COMPUTATIONS OF ALL-SPEED CRYOGENIC CAVITATING FLOWS IN TURBOPUMP INDUCER

Hyeongjun Kim[1], Daeho Min[1], Donghwan Kim[1] and Chongam Kim[1]

1) *Department of Aerospace Engineering, Seoul National University, Seoul 151-742, KOREA*

Corresponding Author: Chongam Kim, chongam@snu.ac.kr

ABSTRACT

The present paper deals with a numerical method for all-speed cryogenic cavitating flows in turbopump inducer. Recently, we have developed an accurate and efficient baseline numerical scheme for the computations of all-speed two-phase flows. By extending such progress, we conduct some modification of preconditioning technique and propose an accurate and efficient numerical method to deal with the computations of cryogenic two-phase flows. To verify pressure and temperature depression effect in cryogenic cavitation, we carry out numerical simulations of cryogenic cavitation flows around hydrofoil. Compared with Hord's experimental data, computed results are turned out to be quite satisfactory. Finally, numerical simulations of KARI turbopump inducer are carried out under various flow conditions with water and cryogenic fluids, and we examine the differences in inducer flow physics depending on the working fluids.

INTRODUCTION

Generally, characteristics of cavitation in cryogenic fluids are quite different to those of waters due to thermal effects and strong variations in fluid properties. Cryogenic cavitation occurs at turbopump inducer which pressurizes oxidizer and fuel in liquid rocket. When cavitation occurs, cavitation instabilities such as rotating cavitation or cavitation surge are frequently observed, causing degradation of turbpump performance or failure. Therefore, understanding and quantifying characteristics of cryogenic cavitation are quite important for the design of turbopump.

For turbopump simulations, the majority of CFD simulations reported in the literature are limited to isothermal incompressible flow conditions (Athavale and Singhal, Dupont and Okamura, and Medvitz *et al.*). The effect of temperature variations in fluids is, by definition, not accounted for in these calculations. Recently, Hosangadi *et al.* has developed an all-speed cryogenic two-phase numerical method and examined pressure and temperature depression for cryogenic cavitation.

Our research group has developed an accurate and efficient numerical scheme for all-speed water-gas two-phase flows. In present paper, we first modify our preconditioning technique to compute more efficiently in low Mach number region and then, we extend our numerical schemes into cryogenic fluids. To validate our numerical code, Hord's experiments are simulated. Finally, numerical simulations of KARI turbopump inducer are carried out under various flow conditions, and we examine the inducer flow physics depending on the working fluids.

NUMERICAL METHODS

Governing Equation

The Homogeneous equilibrium model (HEM) with mass fraction is adopted to describe two-phase flows. Assuming fully compressible flows including thermal effect, the governing equations consist of mixture mass, momentum, and energy conservation law. Then, system preconditioning is introduced to cover the low Mach number region. The preconditioned form of the HEM two-phase governing equations are follows:

$$\frac{1}{J}\frac{\partial Q}{\partial t}+\frac{\Gamma}{J}\frac{\partial Q_p}{\partial \tau}+\frac{\partial E}{\partial x}+\frac{\partial F}{\partial y}+\frac{\partial G}{\partial z}=D+S_{cav}+S_{rotation} \tag{1}$$

Where, Γ, D, S_{cav} are preconditioning matrix, viscous flux vector, and cavitation source term, respectively. In our research, absolute velocity formulation is used to express equations for a rotating reference frame. So, rotating source term is follows:

$$S_{rotation}=\frac{1}{J}\left[0,\rho_m\left(\vec{\omega}\times\vec{v}\right)_x,\rho_m\left(\vec{\omega}\times\vec{v}\right)_y,\rho_m\left(\vec{\omega}\times\vec{v}\right)_z,0,0\right]^T \tag{2}$$

Equation of State

The properties of cryogenic fluids are sensitive to temperature variation due to low latent heat compared to other fluids. Therefore, accurate equation of state is essential part to simulate cryogenic cavitation flow. In present work, thermodynamic properties were generated from the National Institute of Standards and Technology (NIST) for pure fluids. For computational efficiency, all thermodynamic properties are generated by modeling of NIST database using regression analysis.

