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Development and validation of a homogeneous flow model for simulating cavitation in cryogenic fluids

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ABSTRACT

Fluid machinery used for pumping cryogenic liquid fuels are severely impacted by the onset and development of cavitation. Cavitation in non-cryogenic fluids is commonly assumed to be isothermal, but cavitation in cryogenic fluids is substantially influenced by thermal effects. In the present paper, we present a computational fluid dynamics solver for cryogenic cavitation based on modifications to an isothermal cavitating flow solver presently available in the open-source OpenFOAM® software library. The homogeneous flow model is employed to compute the multiphase solution in an Eulerian framework. Thermal effects are captured via a coupled solution of a cryogenic form of the density, momentum, and energy equations. Thermophysical properties of the cryogenic fluid are corrected using the computed pressure and temperature fields to account for the baroclinic nature of the density field and temperature dependence of the fluid's saturation properties, specific heat, and dynamic viscosity. The resulting cryogenic solver is validated against experimental measurements of cavitating flow of liquid nitrogen in a circular orifice and a Laval nozzle, achieving good agreement for a range of operating conditions. Cavitating flow of liquefied natural gas (LNG) in the Laval nozzle is simulated to investigate the influence of thermal effects on the vapor vaporization and condensation processes. The results show that thermal effects slow the condensation of cavitating LNG such that the overall vapor production is enhanced compared to a baseline isothermal case. This behavior is jointly attributed to thermally-modulated variations in the saturation pressure near liquid/vapor interfaces and enhanced production of vorticity owing to the presence of baroclinic production mechanisms in the cryogenic solver.

1. Introduction

Due to environmental and economic factors, there is a recent interest in using cryogenic fluids such as liquefied natural gas (LNG) as an alternative fuel for commercial and marine vehicles [1]. Because of the low boiling temperature of LNG, most of the LNG turbomachinery will operate near the saturation conditions of LNG. Phase change from liquid to vapor may occur if the local temperature exceeds the fluid's saturation temperature (termed boiling) or if the local pressure drops below the fluid's saturation pressure (termed cavitation) [2]. In cryogenic conditions, both cavitation and boiling may occur simultaneously and interactively due to the temperature dependency of saturation pressure. The vapor forms sheets or

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Nomenclature

Roman characters

a	acoustic velocity
b	nozzle throat diameter
$\boldsymbol{c_p}$	specific heat at constant pressure
A	throat cross-section area of nozzle
d	orifice diameter
$\boldsymbol{g}$	gravity
$\boldsymbol{h}$	enthalpy
$\boldsymbol{I}$	identity matrix
$\boldsymbol{K}$	kinetic energy
$\boldsymbol{L}$	latent heat of vaporization
Pr	Prandtl number
$\boldsymbol{p}$	pressure
$\boldsymbol{q}$	heat flux
Re	Reynolds number
$\boldsymbol{T}$	temperature
u, v, w	Cartesian velocity components in streamwise, transverse, and spanwise directions
$\boldsymbol{u}$	velocity vector
$\boldsymbol{z}$	compressibility factor

Symbols

$\boldsymbol{\alpha}$	vapor volume fraction
$\boldsymbol{\kappa}$	thermal diffusivity coefficient
$\boldsymbol{\mu}$	molecular viscosity
$\boldsymbol{\nu}$	kinematic viscosity
$\boldsymbol{\rho}$	density
$\boldsymbol{\tau}$	Shear stress tensor
$\boldsymbol{\psi}$	compressibility function
$\boldsymbol{\omega}$	vorticity magnitude

Math operator

∇	gradient

Subscripts and superscripts

$()^*$	isothermal condition
$()^{\boldsymbol{T}}$	transpose of matrix
$()^0$	quantity at initial condition
$\overline{()}$	mean part of the quantity
$()_{\boldsymbol{c}}$	thermodynamic critical condition
$()_{\boldsymbol{HTR}}$	high temperature range
$()_{\boldsymbol{i,j,\ k}}$	quantity in the x, $\boldsymbol{y}$, z direction
$()_{\boldsymbol{l}}$	liquid phase
$()_{\boldsymbol{LTR}}$	low temperature range
$()_{\boldsymbol{m}}$	cryogenic mixture of vapor and liquid
$()_{\boldsymbol{mean}}$	averaged quantity
$()_{\boldsymbol{n}}$	normalized parameter
$()_{\boldsymbol{r}}$	reduced parameter
$()_{\boldsymbol{sat}}$	saturation condition
$()_{\boldsymbol{v}}$	vapor phase
$()_{\boldsymbol{x,y,\ z}}$	quantity in the x, $\boldsymbol{y}$, z direction

bubbles that may cause undesirable effects if not controlled. In turbomachinery, such as the positive-displacement pumps frequently used in LNG fuel systems, cavitation is typically associated with formation of high-amplitude and high-frequency oscillations that lead to localized stresses on components, material erosion, and significant efficiency drop [3]. Traditional isothermal cavitation scenarios in water pumps or marine propellers are typically considered to occur at constant temperature [2,4]. In contrast, cryogenic fluids such as LNG are characterized by large compressibility variations, a smaller density ratio between the gas and liquid phases, and lower latent heats of vaporization that significantly distinguish their cavitation behavior from the isothermal cases [2]. As a result, accurate prediction of the cryogenic cavitation as well as a clear