rho_v u_j) = R_v - R_c$$

(7)

If $P \leq P_v$

$$R_v = F_{vap} \frac{3 \alpha_{mc}(1-\alpha_v) \rho_v}{R_b} \sqrt{\frac{2 P_v - P}{3 \rho_i}}$$

(8)

If $P > P_v$

$$R_v = F_{cond} \frac{3 \alpha_v \rho_v}{R_b} \sqrt{\frac{2 P - P_v}{3 \rho_i}}$$

(9)

Where $P_v$ is the saturated vapor pressure, $R_b$ is bubble radius, $\alpha_{mc}$ is the nucleation site volume fraction, $F_{vap}$ is evaporation coefficient, and $F_{cond}$ is condensation coefficient.

2.3 Turbulence model

In the current research, the RNG $k-\epsilon$ turbulence model\cite{10} is adopted to simulate submarine missile launching.

Turbulent kinetic equation

$$\frac{\partial}{\partial t} (\rho \kappa) + \frac{\partial}{\partial x_j} (\rho \kappa u_j) = \frac{\partial}{\partial x_j} \left[ \frac{\mu + \mu_t}{\sigma_k} \frac{\partial \kappa}{\partial x_j} \right]$$

$$+ G_k + G_b - \rho \epsilon - Y_M$$

Dissipation rate equation

$$\frac{\partial}{\partial t} (\rho \epsilon) + \frac{\partial}{\partial x_j} (\rho \epsilon u_j) = \frac{\partial}{\partial x_j} \left[ \left( \mu + \mu_t \right) \frac{\partial \epsilon}{\partial x_j} \right]$$

$$+ C_{1\epsilon} \frac{\epsilon}{k} \left( G_k + C_{\alpha_s} G_b \right) - C_{2\epsilon} \rho \frac{\epsilon^2}{k}$$

(11)

where $G_k$ and $G_b$ represent the generation of turbulence kinetic energy due to the mean velocity gradients and buoyancy respectively. $Y_M$ represents the contribution of the fluctuating dilatation in compressible turbulence to the overall dissipation rate. $C_{1\epsilon}$, $C_{2\epsilon}$ and $C_{\alpha_s}$ are constants; $\alpha_k$ and $\alpha_\epsilon$ are the turbulent Prandtl numbers for $k$ and $\epsilon$, respectively. The turbulent viscosity, $\mu_t$, is computed by combining $k$ and $\epsilon$ as follows

$$\mu_t = \rho C_{\mu} \frac{k^2}{\epsilon}$$

(12)

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2.4 Motion equation of missile

In the process of submarine launch, the forces including gravity $G$, acting force $F_{\text{gas}}$ by gas and acting force $F_{\text{liq}}$ by liquid are applied to missile. Thus the motion equation of missile can be expressed as

$$\frac{d(m\vec{v})}{dt} = \vec{G} + \vec{F}_{\text{gas}} + \vec{F}_{\text{liq}} \quad (13)$$

Where $m$ is the missile mass. The UDF is applied to calculate the forces of missile and update the velocity of missile.

3 COMPUTATIONAL METHODS

3.1 Computational model

Figure 1 shows the submarine launch process simplified model. The coupling of pressure and velocity terms use SIMPLIC algorithm. The PRESTO difference scheme is used in pressure term and the second-order upwind discretization scheme is applied in momentum, energy and dissipation terms.

3.2 Boundary conditions

In Figure 1, the missile, tube and deck surface are wall boundary conditions. The gas inlet is set as pressure inlet and $p=p(t)$, $T=300K$, $\alpha=0$. Where $p(t)$ is the pressure in Figure 2. When time comes to 0.5s, the gas-inlet boundary changes to wall boundary condition. The BCS of the water field is set as

$$p = p_0 + \rho_{\text{liq}}gh \quad (12)$$

where $p_0$ is the local atmospheric pressure, $g$ is the gravity acceleration, $h$ is the depth of water and $h=30m$.

4 RESULTS AND DISCUSSION

Figure 3 shows the laws for acceleration and velocity in whole launch process. As we can see from the Figure 3, the law for acceleration is consistent with figure 2 before 0.5s. After missile bottom leaving the tube, the high pressure gas in tube moves into water so that the load in missile bottom and the acceleration drop. Along with the movement of the missile, the water pressure reduces, so the water drag in missile decreases and the acceleration lifts. After 0.65s, the acceleration is always negative so that the velocity is decreasing.

Figure 4 shows the volume fraction contour of water phase in different time. Before the missile bottom leaving the tube, the high pressure gas is restricted within the tube. A small amount of air between missile wall and tube wall pour out along with the missile moving. When missile bottom leaves the tube, the high pressure gas in tube flows out quickly because of the pressure difference and forms cavity in the missile bottom. With the bubbles expanding, the pressure of gas drops rapidly and the expansion velocity of cavity will reduce gradually. When the expansion rate is less than the missile moving velocity, the cavity will follow the missile to move. When the cavity pressure is further reduced to a certain extent, it begins to shrink and breaks into two parts finally. At the moment of 0.8s, the cavity near tube outlet will be compressed by the water and much water will flow into tube.

Figure 5 and Figure 6 show the contour of $\alpha_v$ near missile shoulder and pressure of missile wall are Figure 5 respectively. Because the velocity of missile out of tube and the hydrostatic pressure are small before
0.5s, the cavitation number is relatively large and the missile surface doesn’t appear obvious cavitation. With the missile velocity increasing and the hydrostatic pressure decreasing, the cavity in missile shoulder grows gradually. It can be observed in Figure 6, where $x_0$ is the length of missile. The cavitation zone increases over time and the cavity length in 1.0s is about three times larger than 0.5s.

Figure 4. Volume fraction contour of water phase.

Figure 5. Contour of $\alpha_v$ near missile shoulder.

Figure 6. Pressure of missile wall.
To research the pressure change of deck, seven monitoring points are set as Figure 7 seen. Table 1 shows the specific location of these points, where $D_0$ is the diameter of missile. Figure 8 shows the pressure of monitoring points time history in whole launch process. There are many fluctuations with the pressure of these points because of the existence of cavity. With the missile moving away from the tube, the cavity effect weakened and the amplitude of fluctuation decreased.

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Figure 7. Schematic of monitoring points.

Figure 8. Pressure of monitoring points.

5 CONCLUSION

In the study, the mixture multiphase flow model, RNG k-ε turbulence model and the dynamic mesh model are employed for simulating the process of submarine launch. The formation mechanism of the missile bottom cavity and its evolution process have been analyzed. Cavity formed by interaction between gas and water can lead to the fluctuation of the deck pressure. The natural cavity of missile shoulder produces due to the high speed movement of missile and its length will increase over time. The study reveals the evolution of cavities during the whole process of submarine launch.

REFERENCES