Thermodynamic scaling analysis of cavitating fluid transients in a cryogenic environment

Poster ID : 262
(Thu-Po-3.4)

Arjun Garva, Arpit Mishra, Parthasarathi Ghosh
Cryogenic Engineering Centre, Indian Institute of Technology Kharagpur, West Bengal, 721302, India,

ICEC/ICMC
29th International Cryogenic Engineering Conference
International Cryogenic Materials Conference 2024
July 22-26, 2024, Geneva, Switzerland

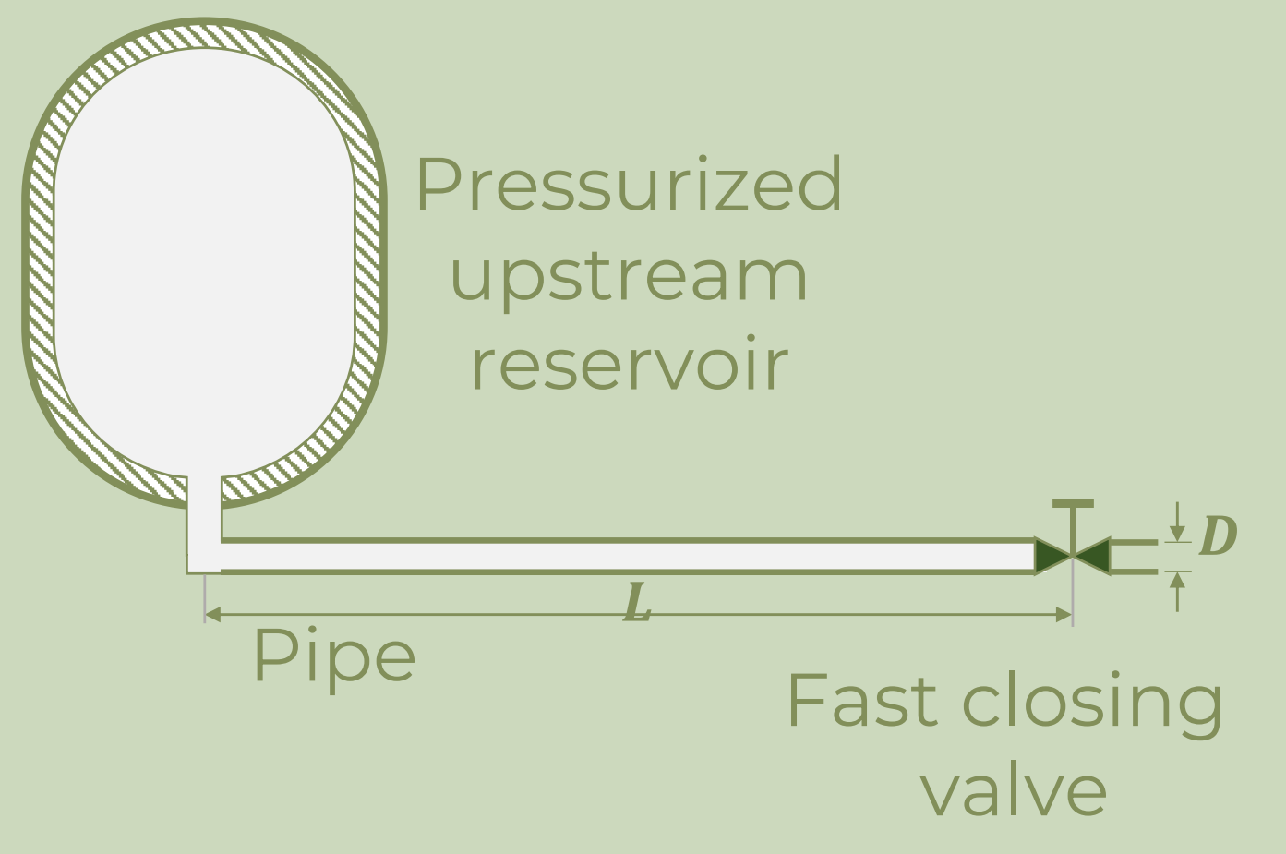
1. ABSTRACT

This article presents a scaling analysis of the cavitation-induced fluid transient within a fluid network consisting of a fast-closing valve at the downstream end. The study employs cryogenic fluid and hot water at a temperature corresponding to the same thermodynamic parameter, using various scaling models. A comprehensive comparative assessment of the cavitation-induced fluid transient behaviour in cryogenic fluid and hot water is conducted to ascertain the similarity in flow conditions. The similarity approach based on this thermodynamic scaling will be used for a proposed scaled-down experimental setup to study the cryogenic fluid transients at IIT Kharagpur.

