Numerical simulations of cryogenic cavitating flows

Hyunji Kim, Hyeongjun Kim, Daeho Min and Chongam Kim
Department of Aerospace Engineering, Seoul National University, Seoul 151-742, Korea
E-mail: chongam@snu.ac.kr

Abstract. The present study deals with a numerical method for cryogenic cavitating flows. Recently, we have developed an accurate and efficient baseline numerical scheme for all-speed water-gas two-phase flows. By extending such progress, we modify the numerical dissipations to be properly scaled so that it does not show any deficiencies in low Mach number regions. For dealing with cryogenic two-phase flows, previous EOS-dependent shock discontinuity sensing term is replaced with a newly designed EOS-free one. To validate the proposed numerical method, cryogenic cavitating flows around hydrofoil are computed and the pressure and temperature depression effect in cryogenic cavitation are demonstrated. Compared with Hord's experimental data, computed results are turned out to be satisfactory. Afterwards, numerical simulations of flow around KARI turbopump inducer in liquid rocket are carried out under various flow conditions with water and cryogenic fluids, and the difference in inducer flow physics depending on the working fluids are examined.

1. Introduction
Cryogenic cavitation occurs at turbopump inducer, one of the key components in liquid rocket propulsion system, which pressurizes oxidizer and fuel. The characteristics of cryogenic cavitation are quite different to those of water due to thermal effect and strong variations in fluid properties. Once cavitation occurs, not only cavitation breakdown but also instabilities such as rotating cavitation or cavitation surge are frequently observed. As these phenomena give rise to degradation of turbopump performance, or even failure, understanding and quantifying characteristics of cryogenic cavitation are crucial for the design of turbopump.

The majority of CFD simulations for turbopump have been limited to the isothermal incompressible flow conditions (Athavale and Singhal [1], Dupont and Okamura [2], Coutier-Delgosha et al. [3], and Kiris et al. [4]). The effect of temperature variations in fluids is, by definition, not taken into account in these calculations. Recently, Hosangadi et al. [5], Utturkar et al. [6] and Goncalves et al. [7] have computed compressible two-phase flows with cryogens as a working fluid.

Based on an accurate and efficient numerical scheme for all-speed two-phase flows (Refs. [8] and [9]), we first modify the numerical dissipations to enhance the numerical stability and accuracy in low Mach number regions. The extension to cryogenic fluids is achieved by removing the EOS(Equation of State)-dependent term. To validate the numerical code, Hord’s experiments are simulated. Numerical simulations of KARI(Korea Aerospace Research Institute) turbopump inducer are then carried out under various flow conditions, and the inducer flow physics depending on the working fluids are examined.
2. Governing equations

2.1. Homogeneous mixture equations

The homogeneous mixture model with mass fraction is adopted to describe two-phase flows by including fully compressible thermal effects. The governing equations consist of mixture mass, momentum, and energy conservation laws with one-phase mass conservation law. Then, system preconditioning is introduced for the convergence in low Mach number regions. The preconditioned form of two-phase governing equations are as follows:

\[
\frac{\partial}{\partial t} \int_{\Omega} Q d\Omega + \Gamma \frac{\partial}{\partial \tau} \int_{\Omega} Q_p d\Omega + \oint_{\partial\Omega} [F - F_v] dS = \int_{\Omega} [H_{rot} + H_{cav}] d\Omega. \tag{1}
\]

The primitive variable vector \( Q_p \) reads

\[
Q_p = [ p \quad u \quad v \quad w \quad T \quad Y_1 ]^T. \tag{2}
\]

In equation (1), \( \Gamma, H_{rot}, H_{cav} \) indicates system preconditioning matrix from Ref. [10], rotating source term and cavitation source term, respectively. Since a pseudo-acoustic speed is defined as \( c' = \min(c, \max(V, V_{ref})) \), the original governing equation is recalled at supersonic regions to achieve hyperbolic system of equations.

2.2. Equation of state

The definition of the mixture density \( \rho \) plays the role of the mixture equation of state (EOS):

\[
\frac{1}{\rho(p, T, Y_1)} = \frac{Y_1}{\rho_v(p, T)} + \frac{(1 - Y_1)}{\rho_l(p, T)}. \tag{3}
\]

In equation (3), \( \rho_v \) and \( \rho_l \) is the density of vapor and liquid phase respectively on each occupied volume within the computational mesh.

The properties of cryogenic fluids are sensitive to temperature variation due to their low latent heat compared to other fluids. Therefore, an accurate EOS is required to simulate cryogenic cavitations. Thermodynamic properties are generated from the National Institute of Standards and Technology (NIST) [11] for pure fluids.

