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Modelling for isothermal cavitation with a four-equation model

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ABSTRACT

In a recent study, an original formulation for the mass transfer between phases has been proposed to study one-dimensional inviscid cavitating tube problems. This mass transfer term appears explicitly as a source term of a void ratio transport-equation model in the framework of the homogenous mixture approach. Based on this generic form, a two-dimensional preconditioned Navier–Stokes one-fluid solver is developed to perform realistic cavitating flows. Numerical results are given for various inviscid cases (underwater explosion, bubble collapse) and unsteady sheet cavitation developing along Venturi geometries at high Reynolds number. Comparisons with experimental data (concerning void ratio and velocity profiles, pressure fluctuations) and with a 3-equation model are presented.

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. In most industrial applications, cavitating flows are turbulent and the dynamics of the interface formed involves complex interactions between the vapour and liquid phases. These interactions are not well understood in the closure region of cavities, where a distinct interface may not exist and where the flow is unsteady.

Several physical and numerical models have been developed to investigate cavitating flows within the framework of averaged two-phase model. 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 two-fluid models with relaxation procedures have been tested on inviscid high-speed applications (see for example (Petitpas et al., 2009; Zein et al., 2010)), whereas one-fluid models have been massively used for industrial cavitating flows.

By assuming the velocity, pressure and thermal equilibrium between phases, various formulations of four-equation model have been expressed. A very popular formulation has been developed to simulate turbulent cavitating flows (Merkle et al., 1998; Kunz et al., 2000; Senocak and Shyy, 2002; Singhal et al., 2002; Venkateswaran et al., 2002; Vortmann et al., 2003; Wu et al., 2005; Wang and Ostoja-Starzewski, 2007; Morgut et al., 2011; Ji et al., 2012). 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 vapourisation and condensation processes. Moreover, this family of models are not thermodynamically well-posed and does not respect thermodynamic constraints (Goncalves and Patella, 2011). Another approach of source term was proposed in (Helluy and Seguin, 2006), based on a constrained convex optimisation problem on the mixture entropy.

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). Vapourisation 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 (Delannoy and Kueny, 1990; Saurel et al., 1999; Schmidt et al., 1999; Ventikos and Tzabiras, 2000; Liu et al., 2004; Schmidt et al., 2006; Sinibaldi et al., 2006; Ihm and Kim, 2008; Goncalves and Patella, 2009).

In addition, the turbulence modelling plays a determinant role in the capture of unsteady behaviours. Cavitation sheets that appear on solid bodies are characterised by a closure region which always fluctuates with the existence of a re-entrant jet. This one is mainly composed of liquid which flows upstream along the solid surface. Moreover, compressibility effects on turbulence are involved. These effects and interactions with two-phase structures

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Table 1
Parameters of the stiffened gas EOS for water at $T = 355$ K.

	γ	P_∞ (Pa)	q (J/kg)	C_p (J/K kg)	ρ_{sat} (kg/m^3)
Liquid	2.35	10^9	-0.1167×10^7	4267	1149.9
Vapour	1.43	0	0.2030×10^7	1487	0.31

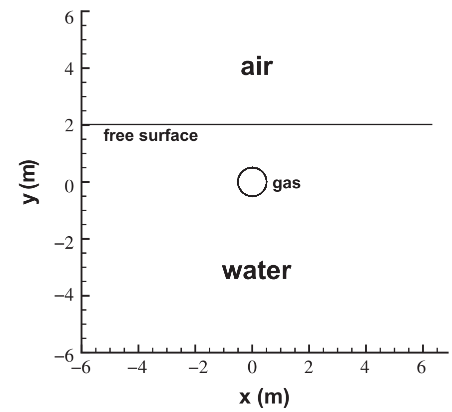

Fig. 1. Underwater explosion, initial.

are not yet well known and understood. For usual applications, three-dimensional time-dependent computations obtained with large eddy simulations (LES) or direct simulations (DNS) are not yet tractable. The Reynolds decomposition is often used with an averaged statistical processing resulting in the RANS equations for the mean flow quantities. The limitation of the turbulent viscosity evaluated with transport-equation turbulence models (through the Boussinesq assumption) is a key point to capture realistic cavitation sheets. Different methods have been investigated to limit or to correct standard turbulence models. One of the most popular limiter was proposed by Reboud to reduce the turbulent viscosity (Reboud et al., 1998), and has successfully been used by different authors (Coutier-Delgosha et al., 2002; Chen et al., 2006; Zhou and Wang, 2008; Srinivasan et al., 2009; Goncalves, 2011).

