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Numerical simulation of cavitation dynamics using a cavitation-induced-momentum-defect (CIMD) correction approach

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Abstract

A new unsteady cavitation event tracking model is developed for predicting vapor dynamics occurring in multi-dimensional incompressible flows. The procedure solves incompressible Navier–Stokes equations for the liquid phase supplemented with an additional vapor transport equation for the vapor phase. The novel cavitation-induced-momentum-defect (CIMD) correction methodology developed in this study accounts for cavitation inception and collapse events as relevant momentum-source terms in the liquid phase momentum equations. The model tracks cavitation zones and applies compressibility effects, employing homogeneous equilibrium model (HEM) assumptions, in constructing the source term of the vapor transport model. Effects of vapor phase accumulation and diffusion are incorporated by detailed relaxation models. A modified RNG k–ε model, including the effects of compressibility in the vapor regions, is employed for modeling turbulence effects. Numerical simulations are carried out using a finite volume methodology available within the framework of commercial CFD software code Fluent v.6.2. Simulation results are in good qualitative agreement with experiments for unsteady cloud cavitation behavior in planar nozzle flows. Multitude of mechanisms such as formation of vortex cavities, vapor cluster shedding and coalescence, cavity pinch off are sharply captured by the CIMD approach. Our results indicate the profound influence of re-entrant jet motion and adverse pressure gradients on the cavitation dynamics.

Keywords: Cavitation; Compressible; Multiphase; Turbulence; Re-entrant jet

1. Introduction

The studies concerning sheet and cloud cavitation phenomena are copious due to their frequent appearance in a wide variety of hydraulic systems. The ensuing instabilities are known to procreate abnormal dynamic

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Nomenclature

$\boldsymbol{U}$	velocity (m/s)
$\boldsymbol{T}$	stress tensor (kg/m s^2)
P	pressure (kg/m s^2)
$\mathbf{D}$	strain rate (1/s)
D	mass exchange coefficient (kg/m s)
$\boldsymbol{F}$	body force (N)
t	time (s)
S	source (kg/m^{3}s)
N	bubble density (1/m^3)
R	bubble radius (m)
$\dot{R}$	bubble wall velocity (m/s)
$\ddot{R}$	bubble wall acceleration (m/s^2)
V	volume (m^3)
a	speed of sound (m/s)
f	drag
Re	Reynolds number
A	acceleration (m/s^2)
g	gravity (m/s^2)
E	energy (J)
H	height (m)
x, y	co-ordinates (m)
$t1$, $t2$	time (s)
ρ	density (kg/m^3)
σ	cavitation number
α	vapor fraction
Ω	surface tension (kg/s^2)
μ	viscosity (kg/m s)
θ	angle (°)

Subscripts

l	liquid
v	vapor
m	mixture
vap	vapor
∞	farfield
k	turbulent kinetic energy
ε	turbulent dissipation rate
cav	cavitation

behaviors, noise, erosion and vibration among others [1,2]. Different types of cavitation, emerging due to variation in geometry and flow characteristics, have been identified to effectuate distinct unsteady characteristics [1]. The mechanism of "sheet cavitation" has a quasi-steady character with notable unsteadiness localized in the closure region. With increase in intensity of perturbations at the rear end of the cavity, large vapor clusters are shedded downstream into the flow, a phenomenon often termed "cloud cavitation". The cavitation cloud, unlike its parent source, exhibits very strong unsteadiness in the whole cavity [3,4]. Several studies have identified the existence of a re-entrant jet that flows under the sheet cavity from its rear part to its upstream end, leading to generation of cloud cavitation [3–6]. Callenaere et al. [7], in their study on re-entrant jet mechanisms, observed that an increase in adverse pressure gradient near the closure region of the cavity has a direct