Flow Instability of Cryogenic Fluid in the Downstream of Orifices

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Abstract

Flow instability in the rocket turbo pump system can be caused by various reasons such as valve, orifice and venturi, etc. The inception of cavitation, especially in the propellant feeding system, is the primary cause of the mass flow and pressure oscillation due to cyclic formation and depletion of cavitation. Meanwhile, the main propellant in liquid rocket engine is the cryogenic one, which is very sensitive to temperature variation, and the variation of propellant properties caused by thermodynamic effect should be accounted for in the flow analysis. The present study focuses on the formation of cryogenic cavitations by adopting IDM model suggested by Shyy and coworkers. Also, the flow instability was investigated in the downstream of orifice by using a developed numerical code. Calculation results show that cryogenic cavitations can lead to flow instability resulting in mass flow fluctuations due to pressure oscillations. And the prediction of cavitations in cryogenic fluid is of vital importance in designing feeding system of LRE.

1. Introduction

The feeding system of Liquid Rocket Engine (LRE) consists of various types of flow control devices such as venturi, valves, orifices and connections of pipe. The flow in the system may experience unstable fluctuations due to the formation of cavitation, turbulent flow and flow separation. And the flow instability in turn results in the destructive damage to structures, even total collapses. And the cavitation in the feeding system is found to be one of the undesirable phenomena because it induces flow instability through the cascade of production and depletion of pressure bubbles in the flow and deteriorates system performances. Also the vaporized gas occupying a volume almost 104 times larger than liquid may reduce the effective flow area in the feeding system. And this blocks mass flow rate to pass through less than design value. So, the engine performance can be affected by the reduced amount of propellants in the feeding system. In this regard, the prediction of the formation of cavitation in the feeding system is of critical importance in determining engine performance and in assessing the flow instability in LRE.

Most of LRE systems rely on cryogenic propellants for generating thrust such as liquid oxygen or liquid hydrogen. The cavitation in cryogenic fluid differs from that found in the conventional liquids such as water. The main differences lie in the temperature sensitivity and dependence on the formation of cavitation. Since the phase change from fluid to vapor requires heats from surrounding fluids, the temperature inside cavitations surrounded by cryogenic fluid is lower than the fluid temperature. This is called “thermodynamic effect” in cryogenic cavitation. [2-3] Due to the thermodynamic effect, the vapor pressure in the cavitation becomes less than that without thermodynamic effect. This is the reason why cavitation size in cryogenic becomes small compared to the size formed without heat transfer. [2] This temperature sensitivity of cryogenic cavitation comes from the physical features that vapor pressure in cryogenic fluid is quite sensitive to small temperature variations. Thus, it is more difficult to predict the cavitation in cryogenic fluids than in conventional fluids because the prediction should take into account thermodynamic properties being sensitive to temperature variations. This requires including the energy equation in governing equations to accommodate the thermodynamic effect in the cavitation formation.

There are two well known methods for numerical simulation of production and depletion of cavitations. First one is the method using Rayleigh–Plesset equation, which describes the time evolution of cavitation nuclei growth when the fluid pressure becomes lower than vapor pressure. This modeling is advantageous in depicting the production and extinction of each bubble in detail. However, it may be burdensome in using computational resources and has convergence problems in dealing with the problem where vapors dominate in volume ratio. Thus, this modeling is not adequate in calculating shallow cavitation layers around turbo pump inducer.

Another method for calculating cavitations resorts to the phase transport equation. The production and extinction of cavitations can be simulated by condensation and evaporation of fluid. And this method is not good at predicting the production and depletion of every bubble in flow. The main advantages, however, are good convergence, simple implementation, and easy application to various types of cavitation problems. Thus, this modeling with phase transport equation was adopted in the present study. Phase transport equation suggested by Merkle[5] and Kunz[6] is the equation describing the phase boundary in terms of two different velocities in each phase. And this equation is capable of predicting the boundary very well if two phases are separated definitely.

In cryogenic fluid, the formation of cavitation deprives heats from the surrounding fluid due to thermodynamic effect and the phase boundary becomes a narrow region filled with frosty particles. Thus, the prediction of cavitations in cryogenic fluid mainly depends on how efficiently model can simulate and capture the frosty boundary. Shyy et al. solved the problem of frosty boundary in cryogenic cavitation by suggesting MUSHY IDM method. [2] This modeling takes boundary region into account with numerical modeling instead of definite boundary in the calculation. So, frosty boundary can be captured in the calculation with IDM method showing better agreement with experimental data than Merkle's model. [3]

The present study concerns about the cavitations in cryogenic fluid and its flow instability in the downstream of orifice. To do this end, the numerical calculation of the prediction of cavitation has done with a developed code implemented with Shyy's cavitation modeling and MUSHY IDM boundary treatment. A developed code was verified its validity and accuracy by the comparison of numerical results with experimental data. And, various orifice configurations are selected and calculation results are compared to investigate the effect of configuration on the generation of cavitations and flow instability in the downstream.