Cavitation Model

In the present effort, the cavitation source term is defined via a simplified nonequilibrium finite rate form as follows:

$$S_{cav}=\frac{1}{J}\left[0,0,0,0,0,\dot{m}_{evaporation}-\dot{m}_{condensation}\right]^T \tag{3}$$

Where the term $\dot{m}_{evaporation}$ is the evaporation rate for vapor being generated from liquid in a region in which the local pressure is less than the vapor pressure. Conversely, $\dot{m}_{condensation}$ is the condensation rate for reconversion of vapor back to liquid regions in which the local pressure exceeds the vapor pressure. Here, Merkle's model, Kunz's model, Singhal's model and Mushy IDM are employed. Detailed formulation of each cavitation model is omitted in this paper.

Shock-Discontinuity-Sensing for Two-Phase-Mixture Flows

The two-phase RoeM [1] and AUSMPW+ schemes have control functions that monitor modified pressure like term around a cell interface. With this information, both schemes are able to sense shock discontinuity and control the amount of the numerical fluxes properly to enhance the stability and/or accuracy of the schemes. However, this modified pressure like terms is not properly applicable for general cryogenic fluid because formulations of equation of state are different each other. To extend general cryogenic fluids, a new version of modified pressure like term is proposed as follows:

$$\overline{p} = \frac{1}{\alpha_g \frac{1}{\rho_g}\frac{\partial \rho_g}{\partial p} + \alpha_l \frac{1}{\rho_l}\frac{\partial \rho_l}{\partial p}} \tag{4}$$

By this modification, previous modified pressure like term can be used for general type of equation of state, i.e. independent of equation of state formulation.

Preconditioning of the Two-Phase RoeM Scheme

In previous research [2], we implement the Harten-Lax-van Leer with contact restoration (HLLC)-type preconditioning strategy by Luo *et al*. into RoeM scheme. By scaling the numerical dissipation of the RoeM scheme using the preconditioned eigenvalues, the preconditioning of the RoeM can be efficiently realized. However, numerical dissipations of this preconditioned RoeM scheme are different compared with the preconditioned Roe scheme. So, the direct derivation of a preconditioned RoeM scheme from the preconditioned Roe scheme is conducted as follows:

$$E_{1/2} = \frac{1}{2}\left[E_L + E_R - M^* A_p \Delta Q_p - c^*\left(M^* \frac{U}{c^*}(1-\alpha) - 1 \right)\Delta Q - gc^*\left(1 - \frac{|U|}{c^*} + \alpha M^* \frac{U}{c^*} \right) B\Delta Q \right] \tag{5}$$

$$B\Delta Q = \left(\Delta\rho_m - f\,\frac{c^* - (1-2\alpha)|U| - \alpha U M^*}{c^* - |U| + \alpha U M^*}\frac{\Delta p}{c'^2} \right)\begin{pmatrix} 1 \\ u \\ v \\ w \\ H_m \\ Y_1 \end{pmatrix} + \rho_m \begin{pmatrix} 0 \\ \Delta u - n_x \Delta\tilde{U} \\ \Delta v - n_y \Delta\tilde{U} \\ \Delta w - n_z \Delta\tilde{U} \\ H_m - \frac{\Delta p}{\rho_m} - \tilde{U}\Delta\tilde{U} \\ \Delta Y_1 \end{pmatrix} \tag{6}$$

NUMERICAL RESULTS

Hord Hydrofoil Problem

As a validation case, numerical simulations of experiments by Hord on a hydrofoil for both liquid nitrogen (Run 289C) and liquid hydrogen(Run 231C) are presented. Compared with experimental data and other researcher's results, computed pressure and temperature depression are reasonable.

