Numerical Investigation of Cavitation-Induced Water-Hammer in Cryogenic Fluid Management System Using Finite Volume Method (FVM) Technique

Rajat Kalla, Arjun Garva , Parthasarathi Ghosh
Cryogenic Engineering Centre, Indian Institute of Technology Kharagpur

Poster ID : 545 (Thu-Po-3.4)
ICEC/ICMC
29th International Cryogenic Engineering Conference
International Cryogenic Materials Conference 2024
July 22-26, 2024, Geneva, Switzerland

Abstract

The study explores the water hammer's intricate dynamics with cavitation in cryogenic fluids through numerical modeling. It employs the finite volume method to delve into the complexities of this phenomenon, including the induced thermal effects that emerge during pressure wave propagation, especially in cryogenic fluid transients.

Introduction

- Water hammer occurs when fluid flow is abruptly stopped or redirected, the fluid's inertia generates a high-pressure wave that travels back through the system.
- During the water hammer when the negative side of the pressure wave reaches the vapor pressure, vapor bubbles start forming, and an increase in localized pressure during the pressure wave causes these bubbles to collapse. Due to the collapse, additional pressure is generated.

Literature review

- Joukowsky performs first analysis of the water hammer. From the fundamental equation the rise in pressure during water hammer is: $\Delta P = \rho a \Delta v$
- Pressure wave always moves with constant velocity for a single phase which depends upon the material physical properties, dimensions, and end conditions. For two-phase it also depends on mass fraction[1].
- In cryogenic fluid due to evaporative cooling during the formation of vapor bubbles, a significant change in vapor pressure is observed that reduces the tendency of cavitation, It is called thermal suppression effect[2].
- In the literature numerical modeling is performed using MOC, DVCM, DGCM models[3].

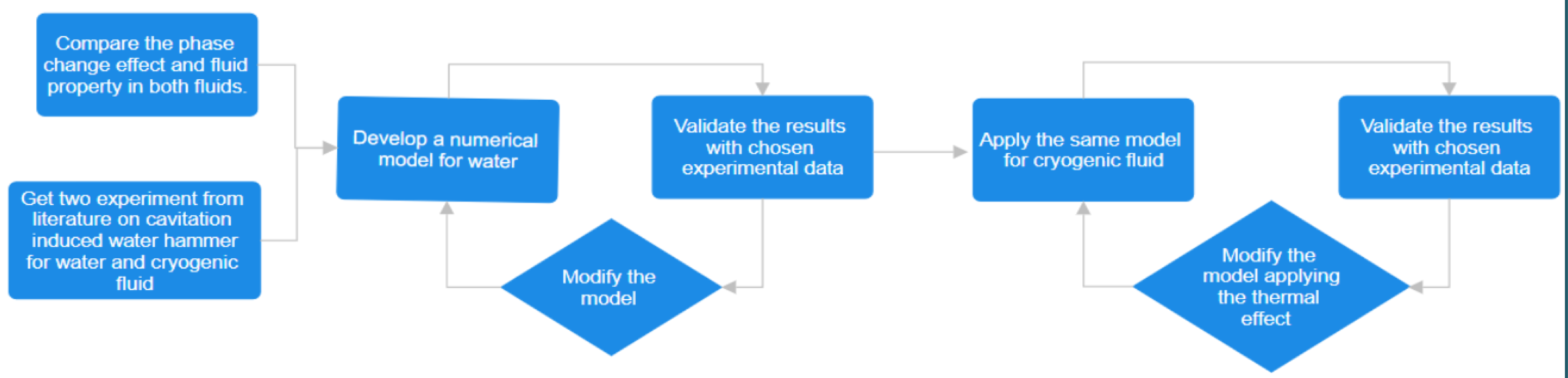
Lacunae

- Scarcity of experimental data for cavitation-induced water hammer for water and cryogenic fluid.
- Only 1D models have been developed for cryogenic fluids. Thermal effect is not included in it.

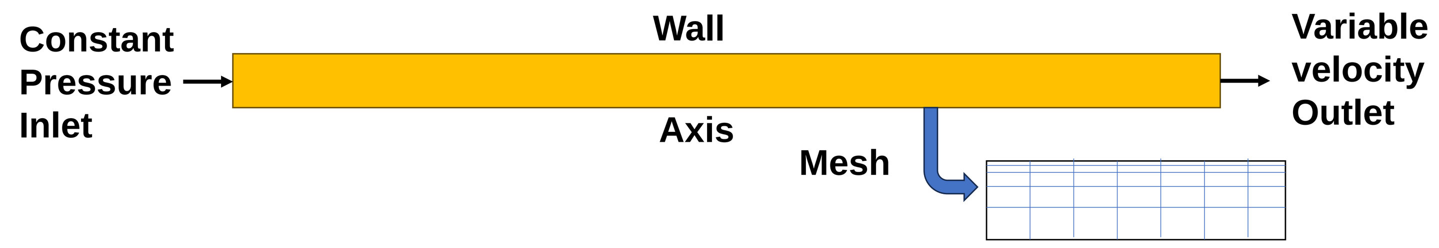
Objectives

- Develop the 2D axis-symmetrical numerical modeling using the finite volume method for water and cryogenic fluid.
- Validate the models using experimental data.

