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Modeling for non isothermal cavitation using 4-equation models

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ABSTRACT

A compressible, two-phase, one-fluid solver has been developed to investigate the behaviour of cavitation models including thermodynamic effects. The code is composed by three conservation laws for mixture variables (mass, momentum and total energy) and a supplementary transport equation for the void ratio. Two formulations for the mass transfer between phases are studied. Numerical simulations are firstly performed on rarefaction cavitating problems in which the working fluid is hot water and freon R-114. A realistic turbulent Venturi case with freon R-114 is performed and comparisons are done between 3- and 4-equation models. A warming effect is highlighted downstream the cavitation pocket in the region of pressure recuperation.

1. Introduction

Cavitation is a significant engineering phenomenon that occurs in fluid machinery, fuel injectors, marine propellers, nozzles, underwater bodies, etc. In most cases, cavitation is an undesirable phenomenon, significantly degrading performance, resulting in reduced flow rates, lower pressure increases in pumps, load asymmetry, vibrations, noise and erosion. Such flows are characterized by important variations of the local Mach number (due to the drastic diminution of the speed of sound in the mixture), large density ratio between the liquid and the vapor phases, compressibility effects and non equilibrium thermodynamic states.

Cavitation can be manifested at a constant temperature, and thus, it is usually assumed to be an isothermal phenomenon. However, the constant temperature hypothesis is no longer valid when cryogenic fluids (also known as thermosensitive fluids) are considered. For such fluids, the liquid–vapour density ratio is lower than that of typical fluids (cold water) and consequently more liquid mass has to vaporize to sustain a cavity. Therefore evaporative cooling effects are more pronounced and the temperature of the liquid in the immediate vicinity of the liquid–vapour interface is depressed below the free-stream temperature. Because of the strong variation of thermodynamic properties (vapour pressure, density), the temperature depression, negligible in water, is quite substantial. The local cooling effect delays the cavitation phenomenon and reduces the local vapour pressure of the fluid, which leads to a lower observed cavity pressure.

Several physical and numerical models have been developed to investigate cavitating flows within the framework of averaged two-phase model or bubbly models based on the Rayleigh-Plesset equation. For the averaged model, there are different approaches according to the assumptions made on the local thermodynamic equilibrium and the slip condition between phases. A hierarchy of models exists, with the numbers of equations ranging from seven to three only. The full non-equilibrium seven-equation models are the most complete. For both fluids, it contains equations for the mass, momentum and energy, and the seventh equation describes the topology of the flow. These models can take into account the physical details occurring in the cavitation phenomenon such as mass exchange, thermal transfer and surface tension. However, the transfer terms have to be known; such quantities are usually very difficult to obtain. Various formulations have been investigated to deal with metastable states and evaporation front dynamics [1–5]. Temperature and free Gibbs enthalpy exchange terms are included in the equations as relaxation terms to model heat and mass transfer. For thermal-hydraulics applications with cavitation, nucleation and boiling flows, a six-equation model has been developed [6,7]. The interfacial mass transfer is modeled as a function of the interfacial heat transfer terms and the interfacial phase-averaged enthalpies.

A reduced five-equation model can be derived with the assumptions of velocity equilibrium and pressure equilibrium. The archetype five-equation model is that of Kapila [8]. It is composed of four conservation laws: two for masses, one for the mixture momentum and one for the mixture energy. It is completed by an equation for a non-conservative quantity describing the flow topology, usually the void ratio. Such a model has been used for inviscid high speed

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Nomenclature

B	B-factor
c	speed of sound
$C_p,\ C_v$	thermal capacities
E	total energy
e	internal energy
g	free Gibbs enthalpy
h	enthalpy
L_{vap}	latent heat of vaporization
$\dot{m}$	mass transfer between phases
P	static pressure
P_{vap}	vapour pressure
P_∞	reference pressure
$Pr,\ Pr_t$	molecular and turbulent Prandtl numbers
Q	total heat flux
q	energy of formation
Re_L	Reynolds number based on the length L
T	temperature
T_{ref}	reference temperature
$u,\ v$	velocity components
w	conservative variables
Y	mass fraction of gas
α	volume fraction of gas
γ	ratio of thermal capacities
$\lambda,\ \lambda_t$	molecular and turbulent thermal conductivity
μ, μ_t	molecular and eddy viscosity
ρ	density
σ	cavitation number
τ	total stress tensor
$()_l$	liquid value
$()_v$	vapour value
$()^{sat}$	saturation value
$()^{v}$	viscous
$()^{t}$	turbulent

cavitating applications and cavitation pocket in fuel injector nozzles [9,10]. Heat and mass transfer processes are modelled through thermal and chemical relaxation procedures.

