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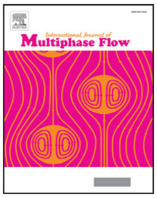

Improvement of cavitation mass transfer modeling based on local flow properties

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ABSTRACT

This paper presents and studies the effect of two modifications to improve cavitation mass transfer source term modeling for transport equation based models by considering local flow properties. The first improvement is by creating an analogy between the phase change time scale and turbulence time scale, and have the model to automatically adjust mass transfer rate based on the flow. This will alleviate the manual calibration of model parameter that is often necessary in presently used models. The second modification introduces an influence of shear stress on the liquid rupture in flows relevant for hydromachinery. This relates to that the pressure threshold, which represents the criteria of when phase change occurs, is normally taken as the value relevant for a fluid at rest, but is in reality affected by the flow conditions.

To demonstrate the effect of the model modifications, the three-dimensional, fully turbulent, cavitating flow around the Delft Twist11 foil is simulated. The suggested modifications are implemented in and evaluated using the Sauer mass transfer model, with simulations performed with an incompressible implicit LES flow model. The pressure distribution across different sections of the foil, lift force, and cavitation behavior, such as generation, separation, and collapse processes, are studied and compared with the experimental data. The comparison shows the capability of the presented model to improve the prediction of the complex physics of the cavitation around the Twist11 foil, compared with using only the original Sauer mass transfer model.

1. Introduction

Cavitation has been categorized as the formation of vapor in a liquid when local pressure in the liquid falls below a critical pressure threshold, depending on flow conditions and liquid quality. The phenomena occurs in a number of engineering applications, most prominently perhaps in fuel injectors, pumps, hydroturbines, and on marine propellers. Further, the occurrence of cavitation is usually negative for the performance and leads to problems with noise, vibration, and material erosion. In spite of its longstanding practical importance, cavitating flow continues to be a topic of a significant challenge to the engineering community due to its rich physics, and reliable prediction methods are still not fully established. For numerical prediction, the simultaneous presence of interfacial dynamics, multiple timescales, and phase change complicates the fluid physics and requires substantial modeling efforts. Numerous modeling strategies have been proposed in the literature, ranging from Rayleigh—Plesset type of bubble formulation to homogeneous fluid approach which treats the cavity as a region consisting of continuous composition of liquid and vapor phases.

The most common modeling approach today is what is often denoted as transport equation-based models, TEM, assuming the flow can be modeled as a single fluid mixture, considering incompressible phases for both liquid and vapor and a source term model for the mass transfer between the phases (HUANG and WANG, 2011; Ji et al., 2014; Merkle et al., 1998; Reboud and Delannoy, 1994; Sauer and Schnerr, 2000; Singhal et al., 2002). An interesting extension to the Sauer model was presented in Hosangadi and Ahuja (2005), the Could Surface Integral model, where an extra transport equation is solved for the summation of the bubbles surfaces, thus allowing the nuclei to convect with the local flow. Other approaches may involve barotropic models, considering only the pressure, ranging to more advanced compressible flow models where the equation of state govern the presence of liquid and vapor. This paper is primarily of relevance for cavitation modeling based on TEM, for a review of alternative approaches we refer, e.g., to the thesis of , Koop (2008), and the references therein.

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Nomenclature

B_{ij}	Subgrid stress tensor
C	Chord length (0.15 m)
CFL	Courant number
C_l	Lift coefficient
C_p	Pressure coefficient
C_v	Vapor production coefficient
D_{ij}	Deformation rate tensor
g	Gravity
L	Reference length
$\dot{m}$	Mass transfer rate
n	Number of cells
n_0	Average nucleus per volume
p	Pressure
R	Nucleus radius
Re	Reynolds number
S	Span length of the foil
S_{ij}	Viscous stress tensor
S_α	Phase change source term
t, t_∞	Time, mean flow time scale
$X = x/C$	Normalized chord length
$Y = y/S$	Normalized span length

Greek

α	Volume fraction
τ	Shear stress
ρ	Density
μ	Viscosity
$\dot{\gamma}$	Shear strain rate
σ	Cavitation number

Mathematical operators

δ_{ij}	Kroneckerdelta
$\nabla, \frac{\partial}{\partial x}$	Gradient operator
∂t	Time derivation operator

Subscripts

i,j=1,2,3	Coordinate indices
l	Liquid phase
m	Mixture
mod	Modified
Nuc	Nuclei
Sat	Saturation Condition
v	Vapor phase
∞	Free stream