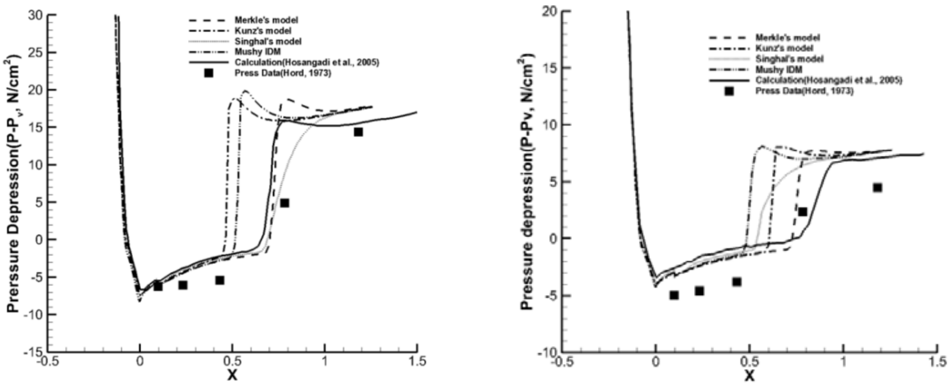

Figure 1. Pressure depression in liquid nitrogen(Left), in liquid hydrogen(Right)

Simulations of KARI Turbopump Inducer

Finally, numerical results of KARI turbopump inducer are presented. Numerical simulations were performed in water, liquid oxygen and liquid hydrogen with design flow rate and off-design flow rate. And then, liquid hydrogen and liquid oxygen are simulated to compare thermal effect.

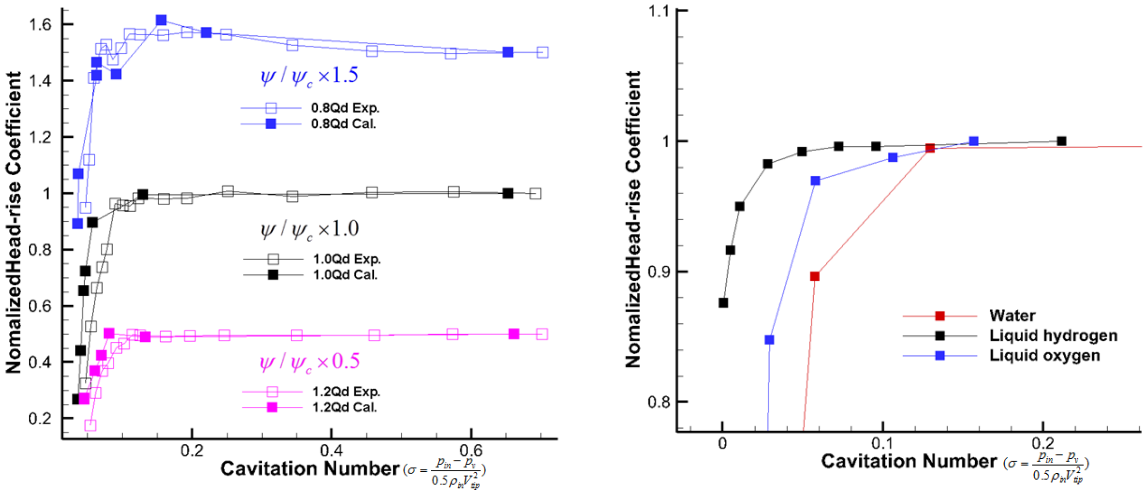

Figure 2. Normalized head-rise coefficient in cold water (Left), comparison with cryogenic fluids (Right)

CONCLUSION

In the present paper, simulations of cryogenic cavitation in turbopump inducer are performed. Firstly, two-phase numerical method which is already developed for water-gas two phase flows is extended into cryogenic flow fields by generalizing the equation of state. And then, other numerical sub-components are successfully applied. Finally, numerical simulation of 3-D KARI turbopump inducer was performed. Computed results with water at three flow rate are reliable compared with experimental data. To examine thermal effect in cryogenic fluids, liquid oxygen and liquid hydrogen turbopump inducer are also successfully computed.

ACKNOWLEDGMENT

The authors appreciate the financial supports provided by NSL (National Space Laboratory) program through the National Research Foundation of Korea funded by the Ministry of Education, Science and Technology (GRANT 20120009099).

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