2. INTRODUCTION

- Fluid transients are generated due to rapid flow acceleration or deceleration in a fluid flow network.
- The oscillatory behaviour of fluid transients can lead to the formation and subsequent collapse of vapour cavities.
- Complexity is heightened in cryogenic fluids due to significant variations in thermophysical properties and the presence of a thermal delay effect resulting in cavitation suppression.
- Dimensionless thermodynamic scaling is a valuable tool for the substitution of cryogenic fluid with a preferred alternative maintaining comparable fluid dynamics and thermodynamic characteristics.

3. METHODOLOGY



Schematic of a system consisting of reservoir, pipe and valve

Method of Characteristics

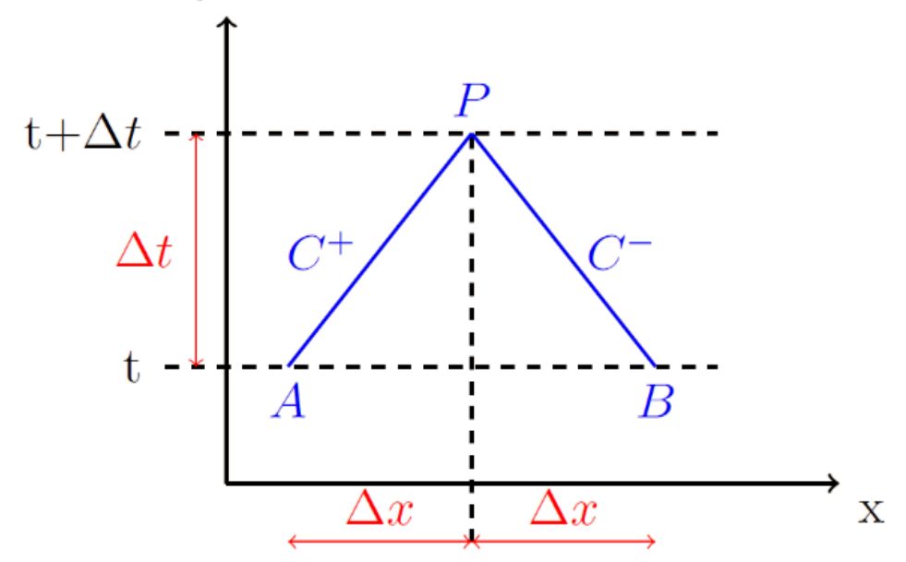
Mass conservation $\frac{\partial H}{\partial t}+\frac{a^2}{gA}\frac{\partial Q}{\partial x}=0$

