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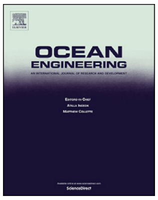

Numerical and theoretical investigation of the high-speed compressible supercavitating flows

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ABSTRACT

The objective of this paper is to investigate the high-speed compressible supercavitating flows with numerical and theoretical methods. In the numerical simulation, calculations are performed by solving the Unsteady Reynolds-averaged Navier-Stokes (URANS) Equations using a cell-centered finite-volume method, and the k-ω SST turbulence model is applied as the closure model. Compressibility effects in liquid phase are modified by the equation of state (EOS), and vapor phase is treated as ideal gas. Firstly, the numerical results are validated with experiments conducted by Hrubes (2001). Results are shown for high-subsonic and transonic projectiles, there is a general agreement between the predicted cavity profiles and the experimental data. Secondly, the influence of the Mach number on the flow structure and cavitation dynamics from subsonic to supersonic flows is investigated. The results show that with the increase of Mach number, the radial dimension of the front cavity is reduced, which is caused by the dramatic increase of pressure around the projectile. An expression is proposed to analyze the flow parameters before and behind the shock wave based on the isentropic and potential assumption at the Mach number on the interval $1 \leq Ma \leq 2.2$. The relationship between pressure and density across the shock wave is also investigated. Overall, these findings are great interest in engineering applications.

1. Introduction

Supercavitation refers to the case where a moving, underwater vehicles is totally enveloped by a large, continuous cavity and is a problem of great interest for many naval applications (Knapp et al., 1970; Kawakami and Arndt, 2011; Liu et al., 2017; Wang et al., 2015). The phenomenon of supercavitation can be used to achieve global stability and a significant reduction of hydrodynamic drag (Wang et al., 2017; Wu et al., 2018). Supercavities can be formed either ventilated or naturally and in the past decades, many researches focus on the ventilated supercavitation due to the application on torpedoes in the relatively low subsonic regimes. Nowadays, the natural supercavitation have gained the attention and is generally applied to the high speed projectile which operate in transonic and supersonic regimes with remarkable performance to defense against frogloks, torpedoes, mines, etc (Tulin, 2001; Jenkins and Evans, 2004). The increasing naval demands for the high speed projectile are leading to investigate the compressible supercavitating flows.

High-speed supercavitating flows is interesting and challenging due to the difficulties in measurement and analysis for the compressibility effects, especially for shock wave. Some experimental and numerical works have been carried out in recent years. In the experiments, Vlasenko (2003) and Savchenko (2001) conducted experiments for supercavitation flow regimes at subsonic and transonic speed. Qualitative features of the high-speed supercavities were described, and obvious compressibility effects were visualized in front of the cavitator at Mach numbers in the range from 0.54 to 0.77 due to the distortion of lines of the scale grid shown in photographs. Schaffar et al. (2005) carried out experiments in a water tank to investigate the behavior of supercavitating projectiles at velocities 600 m/s~1036 m/s. they found a very good agreement for the beginning of the experimental cavity profiles with theoretical results and some deviations appear for the longer cavity due to the movement of projectile and some outside air entering the cavity. Furthermore, experiments under the condition of subsonic, transonic and supersonic projectile flows were performed at the Naval Undersea Warfare Center (NUWC) by Hrubes (2001). In their work, the projectile trajectory, supercavity, and shock wave were captured clearly.

In conclusion, the camera images and velocities measured with laser barriers are generally applied for these high-speed projectile experiments and it is quite difficult to measure more detailed parameters with the consideration of feasibility and accuracy. Due to the limitations of measurement techniques, various numerical methods have been

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developed to investigate the compressible supercavitating flows. There are two ways for numerical simulation, namely potential flow theory and viscous flow method (Wang et al., 2017a). In potential flow theory, Vasin (1998, 2001a; 2011b; 2001) combined the slender body theory (SBT) and matched asymptotic expansion (MAEM) to simulate supercavities in subsonic and supersonic flows. The results shown the SBT is more applicable for study on subsonic water flows, but has a limited application for the shock effects in supersonic cavitation flows. Serebryakov (1992, 2001; 2006; Serebryakov et al., 2009) employed simple heuristic models, together with integral conservation laws, SBT models based on MAEM and nonlinear numerical calculation methods to investigate the supercavitation for both incompressible and compressible fluid in subsonic, transonic, and supersonic flows. The results shown that cavity length and radius increase sharply and then decrease sharply in transonic flows, which is due to the significant increase of the extension of the perturbation zone. Nouri and Eslamdoost (2009) applied an iterative algorithm based on the boundary element method (BEM) to investigate the supercavity boundary in potential flows. The comparison between the computations and the experimental data showed that the algorithm is reliable to predict the characteristics of a supercavitating flow, especially for the cavity capturing in a flow field with low cavitation number. Rozhdestvensky (2001) demonstrated the MAEM is efficient applicable to various supercavitating flow problems. Two model problems were chosen namely the flow around a supercavitating shock free hydrofoil, and supercavitating wing of large aspect ratio beneath the free surface.

