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Recent progress in modeling of cryogenic cavitation for liquid rocket propulsion

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Abstract

Thermal effects substantially impact the cavitation dynamics of cryogenic fluids. The present article reviews recent progress made toward developing modeling and computational strategies to simulate cryogenic cavitation relevant to liquid rocket propulsion applications. We re-examine previously developed cavitation models, including thermal effect and turbulence closures. The experimentally observed "frosty" appearance within the cavity is modeled as a mushy phase boundary. The impact of model parameters and material properties on the prediction is probed by global sensitivity techniques. Performance of the reported cavitation models is compared against the existing cavitation models and experimental data, under both non-cryogenic and cryogenic conditions. Time-dependent computations for various cases of cryogenic cavitation are further reviewed. Impact of the cryogenic environment and inflow perturbations on the flow structure and instabilities is explained via the simulated flow fields and the reduced order strategy of proper orthogonal decomposition (POD).

Contents

Abbreviations: POD, Proper orthogonal decomposition; LSM, Launder–Spalding model; FBM, Filter-based model; IDM, Interfacial dynamics model

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Nomenclature

σ	cavitation number
δ	boundary layer/cavity thickness
L	length (of cavity or cavitating object)
q	heat flux; generalized flow variable in POD representation
V	total volume
t	time
x, y, z	coordinate axes
r	position vector
ξ	streamwise direction in the curvilinear coordinate system
i, j, k, n, N	indices
u, v, w	velocity components
p	pressure
T	temperature
ρ	density
α	volume fraction
f	mass fraction
h	sensible enthalpy
s	entropy
c	speed of sound
τ	stress tensor
P	production of turbulent energy
$C_{\varepsilon 1}$, $C_{\varepsilon 2}$, σ_k, σ_ε, C_μ, C	constants
Q	total kinetic energy (inclusive of turbulent fluctuations)
k	turbulent kinetic energy
ε	turbulent dissipation
F	filter function for filter-based modeling
μ	dynamic viscosity
K	thermal conductivity
υ	volume flow rate
L	latent heat
C_P	specific heat
C_p	pressure coefficient
a	thermal diffusivity
$\dot{m}$	volume conversion rate
B	B-factor to gauge thermal effect
Σ	dimensional parameter to assess thermal effect
β	control parameter in the Mushy IDM
g	gravitational acceleration
U	velocity scale
D	length scale (such as hydrofoil chord length or ogive diameter)
R	bubble radius
CFL	Courant, Freidricks, and Levy number
Pr	Prandtl number
Re	Reynolds number
Δ	difference; filter size in filter-based turbulence modeling
∇	gradient or divergence operator
ψ	POD mode
ϕ	time-dependent coefficient in the POD series
η	energy content in the respective POD mode

Subscripts

∞	reference value (typically inlet conditions at the tunnel)
0	initial conditions
l	liquid
v	vapor
m	mixture
f	friction
Q	discharge
c	cavity
L	laminar
t	turbulent
I	interfacial
n	normal to local gradient of phase fraction
sat	saturation conditions
dest	destruction of the phase
prod	production of the phase
+	condensation
−	evaporation
A, H, S, M, G, B	terms in a discretized equation
nb	neighboring nodes
P	at the cell of interest

Superscripts/overhead symbols

+	condensation
−	evaporation
‘	fluctuating component
*	normalized value; updated value in the context of PISO algorithm
$\rightarrow$	vector
-	average
$\sim$	Favre-averaged
n	time step level
k	iteration level