2.3. Cavitation model

The cavitation source term is defined via simplified non-equilibrium finite rate form. Phase change rates are mainly determined by the difference between the local pressure and the vapor pressure. Here, cavitation models of Merkle [12], Kunz [13], FCM [14] and Mushy IDM [15] are employed.

3. Numerical methods

The numerical methods adopted in the study are based on the work by Kim et al. [9] and Ihm et al. [8].

4. Numerical results

4.1. Cryogenic cavitating flows around hydrofoil

As a validation case, numerical simulation of the experiments by Hord [16] for liquid nitrogen is demonstrated in figure 1. Flow conditions for run number 289C are presented in table 1.
Table 1. Flow conditions for validation problem.

| Run number | Geometry | Working fluid   | T [K] | V [m/s] | σ   |
|------------|----------|-----------------|------|--------|-----|
| 289C       | hydrofoil| liquid nitrogen | 88.64| 23.5   | 1.55|

Figure 1. Numerical results of Hord’s experiments: Run 289C.

Figure 2. Pressure depression(left) and temperature variation(right).

As shown in figure 2, the calculated results qualitatively agree with the experimental ones despite the discrepancy in the cavity closure region. Further analysis on the empirical coefficients of the cavitation models and experimental uncertainty is expected to fill the gap between the computations and the experimental data in this region.

4.2. Cavitating flows around turbopump inducer

Numerical simulations of KARI turbopump inducer are performed in water, liquid oxygen and
liquid hydrogen with design flow rate and off-design flow rates in figures 3 to 5. Liquid hydrogen and liquid oxygen are simulated to compare thermal effect.

5. Conclusions
In the present study, simulations of cryogenic cavitation are performed. Two-phase numerical methods which have been developed for water-gas two-phase flows are extended to cryogenic two-phase flows by generalizing EOS. Scaling of numerical dissipations are also successfully applied so that the stability and accuracy in low Mach number regions are secured. After the validation of the numerical method with cryogenic two-phase flows around hydrofoil, numerical simulation of 3D KARI turbopump inducer is performed. Computed results with water at three different flow rates are reliable compared with experimental data. To examine thermal effect of cryogenic fluids, liquid oxygen and liquid hydrogen turbopump inducer are also successfully computed.

Acknowledgments
The authors appreciate the financial support of the National Research Foundation of Korea funded by the Ministry of Science, ICT and Future Planning (NRF-2014M1A3A3A02034856) and Civil Military Technology Cooperation Center.

References
[1] Athavale M M and Singhal A K 2001 37th AIAA/ASME/SAE/ASEE Joint Propulsion Conf. and Exhibit (Salt Lake City) AIAA 2001-3400 (Virginia: AIAA)
[2] Dupont P and Okamura T 2003 Int. J. Rotating Machinery 9 163
[3] Coutier-Delgosha O, Morel P, Fortes-Patella R and Reboud J L 2005 Int. J. Rotating Machinery 2005.2 135
[4] Kiris C C, Kwak D C and Housman J A 2008 Computers & Fluids 37 535
[5] Hosangadi A, Ahuja V, Ungewitter R J and Busby J 2007 J. Propulsion and Power 23 1225
[6] Utturkar Y, Thakur S and Shyy W 2005 43rd AIAA Aerospace Sciences Meeting and Exhibit (Reno) AIAA 2005-1286 (Virginia: AIAA)
[7] Goncalvs E, Patella R F, Rolland J, Pouffary B and Challier G 2010 J. Fluids Engineering 132
[8] Ihm S and Kim C 2008 AIAA J. 46 3012
[9] Kunz H, Min D and Kim C 2014 Proc. ICCFD8 (Chengdu, China)
[10] Weiss J M and Smith W A 1995 AIAA J. 33 2050
[11] NIST Reference Fluid Thermodynamic and Transport Properties Database (REFPROP): Version 8.0, NIST standard Reference Database 23
[12] Merkle C L, Feng J Z and Buelow P E O 1998 Proc. 3rd Int. Symp. on Cavitation (Grenoble, France)
[13] Kunz R F, Boger D A, Stinebring D R, Chyczewski T S, Lindau J W, Gibeling H J, Venkateswaran S and Govindan T R 2000 Computers & Fluids 29 849
[14] Singhal A K, Athavale M M, Li H and Jiang Y 2002 J. Fluids Engineering 124 617
[15] Senocak I and Shyy W 2004 Int. J. for Numerical Methods in Fluids 44 975
[16] Hord J 1973 Cavitation in liquid cryogens 2: Hydrofoil (Washington: NASA)