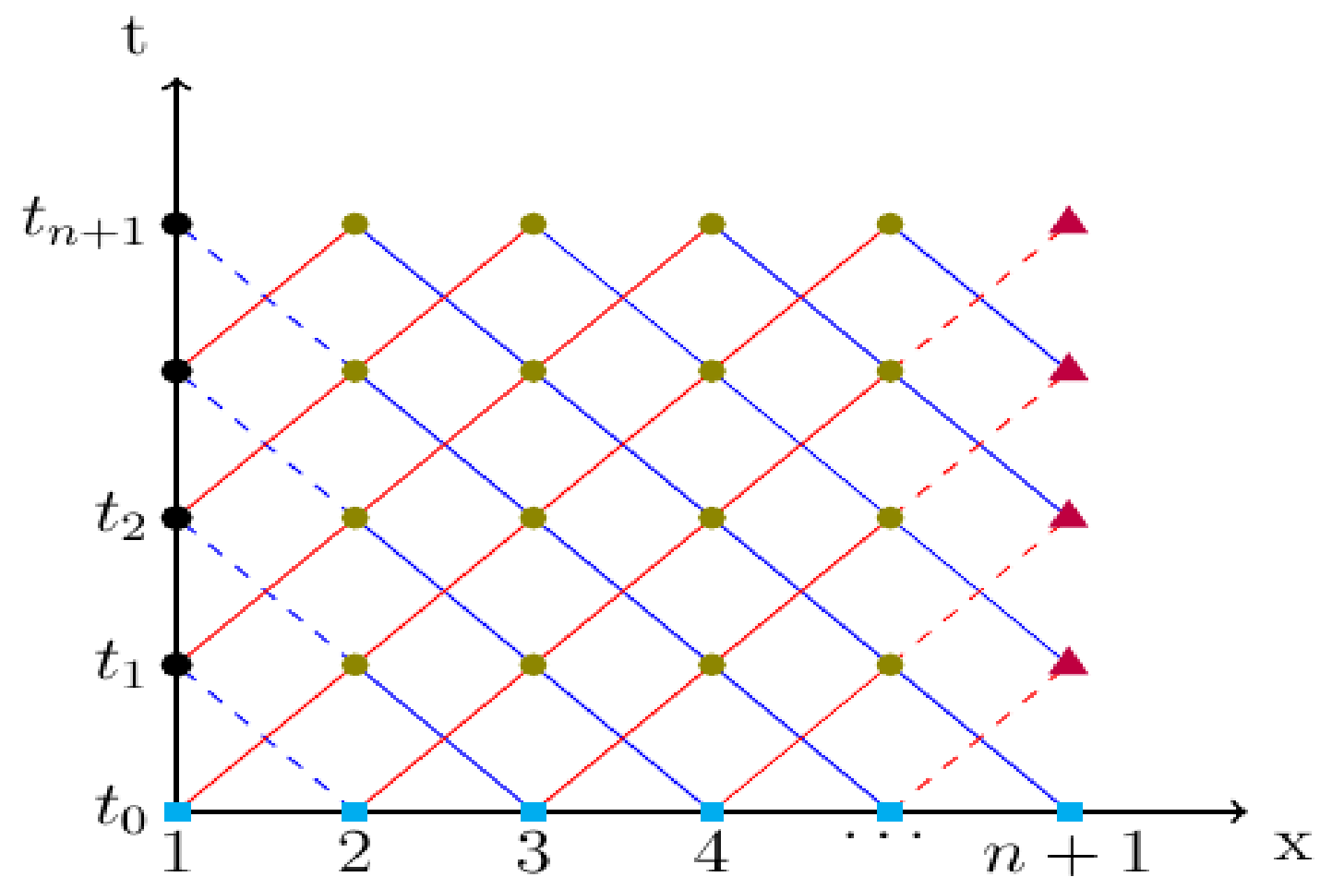
$$a=\sqrt{\frac{K/\rho}{1+c(K\,D/e\,E)}}$$

Momentum conservation $\frac{\partial H}{\partial x}+\frac{1}{gA}\frac{\partial Q}{\partial t}+\frac{4\tau_t}{\rho g D}=0$