The mass transfer model is usually based on the pressure in the flow, derived from simplifications of the Rayleigh–Plesset equation of a single bubble. Using pressure as the main parameter is a reasonable assumption, but several other effects are present and influence the flow development to larger or smaller degree. For example, one aspect is that in order to maintain the thermodynamic balance at the interface of the two phases, the liquid will experience evaporation cooling which causes the temperature to slightly drop around the interface of the cavity. For fluids like water, the density ratio between liquid and vapor is very high, and therefore these thermal effects are not significant thus cavitation formation can be considered isothermal (Franc and Michel, 2006; Goncalvs and Charrire, 2014). Another aspect, important especially in comparison with experiments, is the question of water quality, the amount and distribution of nuclei that initiate cavitation. This has a large impact on when cavitation inception occurs and the extent of cavitation in the flow. In computational modeling, this is often controlled by ad hoc parameter choices, often following some kind of calibration procedure, although some efforts have been made to investigate these effects (Morgut, 2012). Further, local flow conditions, such as flow speed, turbulence levels (Congedo et al., 2015), and shear, also affect the formation of vapor. Some attempts have been made to approach these effects, e.g. including a weighting by modeled turbulent kinetic energy in the model by Singhal et al. (2002), with limited acceptance in the simulation community.

The objective with this work has been to develop a way to incorporate some of these local flow effects into a standard TEM source model to improve the physical consistency of the model and reduce the need of ad hoc parameters and calibration, giving the opportunity to improve on current popular engineering modelling approaches. Thus, the first focus of this paper is to present an appropriate time scale for phase change rate in cavitating flows. One of the main complications in simulation models of cavitating flows with TEM are a number of ad hoc parameters, parameters that need to be adjusted to tune the mass transfer rate so that the numerical results mimic the experimental data. As a result different flow conditions and cases require different coefficients. These coefficients represent the relaxation time that each phase (vapor or liquid) needs to be transformed during that period into the other phase. In the current study, by creating a correlation between the mass transfer modeling and linear turbulence modeling, velocity strain rate is proposed to be considered as an appropriate time scale for calculation of the phase change relaxation time in the fully turbulent cavitating flows, thereby circumventing the need of parameter tuning.

The second focus of this paper is to take into account the viscous shear stress in the calculation of the pressure threshold for phase change. Based on the thermodynamic properties of the liquid, the saturation pressure is normally used as the pressure threshold for the inception and formation of cavitation. This definition, however, has some drawbacks. The thermodynamic saturation pressure is calculated in conditions where the fluid is steady and in an equilibrium state. Therefore, the rupture of the liquid pocket is just due to the pressure tensile, and effects of shear stress caused by shear velocity are not included. Some research has been done during the past decades to consider the effects of the shear stresses in the calculation of the pressure threshold (Bouziad, 2006; Martynov, 2005; Shen and Dimotakis, 1989; Som et al., 2010). Most of these studies were conducted in cavitating nozzle flows, where the flow speed was very high and therefore the shear velocity magnitude was considerable (Som et al., 2010). In the current study the implementation of this approach in medium speed applications, e.g., cavitating propellers and foils, is tested and its effects on cavitation generation, transport and collapse are investigated.

To evaluate the proposed models, the Delft Twist11 hydrofoil is selected as the benchmark. This foil, studied experimentally by Foeth (2008) and Foeth and Terwisga (2006) and later by Peng et al. (2016), generates cavitation which resembles propeller cavitation but in a well defined and easily studied set up; this makes it an attractive test case for evaluation of computational approaches for predicting cavitation in hydromachinery. Moreover, this case was presented as a benchmark case in several workshops on cavitation, thus several numerical studies have been performed on the foil (Bensow, 2011b; Ji et al., 2013; Koop, 2008; Lu et al., 2010; Park and Rhee, 2013; Schnerr et al., 2008; Wu et al., 2016).

Lu et al. (2010) used implicit Large Eddy Simulation modelling and OpenFOAM to simulate cavitation, with a focus on the effects of the varying inflow on the cavity interface in unsteady inlet conditions. Bensow (2011b), tested RANS, DES and LES turbulence models in predicting the cavitation around the Twisted foil. When using RANS turbulence modelling, tests were performed both with and without applying the ad-hoc turbulent viscosity Reboud