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Numerical study of thermodynamic effects on liquid nitrogen cavitating flows

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A R T I C L E I N F O

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The aims of this paper are to study the thermodynamics effects on cryogenic cavitating flows and analyze the specific effects on mass transportation process and flow field structure. Computations of the liquid nitrogen cavitating flows around a 2D quarter caliber hydrofoil are conducted. The Favre-averaged Navier–Stokes equations with the enthalpy-based energy equation, the transport equation-based cavitation model and the k–ω SST turbulence model are applied. The nominal temperature drop ΔT^*, defined as $\Delta T^* = (L\rho_v)/(C_l\rho_l)$, is used to assess the thermodynamic effects on the cavitating flows. The results show that the numerical solution can consistently capture the main features of both pressure and temperature profiles, which show good agreement with the experimental measurements. It is found that the cryogenic cavitation behaviors including pressure and temperature depressions, the variation of thermo-sensible properties, and cavity structures depend on the isothermal free-stream conditions and the thermodynamic effects. The thermodynamic effects significantly affect the liquid nitrogen cavitation behaviors via the following approach that the temperature change during the phase-change process causes the variation of thermo-sensible material properties (especially for the saturated vapor pressure and density), and then the reference free-stream conditions are changed equivalently, resulting in the change of cavity structure. It is indicated that thermodynamic effects could delay or suppress the occurrence and development of the cavitation behaviors. The properties like density ratio $R(T_\infty)$ and the change of vapor pressure dP_v/dT play more significant roles during the nitrogen phase-change process. As temperature increases, the thermodynamic effects become stronger, especially when the temperature is closing to the thermodynamics critical point.

1. Introduction

Cavitation is a phase-change phenomenon that occurs in liquids when the local static pressure drops below the saturated vapor pressure of liquids, this phenomenon is usually assumed to be an isothermal process [1–6]. However, the isothermal hypothesis is no longer valid in cryogenic fluids cavitating flows for their thermo-sensitive properties. When cryogenic cavitation occurs, the temperature drop ΔT (evaporative cooling) inside the cavity changes the local saturated vapor pressure and other temperature-dependent material physical properties, and then cavitation dynamics is affected [7–9].

The study of cavitating flows in cryogenic liquids has practical significance for superconductive magnets to be used for high energy physics accelerators and fusion reactors, and large-scale cryogenic systems of space telescopes and cryogenic fuel supply systems for liquid rocket engines [10–14]. The cryogenic cavitation behaviors have been numerically and experimentally investigated as early as 1956 [15]. Based on a simple heat balance between two phases, Stahl and Stepanoff [15] introduced a 'B-factor' defined as the volume ratio between vapor and liquid phase (V_v/V_l), to estimate temperature drop during phase-change process. Hord [16,17] conducted comprehensive experiments on cryogenic cavitation with liquid nitrogen and liquid hydrogen, under different sets of inlet Reynolds number, cavitation number and temperature conditions. Temperature and pressure data were measured at five locations in hydrofoil and ogive models, which have been commonly employed for numerical validation for thermodynamic effects on cryogenic cavitation [7–9,12,18–24]. Franc et al. [25,26] investigated refrigerant R-114 cavitation instabilities on inducer blades at three different fluid temperature, they demonstrated that the onset of blade cavitation is delayed at higher reference temperature.

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Nomenclature

ρ	density
V	volume
L	latent heat
C	heat capacity
T	temperature
ΔT^{*}	nominal temperature drop
ΔT	actual temperature drop
σ	cavitation number
p	pressure
U	velocity
t	time
α	volume fraction
μ	dynamic viscosity
f	mass volume fraction
h	enthalpy
Pr	Prandtl number
R	liquid/vapor density ratio
C_p	pressure coefficient
Re	Reynolds number
$\dot{m}^{+}$	condensation rate
$\dot{m}^{-}$	evaporation rate
k	turbulence kinetic energy

Subscripts

l	liquid phase
v	vapor phase
∞	reference
m	mixture
T	turbulent
L	laminar
i, j, k	directions of the Cartesian coordinates