Methodology



Model Geometry and Boundary Conditions



Geometrical Parameter	Water	LN2
Length (m)	15.22	9.29
Inner dia. (mm)	20	19
Wall thickness (mm)	1	1.5
Young's modulus (GPa)	120	200
Poisson's Ratio	0.35	0.27

Boundary condition	Water	LN2
Pressure at inlet (bar)	4.50	13.94
Initial velocity at Outlet (m/s)	0.497	8.94
Wall roughness (m)	1.5×10^{-6}	2×10^{-6}
Modified Bulk modulus (GPa)	1.654	0.446
Vapor pressure (Pa)	2329.6	228860

Governing Equations

Continuity Equation: $\frac{\partial \rho}{\partial t} + \frac{\partial(\rho u_j)}{\partial x_j} = 0$

Momentum Equation: $\frac{\partial(\rho u_i)}{\partial t} + \frac{\partial(\rho u_i u_j)}{\partial x_j} = -\frac{\partial P}{\partial x_i} + \frac{\partial}{\partial x_j}\left(\mu\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)\right)$

Energy Equation: $\frac{\partial(\rho T)}{\partial t} + \frac{\partial(\rho u_i T)}{\partial x_j} = \frac{\partial}{\partial x_j}\left(\frac{k}{C_p}\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)\right)$

Equations for mixture model:

Mass avg. velocity $(v_m) = \sum_{k=1}^{n} \alpha_k \rho_k v_k$

Mass avg. density $(\rho_m) = \sum_{k=1}^{n} \alpha_k \rho_k$

Mass avg. viscosity $(\mu_m) = \sum_{k=1}^{n} \alpha_k \mu_k$

Schnerr Sauer model equation:

Mass transfer rate equation for vapor void fraction: $M_v = \frac{\partial}{\partial t}\alpha\rho_v + \frac{\partial}{\partial x_j}\alpha\rho_v \vec{u}_v$

Equations for bubble dynamics model:

Simplified Rayleigh-Plesset equation: $\frac{dR}{dt} = \sqrt{\frac{2}{3}\frac{P_R - P_\infty}{\rho_l}}$