In a recent study, an original source term including the mass transfer between phases was proposed using a void ratio transport-equation model. A particular emphasis was placed on the thermodynamic coherence. The mass transfer was closed assuming its proportionality to the divergence of the homogeneous velocity field. First validations on one-dimensional rarefaction tube problems showed the good behaviour of the model and the low sensitivity to the involved constant (Goncalves, 2012, 2013). In the present paper, the cavitation model is improved and implemented in a compressible two-dimensional RANS/Euler solver. This new formulation is firstly tested on inviscid test cases (solving the compressible one-fluid Euler equations) such as underwater explosion and bubble collapse. Secondly, two turbulent sheets cavitation appearing on Venturi geometries are simulated and compared with the available experimental data (time-averaged void ratio and velocity profiles, pressure fluctuations, oscillation frequency). The influence of the constant is investigated, especially the effect on the sheet cavitation dynamic. Moreover, a comparison with a 3-equation model is proposed.

This paper is organised as follows. We first review the theoretical formulation including physical models, the mass transfer formulation and elements of the numerical methods. The

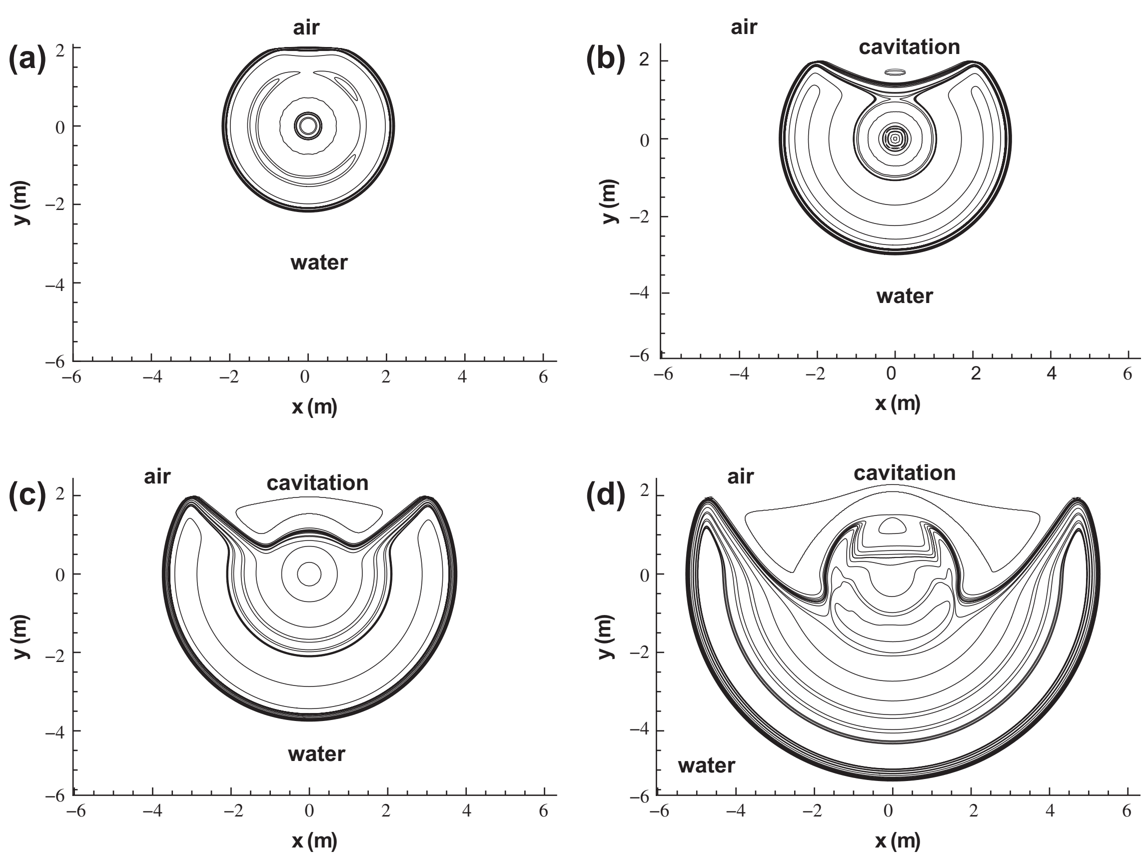

Fig. 2. Underwater explosion.