2. Governing Equations

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

$$\frac{\partial \rho_m}{\partial t}+\frac{\partial(\rho_m u_j)}{\partial x}=0 \qquad (1)$$

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

$$\frac{\partial}{\partial t}[\rho_m(h+f_v L)]+\frac{\partial}{\partial x_j}[\rho_m u_j(h+f_v L)]=\frac{\partial}{\partial x_j}[(\frac{\mu}{\mathrm{Pr}_L}+\frac{\mu_t}{\mathrm{Pr}_t})\frac{\partial h}{\partial x_j}](3)$$

$$\frac{\partial \alpha_l}{\partial t}+\frac{\partial(\alpha_l u_j)}{\partial x_j}=\dot{m}^-+\dot{m}^+ \qquad (4)$$

A mixture density is defined by the summation of liquid density and vapor density associated with volume fraction coefficient α_l. Here f_v is vapor mass fraction, *h* and ρ_m denotes enthalpy and mixture density respectively. Followings are definitions of these variables.

$$f_v=\frac{\rho_v(1-\alpha_l)}{\rho_m},\ h=C_pT\ ,$$

$$\rho_m=\rho_l\alpha_l+\rho_v(1-\alpha_l) \qquad (5)$$

Subscript l represents liquid, v is for vapor and t means terms for turbulent. Also, m is for mixture. And C_p and T is specific heat at constant pressure and temperature, respectively. A conventional k-ε turbulence model was used in the calculation.

Cavitation Modeling

Numerical calculation uses a cavitation modeling of MUSHY IDM (interfacial dynamics model) suggested by Shyy et al. to account for unique features of cryogenic fluid. As previously mentioned, this modeling assumes (that) the region inside cavitation is occupied by a mixture of liquid and vapor and the phase change occurs through a thin bi-phasic region. Thus, mass conservation and momentum transfer between liquid and a mixed region can be expressed as equations (6)

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

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

$$\frac{\rho_l}{\rho_-}=\frac{\rho_l}{\rho_v}+(1.0-\frac{\rho_l}{\rho_v})^{\exp^{-(1-\alpha_l)/\beta}}\ ,\ \frac{\rho_l}{\rho_+}=\frac{\rho_l}{\rho_m} \qquad (6)$$

Here, $U_{m,n}$ is a normal component of velocity vector in mixed region and $U_{I,n}$ is a normal component of velocity vector on the boundary surface. Reference [2] has details for the modeling. The numerical calculation requires energy equation to take thermodynamic effect into account in the formation of cavitation of cryogenic fluid. It is worth noting that flow works and viscous energy dissipation are neglected in source terms of energy equation for cryogenic fluid flow. And energy equation (3) can be further simplified by using relations of mixture density and mass ratio in (5). Final form of energy equation become as

$$\frac{\partial}{\partial t}[\rho_m(h)]+\frac{\partial}{\partial x_j}[\rho_m u_j(h)]=\frac{\partial}{\partial x_j}[(\frac{\mu}{\mathrm{Pr}_L}+\frac{\mu_t}{\mathrm{Pr}_t})\frac{\partial h}{\partial x_j}]+\rho_v L(\dot{m}^++\dot{m}^-) \ (7)$$

It is obvious that energy equation (7) includes terms of production and depletion of cavitations as sources of energy change as seen in phase transport equation. Thus, numerical solutions can effectively treat temperature drops in cavitation region due to evaporation cooling of cryogenic fluid.

Meanwhile, material properties in cryogenic fluid are quite sensitive to temperature variations more than to pressure variations. Table 2 summarizes the temperature dependency of each property such as latent heat, density, viscosity and vapor pressure of liquid hydrogen. Reference [8] shows more detailed information of material properties and dependency on temperature variations in various cryogenic fluids.

