The cavitating flow simulation in cryogenic fluid around 3D objects

Quangnha Thai* · Changjin Lee**

ABSTRACT

This research focuses on the development of numerical code to deal with compressible two phase flow around three dimensional objects combined with cavitation model suggested by Weishyy et al. with k-e turbulent model. The cryogenic cavitation is carried out by considering the thermodynamic effect on physical properties of cryogenic fluids in physical point of view and implementing the temperature sensitivity in the energy equation of the government equations in numerical point of view, respectively. The formulation has been extensively validated for both liquid nitrogen and liquid hydrogen by simulating the experiments of Hord on hydrofoils. Then, simulations of cavitating turbopump inducers at their design flow rate are presented. Results over a broad range of Nss numbers extending from single-phase flow conditions through the critical head break down point are discussed. In particular, thermal depression effects arising from cavitation in cryogenic fluids are identified and their impact on the suction performance of the inducer quantified

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

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

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* 건국대학교 항공우주정보시스템공학과
** 건국대학교 항공우주정보시스템공학과
이창진, E-mail: cjlee@konkuk.ac.kr

modeling methods resort to the growth and collapse of cavitation in 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 simulates the cavitating turbopump inducers at their design flow rate over a broad range of Nss numbers to investigate the thermal depression effects. And the two-phase formulation is validated by simulating Hord's experiments on a cavitating hydrofoil.

2. Governing equations and Modeling

The conservative form of the Favre-averaged Navier-Stokes equations, the energy equation, the k-ε two-equation turbulence closure, and a transport equation for the liquid volume fraction:

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

$$\frac{\partial(\rho_m u_i)}{\partial t}+\frac{\partial(\rho_m u_i u_j)}{\partial x_j}=-\frac{\partial p}{\partial x_i}+\frac{\partial}{\partial x_j}[(\mu+\mu_t)(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}-\frac{2}{3}\frac{\partial u_k}{\partial x_k}\delta_{ij})]$$

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

$$\frac{\partial \alpha_l}{\partial t}+\frac{\partial(\alpha_l u_j)}{\partial x_j}=\dot{m}^{+}+\dot{m}^{-}$$

The original two-equation turbulence model with wall functions (Thakur et al. 2002)

$$\frac{\partial(\rho_m k)}{\partial t}+\frac{\partial(\rho_m u_j k)}{\partial x_j}=\mathrm{P}_t-\rho_m\varepsilon+\frac{\partial}{\partial x_j}[(\mu+\frac{\mu_t}{\sigma_k})\frac{\partial k}{\partial x_j}]$$

$$\frac{\partial(\rho_m \varepsilon)}{\partial t}+\frac{\partial(\rho_m u_j \varepsilon)}{\partial x_j}=C_{\varepsilon 1}\frac{\varepsilon}{k}\mathrm{P}_t$$
$$-C_{\varepsilon 2}\rho_m\frac{\varepsilon^2}{k}+\frac{\partial}{\partial x_j}[(\mu+\frac{\mu_t}{\sigma_\varepsilon})\frac{\partial \varepsilon}{\partial x_j}]$$

Turbulent viscosity and constant for turbulence model:

$$\mu_t=\frac{\rho_m C_\mu k^2}{\varepsilon}, C_\mu=0.09$$

	C_μ	C_1	C_2	σ_k	σ_ε	σ_h	σ_i
$k-\varepsilon$	0.09	1.4	1.92	1.0	1.3	0.9	0.9

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

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

where:

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

3. Validation for cavitation in cryogenic fluids

The two-phase formulation described above has been validated extensively by simulating experiments by Hord on a cavitating hydrofoil. The free-stream liquid nitrogen temperature of 83.06 K, a velocity of 23.9 m/s and the cavitation number of 1.7 is used in the simulation condition. The vapor volume fraction is qualitatively compared with a typical flow visualization of the flow in Fig. 2 and the overall shape and features of the cavity appear to be similar. In Fig. 3. The comparison of the pressure depression indicates excellent overall comparison with data. The leading edge pressure depression is 23.5

percent relative to the free stream vapor pressure. Also, the quantitative comparisons of pressure and temperature depression in the cavity are compared with experimental data. In general, excellent comparison is obtained for the leading edge temperature depression of approximately 2.5 K.

