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Numerical investigation of cavitating flow in liquid hydrogen

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ARTICLE INFO

Article history:
Received 27 September 2013
Received in revised form
4 November 2013
Accepted 11 November 2013
Available online 15 December 2013

Keywords:
Cavitating flow
Thermal effects
Liquid hydrogen

ABSTRACT

The objective of this paper is to investigate the cavitating flow in liquid hydrogen. The aims are to (1) study the physical aspects of cavitation dynamics in cryogenic environment and validate a thermodynamic cavitation model based on bubble dynamic equation, (2) conduct a global sensitivity analysis to assess the sensitivity of the response to temperature dependent material properties and model parameters, and to calibrate the parameters of the cavitation model for suitable flow conditions, (3) assess the thermodynamic cavitation model over a wide range of conditions. Numerical computations are performed on the 2D quarter caliber hydrofoil experimentally investigated by Hord [Cavitation in liquid cryogens II-hydrofoils. NASA CR-2156; 1973a; Cavitation in liquid cryogensIII-Ogives. NASA CR-2242; 1973b]. The numerical simulations are performed by solving the multiphase Unsteady Reynolds-averaged Navier–Stokes (URANS) Equations via the commercial code CFX using a thermodynamic cavitation model, the $k-\omega$ SST turbulence model is used as the closure model. The results showed that the thermodynamic effect has significantly affects the cavitation dynamics, including the vapor pressure and cavity structures. The isothermal case yields a substantially larger cavity attached on the hydrofoil due to the thermodynamic effect under thermal conditions. The predicted pressure and temperature inside the cavity is steeper under the cryogenic condition than that under the isothermal condition, which shows better agreement with the experimental measurements. Based on the surrogate model, the global sensitivity analysis is conducted to assess the role of model parameters regulating the condensation and evaporation rates, and uncertainties in material properties. It is indicated that the material properties are more critical than the model parameter controlling the condensation and evaporation rates. Based on the recommended model parameter values, better prediction of the cryogenic cavitation could be attained.

1. Introduction

Cavitation is a dynamic phase-change phenomenon that occurs in liquids when the static pressure drops below the vapor pressure of liquid [1,2]. Cavitation induces noise, mechanical vibrations, material erosion, and can severely impact the performance as well as the structural integrity of fluid machinery. The study of cavitating flows is complicated by

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http://dx.doi.org/10.1016/j.ijhydene.2013.11.025

simultaneous presence of turbulence, multiple timescales, large density variations or phase change, interfacial dynamics etc. Due to its practical importance and rich physics, cavitating flow is a topic of substantial interest and challenge to the computational community.

In the numerical modeling of cavitating flows, the selection of cavitation models plays a major role on the prediction of the onset, growth, break-up, and collapse of cavitation bubbles. Most cavitation models assume the flow to be homogenous and isothermal, and apply either a barotropic equation of state or a transport equation to solve for the variation of the mixture density. In recent years, significant efforts have been made in the development of cavitation models; examples of recent review articles can be found in Refs. [3–7].

Compared to the experimental [8–10] and numerical research [7,11–19] on cavitating flow in normal temperature liquid, fewer studies on cavitation phenomenon in cryogenic liquids have been conducted. However, the study of cavitating flows in cryogenic environment has practical importance for space applications because cryogens often serve as fuels for space launch vehicles [20]. In cryogenic cavitating flow, the physical and thermal properties of the cryogenic fluid are expected to significantly affect the nature of cavitation [21,22]. The influence of thermal effects on cavitation has been numerically and experimentally investigated as early as 1956 [23], Stahl and Stepanoff introduced a 'B-factor' method to estimate temperature drop in terms of the ratio of vapor volume to liquid volume during vaporization process, and used it to appraise head depression due to thermodynamic effects in cryogenic cavitation. Sarosdy and Acosta [24] carried out water cavitation and Freon cavitation experiments, they showed that for water cavitation, the interface of vapor and liquid in cavitation region is clear, and the cavitation strength is more intense. However, for Freon cavitation under similar condition, the cavity is mushy/frothy with weaker cavitation intensities. Hord [25,26] conducted comprehensive experiments on cryogenic cavitation with liquid nitrogen and liquid hydrogen, under different sets of inlet velocities and temperature conditions. Temperature and pressure data were measured at five locations in the cavitating region, which have been commonly employed for numerical validation for thermodynamic effects in cavitation [27]. Franc et al. [28] employed pressure spectra to investigate R-114 cavitation on inducer blades, the impact of thermodynamic effect was investigated at three different fluid temperatures. They demonstrated that the onset of blade cavitation is delayed at higher reference temperature. Recently, Hosangadi and Ahuja [29] employed the Merkle transport-based cavitation model to simulate cryogenic cavitating flow, they suggested significantly lower values of cavitation model parameters for cryogenic cases as compared to their previous calibrations [30] for non-cryogenic fluid. Zhang et al. [31] demonstrated that the full cavitation model provides a satisfactory robustness and reasonable prediction capability for simulating the cavitating flow in liquid hydrogen over different objects. Utturkar [32] developed a mushy interfacial dynamic-based (IDM) cavitation model to simulate the cryogenic cavitation over two geometries (2D hydrofoil and axisymmetric ogive). The numerical results shows the predicted deviation of temperature from the experiment is not consistent between the hydrofoil and ogive geometry, which needs further experimental and numerical investigation for developing more precise models. Tseng and Shyy [33] conducted global sensitivity analysis to assess the role of model parameters of a transport-based cryogenic model. The cavitation model parameters, which seem to be dependent on the fluid type, in the Merkle model are calibrated for liquid Nitrogen and Hydrogen with numerical experimentation. Rodio et al. [34] performed a parametric study by considering several values of and models for the convective heat transfer coefficient, h_b, and they noted the importance of the choice of h_b for the correct prediction of the temperature drop in the cavitation region, compared with the experimental data.

The objective of this paper is to investigate the cavitating flow in liquid hydrogen. The aims are to (1) study the physical aspects of cavitation dynamics in cryogenic environment and validate a thermodynamic cavitation model based on bubble dynamic equation, (2) conduct a global sensitivity analysis to assess the sensitivity of the response to temperature dependent material properties and model parameters, and to calibrate the parameters of the cavitation model for suitable flow conditions, (3) assess the thermodynamic cavitation model over a wide range of conditions.

The numerical models and summary of the numerical setup are presented in Section 2. In Section 3, the thermal effects on cavitation in liquid hydrogen are first presented, followed by the surrogate-based global sensitivity assessment and optimization of cavitation model parameters, and then the assessment of thermodynamic cavitation model over a wide range of condition is conducted. Finally, the major findings and future work are summarized in Section 4.

2. Numerical model

2.1. *Conservation of mass & momentum*

The set of governing equations for cryogenic cavitation under the homogenous-fluid modeling consists of the conservative form of the Favre-averaged Navier–Stokes equations, the enthalpy-based energy equation (for cryogenic cavitation), the turbulence closure, and a transport equation for the liquid volume fraction. The continuity, momentum, enthalpy, and cavitation model equations are given below. All computations presented below are based on the steady-state equations.

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

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

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