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A sharp interface approach for cavitation modeling using volume-of-fluid and ghost-fluid methods *

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Abstract: This paper describes a novel sharp interface approach for modeling the cavitation phenomena in incompressible viscous flows. A one-field formulation is adopted for the vapor-liquid two-phase flow and the interface is tracked using a volume of fluid (VOF) method. Phase change at the interface is modeled using a simplification of the Rayleigh-Plesset equation. Interface jump conditions in velocity and pressure field are treated using a level set based ghost fluid method. The level set function is constructed from the volume fraction function. A marching cubes method is used to compute the interface area at the interface grid cells. A parallel fast marching method is employed to propagate interface information into the field. A description of the equations and numerical methods is presented. Results for a cavitating hydrofoil are compared with experimental data.

Key words: Incompressible flow, two-phase flow, cavitation modeling, sharp interface method, ghost fluid method, volume of fluid method, level set method, parallel fast marching method, marching cubes method

Introduction

Cavitation is the term for the change of state from liquid to vapor when it is caused by a low-pressure region within the flow field at an ambient temperature. Although the physical mechanism is the same, in contrast the term boiling is used to describe the change of state from liquid to vapor when it is caused by a local increase in temperature at the ambient pressure. For cavitation, the phase change rate is governed by the local pressure, while for boiling it is governed by the local temperature.

Cavitation degrades the performance of lifting surfaces found on ships, such as propeller blades and rudders. In addition to reducing lift, the violent collapse of cavitation bubbles can also remove material leading to further degradation and possible failure.

Potential flow cavitation models have been developed for propellers in Refs.[1,2]. The cavity is treated as additional thickness and the location is solved iteratively. A number of cavitation models for viscous flows have been developed, primarily for homogenous mixture models. Some examples are Refs.[3,4]. A more recent model in Ref.[5] adds the effect of non-condensable gas within the bubbles. Recent computations in Refs.[6-9] using models of this type have compared well with hydrofoil experiments. For visualization, the cavity interface is assumed to be at a constant volume fraction, typically 0.5. For summaries of recent research on cavitation models, especially, homogeneous mixture models, and their applications, the reader is referred to [10-13].

Sharp interface phase change models have been used to compute film boiling in Refs.[14,15]. Here we seek to apply similar techniques to the problem of cavitation, with the development of a suitable model for phase change due to cavitation.

The focus of this paper is the development of a model for predicting the phase change rate suitable for use with a sharp interface and the necessary models and methods to support this combination. The model is implemented in a two-phase incompressible viscous flow solver with a sharp interface approach. Results

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are presented for a cavitating hydrofoil. The results are analyzed to reveal details of the physics of the reentrant jet and cavity shedding. The averaged results are compared with experimental data.

1. Mathematical model

1.1 *Incompressible viscous flow*

The Navier-Stokes equations for the incompressible viscous flow of the liquid and vapor phases are written as follows:

$$\nabla \cdot \boldsymbol{u} = 0 \tag{1}$$

$$\frac{\partial \boldsymbol{u}}{\partial t} + \boldsymbol{u} \cdot \nabla u - \frac{1}{\rho} \nabla \cdot (-p\mathbf{I} + \boldsymbol{T}) + \boldsymbol{g} \tag{2}$$

where $\mathbf{I}$ is the identity matrix and

$$\boldsymbol{T} = \mu \boldsymbol{S} \tag{3}$$

where μ is the viscosity of the fluid and

$$\boldsymbol{S} = \frac{1}{2}[\nabla \boldsymbol{u} + (\nabla \boldsymbol{u})^{\mathrm{T}}] \tag{4}$$

1.2 *Phase change*

With phase change, a volume source must be added due to the different densities of liquid and vapor. The volume source satisfies the requirement for mass conservation and results in a jump in the fluid velocity at the interface so that Eq.(1) becomes

$$\nabla \cdot \boldsymbol{u} = \dot{m}\left(\frac{1}{\rho_l} - \frac{1}{\rho_v}\right) \tag{5}$$

where $\dot{m}$ is the mass flux between phases and the subscripts l and v stand for liquid and vapor, respectively.

1.3 *Interface tracking*

A volume of fluid (VOF) method described in Ref.[16] with the addition of a velocity component due to phase change is used to track the interface position. Without phase change, the boundary between liquid and vapor moves with a velocity which is continuous across the interface. Phase change introduces a velocity discontinuity at the interface which is proportional to the phase change rate and the difference in density across the interface. The VOF equation is

$$\frac{\partial F}{\partial T} + \boldsymbol{U} \nabla \cdot F = 0 \tag{6}$$

where $\boldsymbol{U}$ is the interface velocity, defined relative to the local liquid or vapor velocity by

$$\boldsymbol{U} = \boldsymbol{u}_f + \frac{\dot{m}\boldsymbol{n}}{\rho_f} \tag{7}$$

where $\boldsymbol{u}_f$ is the fluid velocity, and ρ_f is the fluid density and f is liquid or vapor. This satisfies the conservation of mass between the phases at the interface.

1.4 *Modeling mass flux between phases*

The rates of vaporization and condensation are determined by a simplification of the Rayleigh-Plesset equation which assumes a spherical bubble subject to uniform pressure variations

$$\rho_l\left(R\ddot{R} + \frac{3}{2}\dot{R}^2\right) = p_{\mathrm{vap}} - p_\infty + p_{g0}\left(\frac{R_0}{R}\right)^{3\gamma} - \frac{2S}{R} - 4\mu\frac{\dot{R}}{R} \tag{8}$$

where p_{vap} is the vapor pressure, p_{g0} is the initial partial pressure of non-condensable gasses, R_0 is the initial radius of the bubble, S is the surface tension, and γ is the ratio of the gas heat capacities. The third term on the right-hand side represents the effect of the non-condensable gasses. The last two terms on the right represent the effects of surface tension and viscosity, respectively.

The surface tension can be neglected for all but the smallest bubbles and the viscous effects can be neglected for the Reynolds numbers of interest in ship flows. By also neglecting the non-condensable gasses, the equation can be integrated with respect to time and simplified to yield

$$\dot{R} = \sqrt{\frac{2}{3}\frac{p_\infty - p_{\mathrm{vap}}}{\rho_l}} \tag{9}$$

This simplification is the foundation of several cavitation models used with two-phase mixture models where further assumptions about bubble number or size are utilized to arrive at a surface area and mass flux.

With a sharp interface method, the bubble must be larger than the cell to be accurately modeled. If the radius is sufficiently large, it is reasonable to represent it by a plane within the cell, as in the volume of fluid method. Then, the velocity is

$$\frac{\dot{m}\boldsymbol{n}}{\rho_l} = \sqrt{\frac{2}{3}\frac{p - p_{\mathrm{vap}}}{\rho_l}}\boldsymbol{n} \tag{10}$$