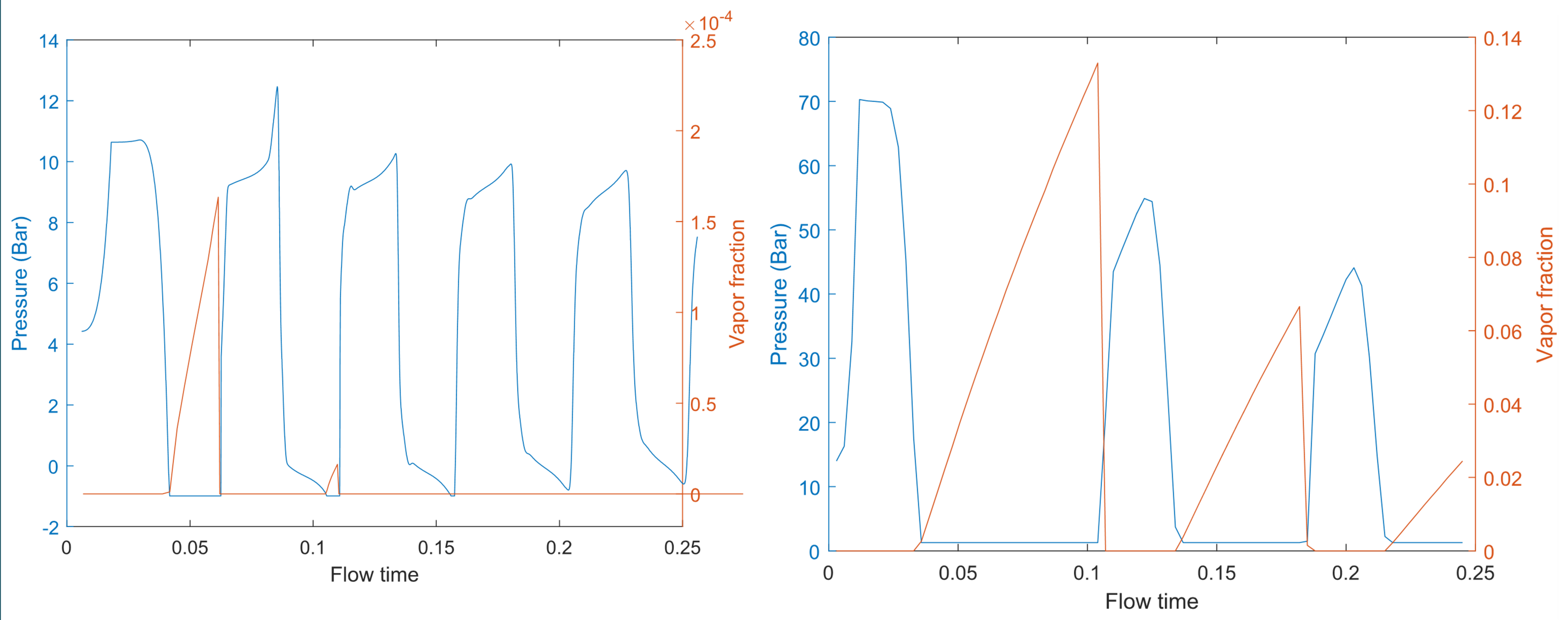
Modelling Parameters

Parameter	Value	Parameter	Value
Solver type	Pressure Based	Velocity formulation	Absolute
P-V coupling scheme	Coupled	Transient formulation	FOU

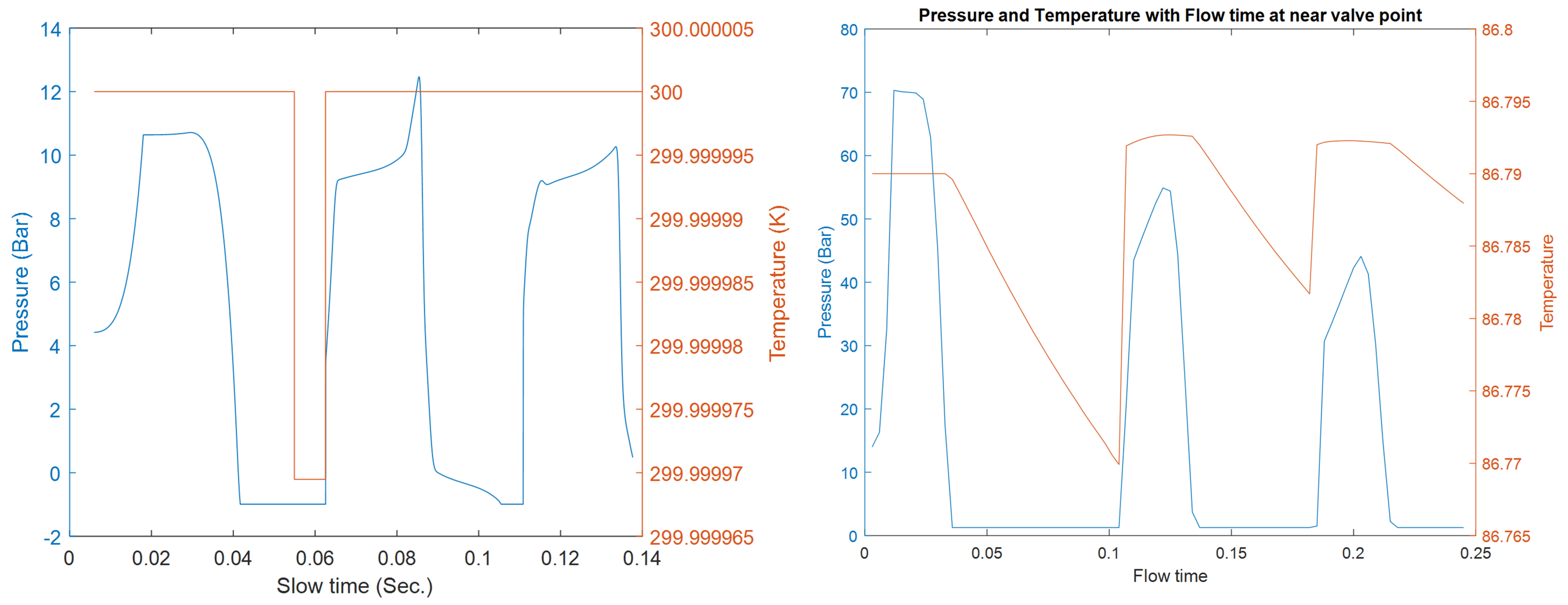
Spatial Discretization					
Gradient	LSEC	Pressure	PRESTO!	Volume Fraction	QUICK
Density, Momentum, Turbulent K.E., Specific dissipation rate, Energy					SOU

Results

Pressure & vapor fraction profile



Temperature Profile



Validation

Developed numerical models are validated using the experimental data from following literature.

- Numerical model for water : Soares et.al.[4]
- Numerical model for LN2: T. Traudt et.al.[1]

Conclusions

- 2D Axis-symmetric numerical modeling of cavitation induced waterhammer for cryogenic fluid is performed using finite volume method.
- Formation of vapor during two Phase and thermal effect associated with this is captured

References

[1] S. Klein, et al. *Exp, in Fluids*, vol. 64, no. 2, p. 30, 2023.
[2] C. C. Tseng et al. *47th AIAA Aero. Sci. Meeting*, 2009, p. 1215.
[3] T. U. Jang, et al. *Jour. of Harbin Inst. of Tech.* (New Series), vol. 23, no. 2, pp. 9–15, 2016.
[4] A. K. Soares, et al. *Proc. Engg*, vol. 119, pp. 235–242, 2015.