Latent Heat	$L = \frac{dp_v}{dT}(V_v - V_l)T$
Density(g/ml)	$\rho_L = A \cdot B^{-(1-T/T_c)^n}$
	A=0.43533, B=0.28772 n=0.29240, T_c=154.58
Viscosity(cp)	$\log_{10}\mu_L = A + B/T + C \cdot T + D \cdot T^2$
	A=-5.0957, B=1.7983E2 C=3.9779E-2, D=-1.4664E-4
Vapor Pressure(mmHg)	$\log_{10}P = A + B/T + C\log_{10}T + D \cdot T + E \cdot T^2$
	A=20.6695, B=-5.2697E2, C=-6.7062, D=1.2926E-2, E=-9.8832E-13

For numerical scheme, a conventional finite volume method implemented with SIMPLE algorithm was used. And the collocated grid system was also used for allocation of velocity components u, v and dependent variables. The calculation utilizes SIMPLE algorithm and convective terms can be differenced by upwind scheme in the grid system. Details of numerical schemes are found in ref. [7]

SoS Modeling

The formation of cavitation produces a mixture phase region where liquid and vapor coexists. And the speed of sound in this region is much lower than that in single phase regions as shown in figure 1. The mismatch of speed of sound comes from the density variations in mixture region. And the calculation with pressure based algorithms requires methods to compensate density variations due to pressure changes and the density changes in the mixture region. SOS modeling is the method to take an additional density changes in mixture region into account in the numerical calculation. [3] Equation [8] shows a relation used for density compensation with the implementation of SOS modeling.

$$\rho' = \boldsymbol{C}\left(\boldsymbol{1} - \alpha_l\right)\boldsymbol{P}' \tag{8}$$

Here C is an arbitrary constant. It is determined by experiences as an order of O(1) since larger C makes unstable convergence feature by changing the convergence trajectory during the calculation.

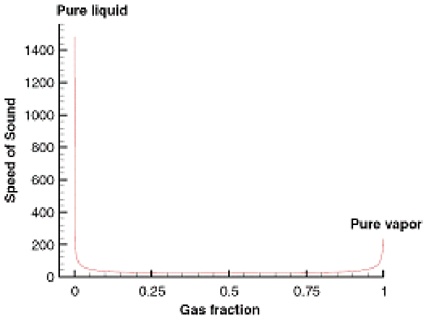

Fig 1. Speed of Sound in pure liquid, vapor, and mixture region [3]

3. Numerical calculations

Code validation

Numerical calculations were done to assess code validity and the accuracy by comparing numerical results with experimental data for orifice cavitations. [9] The configuration of orifice and numerical calculation conditions are the same as shown in reference [9]. Rectangular duct with 2mm in diameter, 15mm of inlet diameter is used in calculation. Grid points are 150x80 and liquid nitrogen (LN2) is a working fluid having initial pressure and temperature of 77.2K and 0.239MPa, respectively. And Reynolds number is 0.221E6.

Figure 2 shows the comparison of calculation results of evolution of cavitation with experimental data. [9] The inception of cavitation is found as a small bubble at the front edge of orifice. Bubble becomes larger stretching to downstream and finally pass through the orifice. Numerical results show a very good agreement qualitatively with experimental data capturing the evolution of cavitations in the orifice.

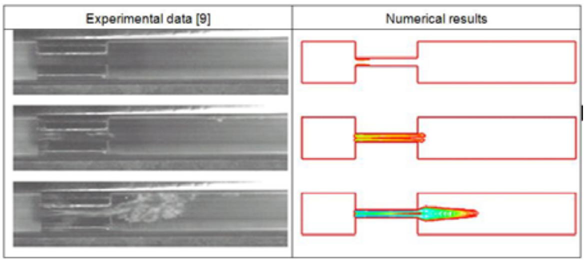

Fig 2. Validation checking of developed code by the comparison with experimental data.

Also, the comparison of pressure fluctuations with experimental measurements is made to investigate flow instability by the formation of cavitations in the downstream. The inception of cavitation starts at the edge of orifice due to velocity increase and pressure drop. As seen in the figure, cavitation elongates and collapses periodically in the downstream even though the production of cavitation continues at the orifice edge. The cyclic behavior of production, growth and collapse of cavitation dominate in the orifice and the downstream. This can trigger pressure fluctuations resulting in flow instability in the downstream.

Figure 3 compares calculated pressure fluctuations with experimentally measured data in the downstream. Results show a very good agreement.

