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Numerical simulation of cavitating flow past axisymmetric body

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ABSTRACT: *Cavitating flow simulation is of practical importance for many engineering systems, such as marine propellers, pump impellers, nozzles, torpedoes, etc. The present work has developed the base code to solve the cavitating flows past the axisymmetric bodies with several forebody shapes. The governing equation is the Navier-Stokes equation based on homogeneous mixture model. The momentum is in the mixture phase while the continuity equation is solved in liquid and vapor phase, separately. The solver employs an implicit preconditioning algorithm in curvilinear coordinates. The computations have been carried out for the cylinders with hemispherical, 1-caliber, and 0-caliber forebody and, then, compared with experiments and other numerical results. Fairly good agreements with experiments and numerical results have been achieved. It has been concluded that the present numerical code has successfully accounted for the cavitating flows past axisymmetric bodies. The present code has also shown the capability to simulate ventilated cavitation.*

KEY WORDS: Cavitating flow; Navier-stokes equations; Homogeneous mixture model; Axisymmetric bodies; Reentrant jet; Ventilated cavitation.

NOMENCLATURE

σ : Cavitation number
$\dot{m}^{+}$: Condensation rate
$\dot{m}^{-}$: Evaporation rate
α : Volume fraction, Angle of attack
β : Preconditioning parameter
p_{∞} : Pressure
p_{v} : Vapor pressure
ρ : Density
ρ_{m} : Mixture density
ρ_{l} : Density of liquid
ρ_{v} : Density of vapor
μ : Dynamic viscosity
μ_{m} : Mixture viscosity
t_{∞} : Characteristic flow time
k_{v} : Evaporation coefficient
k_{l} : Condensation coefficient
k_{p} : Scaling coefficient
τ : Pseudo time
τ_{ref} : Reference time
τ_{relax} : Relaxation time
$\hat{S}$: Source vector
Re : Reynolds number
V : Velocity
H : Water depth
Γ : Precondition matrix
Γ_{e} : Flux jacobian matrix
u, v, w : Cartesian velocity
$\hat{E}, \hat{F}, \hat{G}$: Flux vector
$\hat{E}_{v}, \hat{F}_{v}, \hat{G}_{v}$: Solution vector

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INTRODUCTION

Cavitation generally occurs if the pressure in a certain region of liquid flow drops below the vapor pressure and, consequently, the liquid is vaporized and filled with cavity. The cavitating flow is usually observed in various propulsion systems and high-speed underwater objects, such as marine propellers, impellers of turbomachinery, hydrofoils, nozzles, torpedoes, etc. This phenomenon usually causes severe noise, vibration and erosion.

Even though cavitating flow is a complex phenomenon which has not been completely modeled, a lot of attention was gathered in CFD community as the methodologies for single-phase flow was relatively much matured. In solving multiphase flows by CFD method, they can be categorized into three groups: The first group use a single continuity equation (Reboud and Delannoy, 1994; Song and He, 1984). This method has been known that it is unable to distinguish between condensable and non-condensable vapor (Kunz, Lindau, Billet and Stinebring, 2001). Next group is to solve separate continuity equations for liquid and vapor phases by adding source terms accounting for the mass transfer between phases (Kunz, Lindau, Billet and Stinebring, 2001; Merkle, Feng and Buelow, 1998; Kunz, et al., 2000; Ahuja, Hosangadi and Arunajatesan, 2001; Shin and Itohagi, 1998). This model is usually so called 'homogeneous mixture model', because the liquid-gas interface is assumed to be in dynamically and thermally equilibrium in the process of mass transfer between liquid and vapor phases and, consequently, mixture phase of momentum and energy equations are used. They consider in the process of the mass transfer between liquid and vapor phases. Final group solves full two-fluid modeling, wherein separate momentum and energy equations are employed for the liquid and the vapor phase (Grogger and Alajbegovic, 1998; Staedtke, Deconinck and Romenski, 2005). This method is widely used in nuclear engineering.

If adding more information to the second group that uses the homogeneous mixture model, some authors have reported preconditioning algorithms for multiphase mixtures. Kunz, et al. (2000) developed a code for the presence of a non-condensable vapor. The governing equations, in which a separate continuity equation is used for an individual phase while the momentum equations are described for the mixture phase, were solved by using the preconditioning and the dual time stepping method. However, in this model, the compressibility effects were not taken into account in the multiphase mixture region. Recently, Lindau, Venkateswaran, Kunz and Merkle (2003) and Owis and Nayfeh (2003) have been presented the fully compressible multiphase flow models which have taken into account the changes of both compressibility and temperature.

Coutier-Delgosha, Patella and Reboud (2003) reported that the unsteadiness of cavitating flows strongly depends on the turbulence model, and it has a great effect on the mean and fluctuating fields of vapor fraction and velocity. A simple modification of turbulence model was introduced to reduce the effective viscosity in the mixture and to take into account the influence of liquid-vapor mixture high compressibility on the turbulence structure.

Senocak and Shyy (2004) compared three cavitation models, namely by Merkle, Feng and Buelow (1998), Kunz, et al. (1999), and Singhal, Athavale, Li and Jiang (2002). The comparison of surface pressure distribution over a hemispherical object gave a good agreement among these three models. However, the density profiles do not reach an agreement each other, indicating that the cavitation models generate different compressibility characteristics. A new interfacial dynamics-based cavitation model was also developed for steady flow case, resulting in an additional equation for the normal velocity of the vapor phase on the interface.

The objective of the present work is to develop an in-house base code which will be used to simulate cavitating flow past supercavitating projectiles, whose final goal is to include the effects of condensable/non-condensable vapor, compressibility effects, and hot plume gas of propulsive exhaust gas after long-term nine years project. The present goal of the first stage for three years is to develop the base code that would follow the homogeneous mixture models, and then compare the results with other published numerical and experimental results.

MAIN TEXT

Governing equations and numerical method

Based on the homogeneous mixture model, the governing equation is comprised of the continuity equation for liquid and vapor phases and momentum equation in mixture phase as follows (2000):