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Simulation of three-dimensional cavitation behind a disk using various turbulence and mass transfer models

Ehsan Roohi *, Mohammad-Reza Pendar, Amin Rahimi

High Performance Computing (HPC) Laboratory, Department of Mechanical Engineering, Faculty of Engineering, Ferdowsi University of Mashhad, P.O. Box 91775-1111, Mashhad, Iran

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ABSTRACT

In this study, we performed numerical investigations of the cavitating and supercavitating flow behind a three-dimensional disk with a particular emphasis on detailed comparisons of various turbulence and mass transfer models. Simulations were performed using the OpenFOAM package and flows at three different cavitation numbers, (σ = 0.2, 0.1, and 0.05) were considered. Large eddy simulation (LES) and k—ω shear stress transport turbulence approaches were coupled with various mass transfer model types (e.g., Kunz, Schnerr–Sauer, and Zwart models). The Zwart mass transfer model was added to the standard OpenFOAM package. A compressive volume of fluid method was used to track the interface between the liquid and vapor phases. Our numerical results in terms of the cavity length, diameter, and drag coefficient compared fairly well with experimental data and a broad set of analytical relations. Moreover, this study provides a better understanding of the cavitation dynamics behind disk cavitators. Our results indicate that the most accurate solutions will be obtained by applying an LES turbulence approach combined with the Kunz mass transfer model.

1. Introduction

Cavitation is a multi-phase and complex physical phenomenon, which occurs when the local liquid pressure becomes lower than its saturated vapor pressure [1]. This phenomenon appears often over marine vehicle applications such as submarines and marine propeller blades. To increase the performance of submarines by reducing viscous drag, underwater vehicles usually operate in cavitating conditions [2].

Cavitation is an unsteady, three-dimensional (3-D), and discontinuous or periodic phenomenon, which occurs during the formation, growth, and rapid collapse of bubbles [3]. A dimensionless number characterizes this process, i.e., $\sigma = (P_\infty - P_\vartheta)/0.5\rho U_\infty^2$, which is called the cavitation number [1]. If the moving body is accelerated to high speeds, supercavitation will occur, which refers to a long cavity that extends more than the body length and that closes in the liquid. There is a constant movement of a re-entrant liquid jet in the cavity closure section.

Studying the cavitating flow behind a 3-D disk cavitator has been an interest of the scientific community in this field for many years. Challenging issues that need to be considered during the numerical simulation of a 3-D cavitation are: the

* Corresponding author. Tel.: +98 (51) 38805136; fax: +98 (511) 8763304.
E-mail address: e.roohi@ferdowsi.um.ac.ir (E. Roohi).

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Nomenclature

A_ε, A_μ parameters in near wall length scales
B unresolved transport term in LES
C_ε, C_K LES empirical constant coefficients
C_d drag coefficient
C_l parameter in near wall length scales
$CD_{K\omega}$ positive portion of the cross-diffusion
C_{dest}, C_{prod} Kunz mass transfer model constants
C_{d0} constant in the drag coefficient for a disk cavitator
C_γ constant between 0 and 1
Co courant number ($C = U \cdot dt/dx$)
D cavity diameter
d cavitator diameter
$\boldsymbol{D}$ rate of strain tensor
$\tilde{D}_D$ eddy diffusivity tensor
E constant coefficient
F_e, F_c Zwart two empirical coefficients
F_1 turbulence Function (given by Eq. (15))
G filter function
$\boldsymbol{I}$ unit tensor
$\mathbf{I}$ turbulent intensity
k kinetic energy
L cavity length
l liquid
l_μ, l_ε near wall length scales
L characteristic length (disk diameter)
δ turbulence length scale
$\dot{m}$ mass transfer rate between the phases
n_0 initial number of bubbles
p pressure
Re Reynolds number
R_b radius of bubbles
R_B radius of a nucleation site
r_{nuc} nucleation site volume fraction
$\boldsymbol{S}$ viscous stress tensor
S strain rate
u_τ friction velocity
v_{SGS} subgrid scale viscosity
t_∞ mean flow time
U velocity magnitude
u^+ non-dimensional velocity
X_j components of the Cartesian coordinate
y distance between surfaces
y_w wall distance
y^+ non-dimensional wall distance
σ cavitation number
∞ free stream value
ϕ volumetric flux
κ Von Karman Constant
v velocity vector
ϑ vapor
ρ density
τ wall shear stress
ω specific dissipation rate
μ viscosity
Δ filter width
γ volume fraction
τ_{ij} shear stress tensor