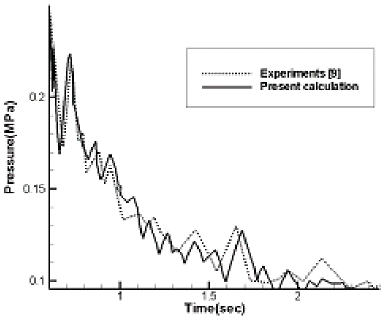

Fig 3. Comparison of pressure oscillations with measurements

Flow Instability of various Orifice Configurations

In numerical calculations, flow instability was investigated with various orifice configurations focusing on the pressure fluctuations in the downstream. Figure 4 shows orifices used in the calculations. Case A is the same orifice from reference [10] as a baseline one to compare numerical accuracy with experimental data. Case B and C were selected with modifications of orifice shape as shown in figure 4. Numerical calculations focus on the effect of orifice shape on the formation of cavitation and pressure oscillations leading to flow instability.

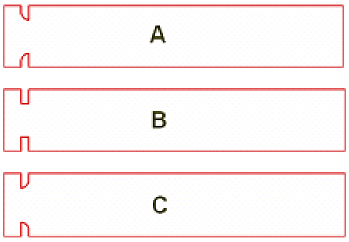

Fig 4. Configurations of selected orifice for calculation

The calculation conditions can be summarized as follows; liquid hydrogen of Inlet temperature, 21.7K, and vapor pressure of 4.86x104Pa at inlet. The mass flow rate is fixed as 130lbm/sec and inlet pressure is 106Pa. Orifice diameter is 0.1524m from reference [10]. Also, grid points are 246x80 in the calculation. It is useful to note that these numerical conditions are used to all calculations.

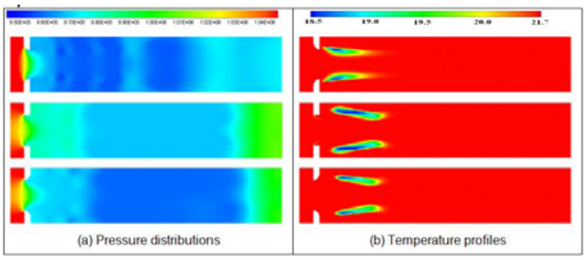

Fig 5. Pressure and Temperature profile in the downstream of selected orifices

Figure 5 shows pressure (a) and temperature (b) distribution in the downstream of each orifice. A cyclic behavior of production and depletion of cavitation at orifice is the source of the generation of pressure oscillations as observed in figure 5. Also, temperature drops are observed in the downstream of all orifices, which leads to the inception of cavitation. It is obvious that case B and C show a similar behavior of pressure oscillation and temperature drop while pressure distribution in case A shows a bit different oscillations with lower frequency. Since the inception of cavitation requires heats from surrounded fluid, the region with temperature drop matches with the cavitating regions. And temperature drop in case A occurs relatively in a small volume and length. In this calculation, the amount of temperature drops is revealed about 3K in cavitations.

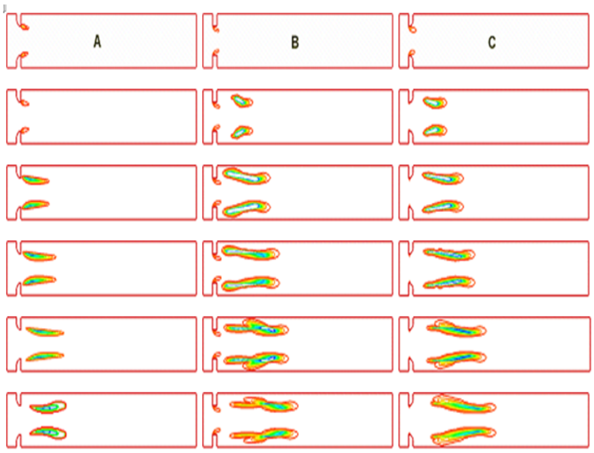

Fig 6. Time Evolution of cavitations in various orifices

Figure 6 shows the time evolutions of cavitation in each case. As expected, case B and C show similar patterns of evolution showing the breakup in the middle of cavitation with elongated shape. However, the pattern in case A differs from other cases in that flow passes through orifice A very smoothly and makes a relatively short cavitations without breakups. Thus, it can be summarized that the flow smoothly passing through the orifice is not easy to yield big cavitations.