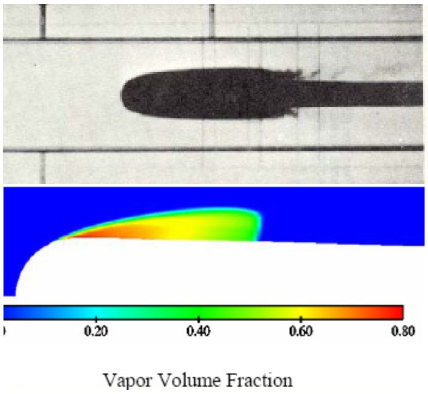


Fig. 2. Comparison of cavitation shape represented by the vapor volume fraction

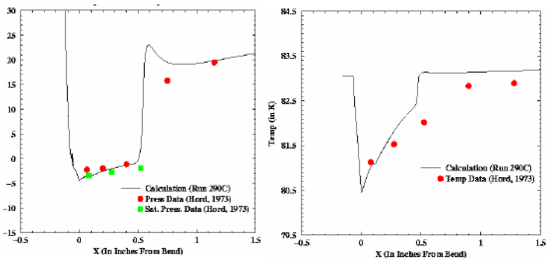


Fig. 3. Blade Suction Side Pressure at Various Nss Numbers in LOX Inducer

4. Cryogenic cavitation in LOX inducer

The LOX inducer was simulated over a range of Nss numbers ranging from 10000 to 30000 to model inducer performance from mildly cavitating conditions through head breakdown. Fig. 4 shows the vapor volume fraction iso-surface over four different Nss numbers. We note the formation of the primary cavitation front at the leading edge which grows preferentially near the shroud as the Nss number increases. However, interestingly we also evidence the formation of a second cavitation front at a bend in the blade where the blade goes to its full thickness. The temperature depression levels due to thermal effects of cavitation are shown in Fig. 5. Lower temperatures occur in regions where vaporization of liquid takes place. This figure indicates that the temperature depression is localized around the leading edge of the blade; the primary location of vapor formation, therefore, is at the leading edge while in the remainder of the vapor cloud condensation back to liquid is taking place.

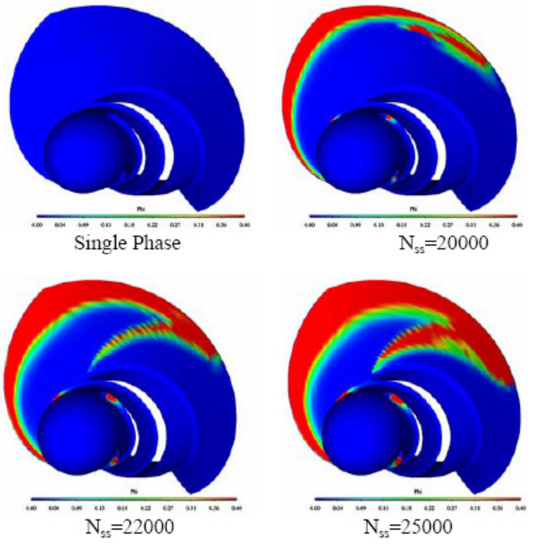
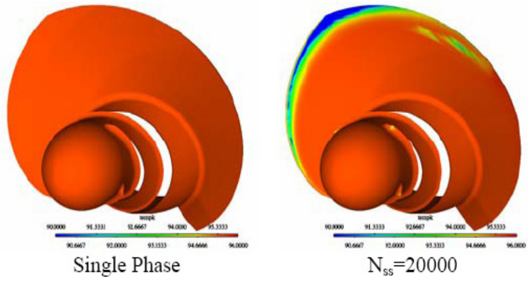
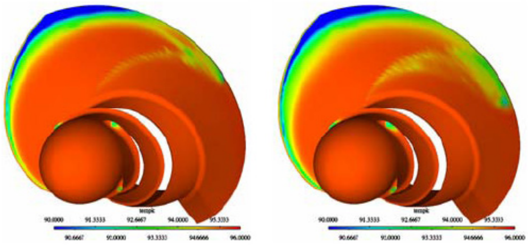

Single Phase
N_{ss}=20000
N_{ss}=22000
N_{ss}=25000

Fig. 4. Vapor Isosurface ($\Phi = 0.4$) Contours at Various Nss Numbers in LOX Inducer


Single Phase
N_{ss}=20000



N_{ss}=22000 N_{ss}=25000

Fig. 5. Blade Suction Side Temperature at Various Nss Numbers in LOX Inducer

5. Summary and Conclusion

This study focuses on the development of computational code to investigate the flow characteristics around 3D objects with transport equation. The prediction of cavitation formation in cryogenic fluid is carried out by implementing the energy equation along with modified vapor production and depletion terms. The two-phase formulation is validated by simulating Hord's experiments on a cavitating hydrofoil and shows a qualitatively good agreement. Then, the two-phase formulation is used to simulate a LOX inducer. The head breakdown appears to be in the range of 30000 Nss for the inducer. The increase in suction performance is attributed to effect of thermal depression in LOX. The temperature depression was observed primarily at the leading edge with the largest temperature drop being at the leading edge tip.

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