As the CFD technology develops rapidly, various numerical methods have been developed to investigate the cavitating flows. In the numerical methods of cavitating flows, modeling of cavitation model plays a significant role on the prediction of the inception, growth, break-up, and collapse of cavitation bubbles or flows. Most cavitation models assume the multiphase flow to be a homogenous single-fluid, and apply either a barotropic equation of state (EOS) [27–30] or a transport equation [2,31–36] to solve the variable mixture density field in the cavitation process. The physical properties are expected to significantly affect the nature of cavitation behaviors in cryogenic cavitating flows [28], and then the thermodynamic effects on this mass and heat transfer process are highlighted [37–42]. The major challenge in using these transport equation-based cavitation models is the formation of the source terms and the empirical coefficients involved for vaporization and condensation processes. Recently, Hosangadi and Ahuja [24] employed the transport-based cavitation model to simulate cryogenic cavitating flows, lower values of cavitation model parameters for cryogenic cases as compared to their previous calibrations [43] for non-cryogenic fluid were suggested. Zhang et al. [21,44] demonstrated that the full cavitation model provides a reasonable prediction capability for simulating the cavitating flows in cryogenic cases. They further conducted better predictions by re-calculating the bubble radium in the full cavitation model taking the effect into account of local pressure [20]. Experimental visualizations of cryogenic cavitating flows [16,17] have clearly indicated a mushy nature of the cavity. This salient feature of cryogenic cavitation was lately adapted into the derivation of the interfacial dynamic-based (IDM) cavitation model [45] to yield a Mushy IDM [7]. The numerical results shows the predicted deviation of temperature from the experiment is not consistent between different geometry, which indicates further experimental and numerical investigation are needed for developing precise models. Rodio et al. [19] modified the Rayleigh–Plesset equation by the addition of a term for convective heat transfer at the interface between the liquid and the bubble coupled with a bubbly flow model to assess the prediction of thermal effects. Huang et al. [18] validate a thermodynamic cavitation model based on bubble dynamic equation and calibrate the parameters of the cavitation model for liquid hydrogen cavitating flows. Zhu et al. [22] developed an effective computational strategy to simulate cryogenic cavitation by implementing the “Schnerr–Sauer cavitation model”, coupled with the energy equation.

Although the thermodynamic effects on cryogenic liquid cavitating flows have received much attention in the past years, the thermodynamic effects on cryogenic cavitating flows and the specific effects of thermo-sensible material properties on cavitation behaviors are still not well understood.

Reviewing the state-of-the-arts numerical method for attached cavitating flows, homogeneous model, Favre-averaged Navier–Stokes equations and turbulence closures, and a transport equation-based cavitation model is capable handling because of its satisfactory robustness and reasonable prediction capability for simulating the cavitating flows [7–9,23,31,33,45–48]. Based on the framework which is coupled with energy equation, the liquid nitrogen cavitating flows are numerical investigated, the present aims are to study thermodynamics effects on cryogenic cavitating flows and analyze the specific effects on cavitation mass transportation process and flow field structure.

2. Governing equations and numerical approaches

2.1. Governing equations

The set of governing equations for cryogenic cavitation under the homogeneous multiphase flows strategy consists of the conservative form of the Favre-averaged Navier–Stokes equations, the enthalpy-based energy equation, the turbulence closure, and a transport equation for phase change. The continuity, momentum, enthalpy, and cavitation model equations are given below in the Cartesian coordinates. All computations presented below are based on the steady-state equations.

$$\frac{\partial \rho_m}{\partial t} + \frac{\partial(\rho_m U_j)}{\partial x_j} = 0, \tag{1}$$

$$\frac{\partial(\rho_m U_i)}{\partial t} + \frac{\partial(\rho_m U_i U_j)}{\partial x_j} = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j}\left[(\mu_m + \mu_T)\left(\frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i} - \frac{2}{3}\frac{\partial U_k}{\partial x_k}\delta_{ij}\right)\right], \tag{2}$$

$$\frac{\partial}{\partial t}(\rho_m(f_L L)) + \frac{\partial}{\partial x_j}(\rho_m U_j(f_L L)) = \frac{\partial}{\partial x_j}\left[\left(\frac{\mu_m}{\mathrm{Pr}_L} + \frac{\mu_T}{\mathrm{Pr}_T}\right)\frac{\partial h}{\partial x_j}\right] \tag{3}$$