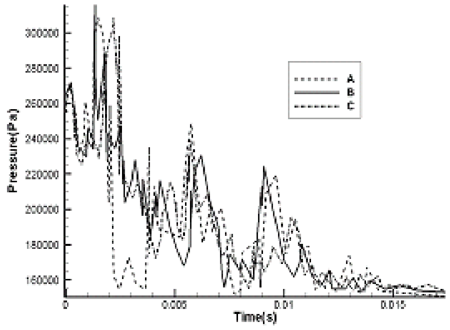

Fig 7. Trace of Pressure Fluctuations at 5 inch from orifice

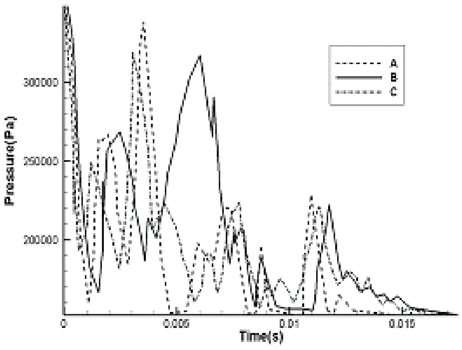

Fig 8. Traces of Pressure Fluctuations at 10 inch from orifice

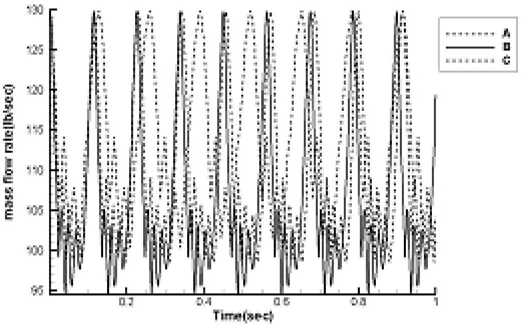

Fig 9. Traces of mass flow fluctuations of case A, B, and C at 5 inch from orifice

The cyclic behavior of production and extinction of cavitations in the flow can trigger pressure oscillations in the downstream of orifice leading to mass flow fluctuations. This is of critical importance in predicting the thrust performance and assessing combustion instability in LRE system because mass flow rate is directly related with the amount of thrust generated in the combustion chamber. Thus the primary concern of present study is to predict and estimate the effect of orifice configurations on pressure oscillations and mass flow fluctuations due to cavitations.

Figure 7 and 8 show numerical trajectories of pressure oscillation at locations of 5 and 10 inch from orifice, respectively. As seen in figure 6, the pressure oscillations in case A shows relatively small amplitude compared to other cases even though the overall behavior of amplitudes decreases monotonically in time. In figure 8, it is found that all cases show quite large amplitudes in oscillation compared to the amplitude in figure 7. This is due to the partial depletion of cavitations and pressure recovery near this location. This can explain why large pressure oscillations are observed in figure 8. The pressure oscillations can be transferred to structural vibrations or leads to total damage sometimes and triggers combustion instability.

Figure 9 is the oscillations of propellants mass flow measured at 5 inch from orifice. In this calculation, input mass flow rate is fixed as 130lbm/sec if cavitations are not formed in the flow. However, the generation of cavitations may reduce the amount of propellants passing through the orifice due to the blockage of effective flow passage because cavitating vapors of cryogenic fluid occupy almost 10^4 times larger volume in the flow than liquid fluid. This is the main reason why mass flow rate is reduced and fluctuated in the downstream. The calculations in figure 9 show that the maximum value of oscillations is about 30 to 35 lbm depending on the configuration of orifices. Since the present calculation did not account for viscous dissipation in energy equation, calculation results may show somewhat exaggerations in oscillation amplitude. Nonetheless the oscillation of mass flow rate in the downstream to combustion chamber is not desirable and should be avoided by all means. If happens, combustion instability or structural damages are inevitable during the operation. In this sense, the prediction of cavitations and assessment of flow instability of cryogenic fluid flow are of vital importance in the design of feeding system of LRE.

4. Conclusions

This paper focuses on the numerical simulation for cavitations in cryogenic fluid and investigates the effect of configuration of orifice on the flow instability due to cavitation formations in the downstream. Cavitation modeling for cryogenic fluid requires additional treatments by taking thermodynamic effect into account in energy equation suggested by Shyy et al. The accuracy and validity were checked by the comparison with experimental data. Also, numerical calculations were done to predict mass flow fluctuations and simulate flow instability in the downstream of orifice with several selected orifice configurations. Results show a very good agreement with experimental data. Also, results for several orifice configurations show that mass flow fluctuations are strongly dependent on the behavior of production and depletion of cavitations since cavitations may block the effective flow passage. Case B and C were found to produce more severe pressure oscillations than case A because the size and length of cavitation in case A are adequately small compared to other cases. And time evolution of cavitations in the downstream of orifice can provide a guideline to determine the good orifice shape generating less severe flow instability. Thus, it can be summarized that the prediction of cavitations in cryogenic fluid is of vital importance in estimating the performance of feeding system and LRE in the preliminary design stage.

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