By assuming the thermal equilibrium between phases, a 4-equation model can be expressed. A very popular formulation, originally developed to simulate turbulent cavitating flows in cold water, has been adapted to cryogenic applications [11–14]. It is composed by three conservation laws for mixture quantities (mass, momentum, energy) plus a mass equation for the vapour or liquid density including a cavitation source term. The main difficulty is related to the formulation of the source term and the tunable parameters involved for the vaporization and condensation processes (different sets of parameters are presented in [12]). Moreover, this family of models are not thermodynamically well-posed and does not respect thermodynamic constraints [15]. Another popular model devoted to ebullition problems uses a mass fraction equation with a relaxation term (Homogeneous Relaxation Model). The source term involves a relaxation time that is the time for the system to regain its thermodynamic equilibrium state. This time is difficult to determine and is estimated from experimental data [16–19].

With the assumption of complete thermodynamic equilibrium between phases (local temperature, pressure and free Gibbs enthalpy equality between phases), we obtain the 3-equation models or Homogeneous Equilibrium Models (HEM). Vaporization or condensation processes are assumed to be instantaneous. An equation of state (EOS) is necessary to close the system. Different closure relations (tabulated EOS or combination of pure phase EOSs) that link the pressure to the thermodynamic variables have been proposed [20–24].

The bubbly flow models are composed by three balance equations for the mixture quantities coupled with a macroscopic model for the bubble dynamics based on the Rayleigh–Plesset equation. This model is capable of handling either single bubbles or clouds of bubbles that grow and decrease through a pressure field [25–27]. In the case where heat transfer is negligible, the phase change is driven by inertia effects. Yet, when thermal effects are involved, the liquid inertia become rapidly negligible and the evolution is controlled by the heat flux provided by the liquid at the bubble surface. By comparing characteristic times of thermal and inertial phenomena, it can be shown that this thermal regime is an accurate representation of reality for moderate levels of superheating or subcooling [28–30].

In a recent study, we proposed a new mass transfer formulation associated to a 4-equation model for isothermal cavitation [31,32]. The generic formulation involves the ratio c^2/c^2_{wallis} between the mixture speed of sound and the Wallis velocity, which is the speed of sound without heat and mass transfer. First, we extend the isothermal formulation with a non isothermal thermodynamic path using a linear approximation of the vapour pressure evolution. This model is built using the mixture speed of sound evaluated with a modified barotropic equation of state [24]. A second closure is investigated using a mixture of stiffened gas EOS and its associated mixture speed of sound. The validation is done through one-dimensional inviscid double rarefaction test cases in which reference solutions have been computed [5]. A new test case is proposed with the thermosensitive freon R-114 ($C_2Cl_2F_4$) as working fluid. Secondly, models are compared with experimental data on a turbulent Venturi case in which the running fluid is freon R-114. Local analyses with void ratio profiles and wall temperature depression are proposed. A warming effect downstream the cavitation pocket is exhibited.

This paper is organized as follows. We give a brief description of models. The averaged Navier–Stokes equations are presented and the numerical methods are described. Numerical results are presented with comparisons between models and validations against two-fluid solutions. The study of the turbulent Venturi case is described. Finally, conclusions and future investigations are discussed.

2. Mixture models and mass transfer

The numerical simulations are carried out using an in-house CFD code solving the one-fluid compressible Euler and Navier–Stokes systems.

The homogeneous mixture approach is used to model two-phase flows. The phases are assumed to be sufficiently well mixed and the disperse particle size are sufficiently small thereby eliminating any significant relative motion. The phases are strongly coupled and moving at the same velocity. In addition, the phases are assumed to be in thermal and mechanical equilibrium: they share the same temperature T and the same pressure P. The evolution of the two-phase flow can be described by the conservation laws that employ the representative flow properties as unknowns just as in a single-phase problem.

We introduce α the void fraction or the averaged fraction of presence of the vapour. The density ρ, the center of mass velocity u and the internal energy e for the mixture are defined by Ishii and Hibiki [33]: