Progress of the cavitating flow simulation in cryogenic fluid around 3D objects

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ABSTRACT

Since the coupling of cavitation modeling with turbulent flow is the difficulty topic, a numerical simulation for two phase flow remains as one of the challenging issues in the society. This research focuses on the development of numerical code to deal with incompressible two phase flow around conical body combined with cavitation model suggested by Kunz et al. with k-e turbulent model. The simulation results are compared to experimental data to verify the validity of the developed code. The calculation results show very good agreement with experimental observations. Also, the calculation of cavitation in cryogenic fluid is being done by implementing the temperature sensitivity in government equations and it is still in the progress. This code have been being further extended to 3D compressible two phase flow for the study on the fluid dynamics around inducers and impellers in turbo pump system.

Key Words: Cavitation, cavitating flow, cryogenic fluid, simulation

1. Introduction

Cavitation leads to flow instability and causes strong pressure shock and corrosion on the surface by periodic inception, growth and depletion of cavitation bubbles. Thus, many studies have been conducted to analyze the characteristics of cavitation flow both in experiments and CFD. Especially a CFD code development has been also difficult tasks due to the inception of cavitation bubble and complicates natures between turbulence and cavitation in two phase flow. And the amorphous boundary between liquid and gas phase should be clearly captured and taken into account. Assumptions commonly made in the modeling of phase change includes that the phase change means liquid – vapor change and no slip condition is valid between two phases. And the parameter can be introduced to express all the phase from liquid to vapor by using the fraction of liquid density in the mixture [1]. A various method of cavitation modeling depends on the physical modeling of how the mixture density can be expressed in terms of density parameter. One of the popular modeling suggested by Delanoy and Kueny [2] uses a mixture density of mixture with equation of state. Other types of modeling methods resort to the growth and collapse of cavitation in

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terms of density variation of the two phase mixture. Specially, Kunz et al. used two competing equations for vapor production and depletion in the governing equations [3]. And Singhal and Sauer [4] modified Rayleigh- Plesset equation by assuming the vapor production rate. Meanwhile, two different algorithms have been developed for numerical calculation. Shyy et al. [5] focused on the pressure based algorithm while Kunz and coworkers used density based algorithm in the calculation. The present study was done to simulate the cavitating flow over the conical fore-body object and compared to experiment and reference. Also the computation was extended to cryogenic flow and it is now in the progress.

2. Governing equations and Modeling

A couple of modeling has been implemented with governing equations: continuity, momentum equations, and volume fraction transport equation in the Cartesian coordinate system as following:

$$\frac{\partial}{\partial t}\int_V \rho_m dV + \int_S \rho_m \vec{V} \bullet \vec{n} dS = 0 \qquad \text{eq. 1}$$

$$\frac{\partial}{\partial t}\int_V \rho_m \vec{V} dV + \int_S \rho_m \vec{V}\vec{V} \bullet \vec{n} dS \qquad \text{eq. 2}$$
$$= \int_S \vec{T} \bullet \vec{n} dS + \int_V \rho_m \vec{b} dV$$

$$\frac{\partial}{\partial t}\int_V \alpha_l dV + \int_S \alpha_l \vec{V} \bullet \vec{n} dS \qquad \text{eq. 3}$$
$$= \int_V (\dot{m}^+ + \dot{m}^-) dV$$

here $T_{ij} = -(p + \frac{2}{3}(\mu + \mu_t)\frac{\partial u_j}{\partial x_j})\delta_{ij} + (\mu + \mu_t)(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i})$

Cavitation terms, based on Kunz et al.'s model, are used in this study. The evaporation and condensation rates are given as follows:

$$\dot{m}^- = \frac{C_{dest}\rho_v \alpha_l Min[0, p - p_v]}{\rho_l(\frac{1}{2}\rho_l U_\infty^2)t_\infty}$$

$$\dot{m}^+ = \frac{C_{pro}\rho_v \alpha_l^2 (1 - \alpha_l)}{\rho_l t_\infty}$$

where: $C_{pro} = 9 \times 10^5$, $C_{dest} = 3 \times 10^4$, $t_\infty = 1$

3. Cavitating flow over a conical object

The formulation presented in the previous section is applied to conical geometry (22.50 cone half-angle). The results include steady-state computations of noncavitating and cavitating flows at a Reynold number of 1.36x 10^5. Results are compared with experimental results [6] to verify the developed code. Figure 1 shows the comparison among predicted, experimental and referred surface pressure distributions under noncavitating condition and a good agreement among results can be obviously observed here. And a similar result is provided under cavitating condition in figure 2 at the cavitation number of 0.3. Here, the present simulation underpredicts the length of the bubble but qualitative trends remain correctly predicted. It's obviously observed in figure 3.

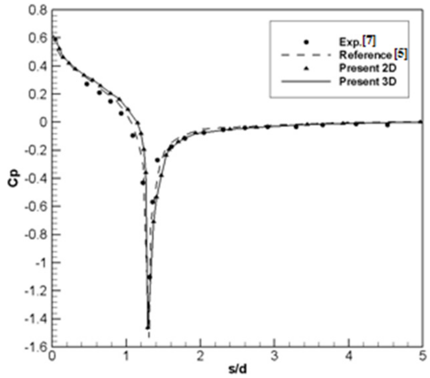

Fig. 1. Comparison of pressure coefficient distribution under noncavitating condition

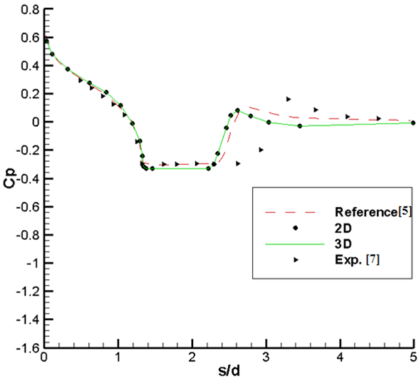

Fig. 2. Comparison of pressure coefficient distribution under cavitating condition (σ = 0.3)

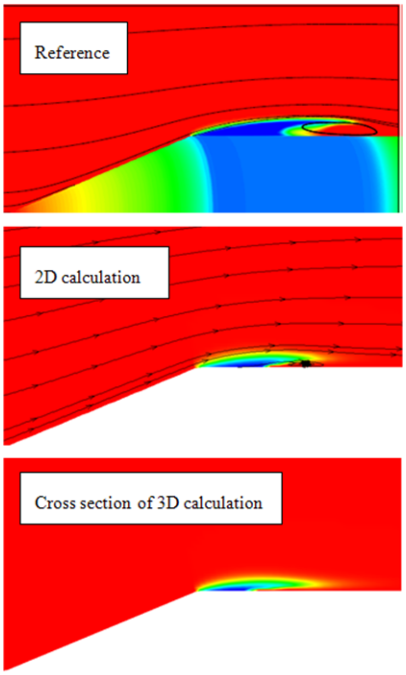

Fig. 3. Cavitation shape represented by contour of liquid volume fraction

4. Cavitation in cryogenic fluid

Cryogenic fluid has its own particular features such as high sensitivity in vapor pressure to temperature variation and big mass transfer to vapor bubble from fluid. The additional temperature term is in the energy equation, then rearrange we get this form:

$$\frac{\partial}{\partial t}\left[\rho_m(C_pT)\right]+\frac{\partial}{\partial x_j}\left[\rho_m u_j(C_pT)\right]$$
$$=\frac{\partial}{\partial x_j}\left[C_p\left(\frac{\mu}{\mathrm{Pr}_L}+\frac{\mu_t}{\mathrm{Pr}_t}\right)\frac{\partial T}{\partial x_j}\right]$$
$$-\left\{\frac{\partial}{\partial t}\left[\rho_m(\alpha_l L)\right]+\rho_m L\left(\dot{m}^{+}+\dot{m}^{-}\right)\right\}$$

In the cavitation modeling, a special treatment for vaporization of cryogenic fluid is required by using IDM (interfacial dynamics model) concept which suggests:

$$\dot{m}^{-}=\frac{\rho_l Min\left[0,p-p_v\right]\alpha_l}{\rho_-(U_{m,n}-U_{I,n})^2(\rho_l-\rho_v)t_\infty}$$
$$\dot{m}^{+}=\frac{\alpha_l Max\left[0,p-p_v\right](1-\alpha_l)}{\rho_+(U_{m,n}-U_{I,n})^2(\rho_l-\rho_v)t_\infty}$$

where:

$$\frac{\rho_l}{\rho_-}=\frac{\rho_l}{\rho_v}+\left(1.0-\frac{\rho_l}{\rho_-}\right)e^{-(1-\alpha_l)/\beta}\;;\;\frac{\rho_l}{\rho_+}=\frac{\rho_l}{\rho_m}$$

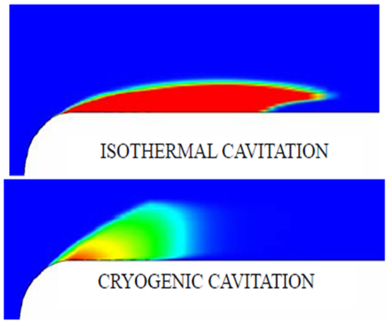

Fig. 4. Effect of real fluid property variations on cavity shape and volume distribution

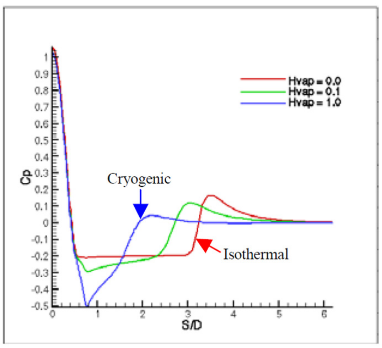

Fig. 5. Effect of real fluid property on cavity pressure distribution

Figure 4 shows comparisons of cavities in liquid nitrogen with and without thermal effects at a temperature of 89 K, and a velocity of 20 m/s flowing over a headform of 1 inch diameter [7]. For the isothermal case, a sharp and distinct cavity is obtained with vapor volume fraction in the cavity being near unity. As the thermal effects become pronounced the cavity interface becomes less sharp and the volume fraction of vapor in the cavity drops dramatically. The corresponding pressure profiles in the cavity are plotted in figure 5. For the isothermal case, the pressure in the cavity is at a constant value given by the freestream cavitation number. With increasing thermal effects there is depression at the leading edge due to local temperature drop and a gradual relaxation back to the freestream value as the temperature rises again in the aft of the cavity as vapor condenses back to liquid.

5. Summary and Conclusion

This study focuses on the development of computational code to investigate the flow characteristics around 2D axisymmertric body such as conical body with transport equation. Also, the prediction of cavitation formation in cryogenic fluid is done by using the implementation of energy equation along with modified vapor production and depletion terms. However, it is still in the progress now. The calculation results were also compared with experimental data to verify the capability of developed code. The prediction results reveal the code can simulate the bubble formation and depletion and life span showing a qualitatively good agreement. Also, the code was extended to grasp the sensitivity of vapor pressure of cryogenic fluid to temperature variation due to the formation of cavitation and the result comparison is going to shown in near future.

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