Although the potential flow theory is time efficient for investigation of supercavities, it has a limited application for investigation of detail flow structures and dynamic characteristic of high-speed supercavitating flows. For the low subsonic supercavitating flows, it is often treated generally incompressible and isothermal with constant value of liquid density, and the energy equation is ignored. As for high-speed supercavitating flows, many complex hydrodynamic problems must be considered such as phase change with large variations in fluid density and pressure fluctuations, multiphase compressible flows and shock wave effects (Zheng et al., 2013; Dang et al., 2016). In order to account for these complexities, the Navier-Stokes equations governing a multiphase are generally required and the compressibility effects plays a significant role on predicting such flows, as density of each phases begin to vary with pressure (Chen et al., 2014, 2016). In addition, the numerical methods must include the energy equation, an equation of state (EOS) and the cavitation model. Aleve (1983) investigated the problem of separation flow of water about a circular cone at subsonic, transonic and supersonic regimes by considering water as an ideal compressible fluid. The results show that the numerical results for supersonic flow are in good agreement with the data from the linear theory and the separation incompressible flow about a cone. Vasin (2001) worked out an algorithm of calculation of axisymmetric cavities in subsonic and supersonic compressible flows. The results shown that the shock effects weakly prevent from the cavity expansion and the narrowing and change of the cavity shape are not obvious as compared with subsonic flows in supersonic flows. In addition, the shocks for supersonic flows were deeply discussed in his work, and the relationship of the flow parameters across the shock was proposed and validated with the results of Cole (1948). Owis and Nayfeh (2003) investigated high-speed cavitating flows by solving unsteady compressible Navier-Stokes and considered compressible energy equation and EOS of liquid and vapor phase. The results show that the compressible computations are in better agreement with the experimental measurements compared with the incompressible computations. Schaffar et al. (2005) combined the EOS and Euler model without thermal conduction to investigate the effect of cavitator shapes in high-subsonic flows, and the results show that there is a general agreement between the predicted cavity profiles and the experimental data for the beginning of the cavity. Neaves and Edwards (2004a, b; 2006) developed an algorithm based on the time-derivative preconditioning strategies and applied the algorithm to investigate the subsonic and transonic projectiles in water, general multiphase shock tubes, and a high-speed water entry problem. For high-subsonic and transonic projectile flows, the prediction of cavity and shock wave forms are in good agreement with theoretical results and experimental imaging results of Hrubes (2001).

Although the supercavitation research in water has significantly increased in the past years, the compressibility effects and the specific effects of pressure wave on cavitation dynamics in high-subsonic, transonic and supersonic flows are still not well understood. The objective of this paper is to investigate the high-speed compressible supercavitating flows. (1) investigate the compressibility effects on supercavitating flow structures and cavitation dynamics in high-speed flows, and (2) investigate the relationship between pressure and density across the shock wave in water and propose an expression to analyze the flow parameters before and behind the shock wave.

2. Governing equations and numerical approaches

2.1. Governing equations

The numerical model solves the Navier-Stokes equations governing a Newtonian fluid using a cell-centered finite-volume method. The set of governing equations for compressible supercavitating under the homogeneous multiphase flows consists of the conservative form of the Favre-averaged Navier-Stokes equations, the total energy equation, the turbulence closure, and a transport equation for phase change (Goncalvès and Patella, 2010). The continuity, momentum, energy, and cavitation model equations are given below in Cartesian coordinates.

$$\frac{\partial \rho_m}{\partial t}+\frac{\partial(\rho_m u_j)}{\partial x_j}=0 \tag{2.1}$$

$$\frac{\partial(\rho_m u_i)}{\partial t}+\frac{\partial(\rho_m u_i u_j)}{\partial x_j}=-\frac{\partial p}{\partial x_i}+\frac{\partial}{\partial x_j}\left[(\mu_m+\mu_T)\left(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}-\frac{2}{3}\frac{\partial u_k}{\partial x_k}\delta_{ij}\right)\right] \tag{2.2}$$

$$\frac{\partial(\rho h_{hot})}{\partial t}-\frac{\partial p}{\partial t}+\nabla\cdot(\rho u h_{hot})=\nabla\cdot(\lambda\nabla T)+u\cdot\nabla p+\nabla(u\cdot\tau) \tag{2.3}$$

$$\frac{\partial \rho_l \alpha_l}{\partial t}+\frac{\partial(\rho_l \alpha_l u_j)}{\partial x_j}=\dot{m}^{+}+\dot{m}^{-} \tag{2.4}$$

$$\rho_m=\rho_l\alpha_l+\rho_v\alpha_v \tag{2.5}$$

$$\mu_m=\mu_l\alpha_l+\mu_v\alpha_v \tag{2.6}$$

Where, ρ_m is the mixture density, ρ_l is the liquid density, ρ_v is the vapor density, α_v is the vapor fraction, α_l is the liquid fraction, u is the velocity, p is the pressure, μ_m is the mixture laminar viscosity, μ_l and μ_v are respectively the liquid and vapor dynamic viscosities, and μ_T is the turbulent viscosity. h_{hot} is total enthalpy defined as $h+u^2/2$, $\nabla(u\cdot\tau)$ is shear stress. The subscripts (i, j, k) denote the directions of the Cartesian coordinates. The source term $\dot{m}^{+}$, and the sink term $\dot{m}^{-}$, in Eqn. (2.4) represent the condensation and evaporation rates, respectively, as will be discussed below.

The numerical results shown in this paper are performed using the commercial CFD code FLUENT to solve the URANS equations. The k-ω SST (Shear Stress Transport) turbulence model is used, which combines the advantages of the original k-ε and k-ω models by using the k-ω model near the wall, and the k-ε model away from the wall (Menter, 1992). The k-ω SST has been found to give good predictions of boundary layer detachment characteristics, and it becomes the workhorse of practical engineering flow calculations.

2.2. Kubota cavitation model

The Kubota model (Kubota et al., 1992) is a transport-equation based