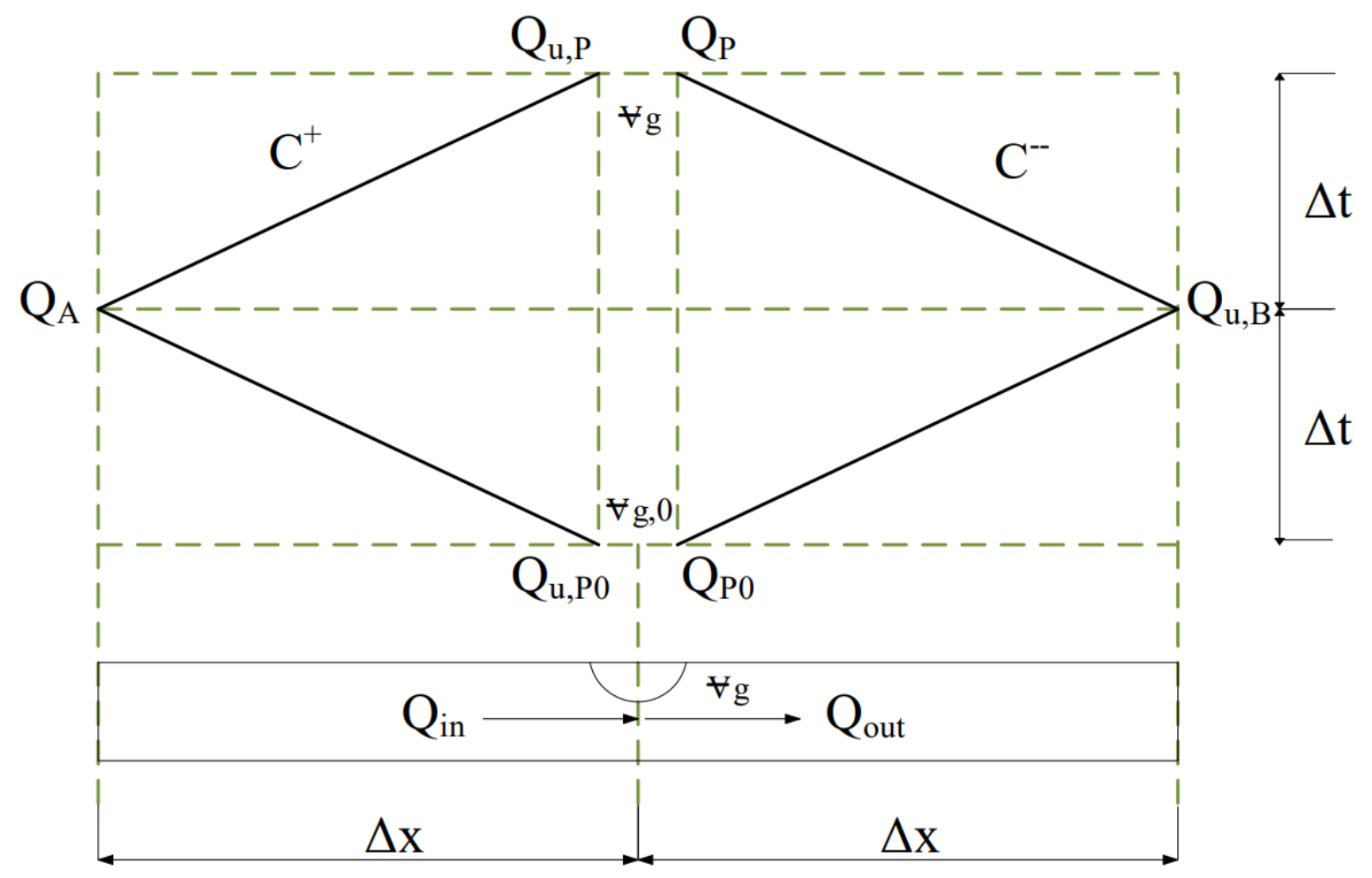
$$\tau_t=\frac{f|Q|Q\rho}{8A^2}+\tau_u \qquad \tau_u=\frac{k\rho D}{4}\left(\frac{\partial u}{\partial t}-a.sign(u)\frac{\partial u}{\partial x}\right)$$

$$\frac{dQ}{dt}\pm\frac{gA}{a}\frac{dH}{dt}+\frac{4\tau_t A}{\rho D}\mp\frac{g}{a}\sin(\theta)Q=0$$





Discrete Vapor Cavity Model



$$\frac{d\forall_g}{dt}=Q_{out}-Q_{in}$$

$$\forall_{g,P}=\forall_{g,P0}+2\Delta t(\psi(Q_P-Q_{u,P})+(1\text{-}\psi)(Q_{P0}-Q_{u,P0}))$$

Scaling analysis of cavitation

Stahl and Stapanhoff factor	$B=\frac{\rho_l C_{pl}\Delta T}{\rho_v h_{fg}}$
Brennan Parameter	$\Sigma=\frac{\rho_g^2\,h_{fg}^2}{\rho_l^2 C_{pl} T\sqrt{\alpha}}$
Ehrlich and Murdock	$DB=\frac{\rho_l^2 C_{pl} T_0\sqrt{\alpha}\,r_{tip}\Omega^{3/2}}{\rho_{go}^2 h_{fg}^2}$

Modified Ehrlich and Murdock

$$DB=\frac{\rho_l^2 C_{pl} T_0\sqrt{\alpha}\,u^{3/2}}{\rho_{go}^2 h_{fg}^2\sqrt{r}}$$

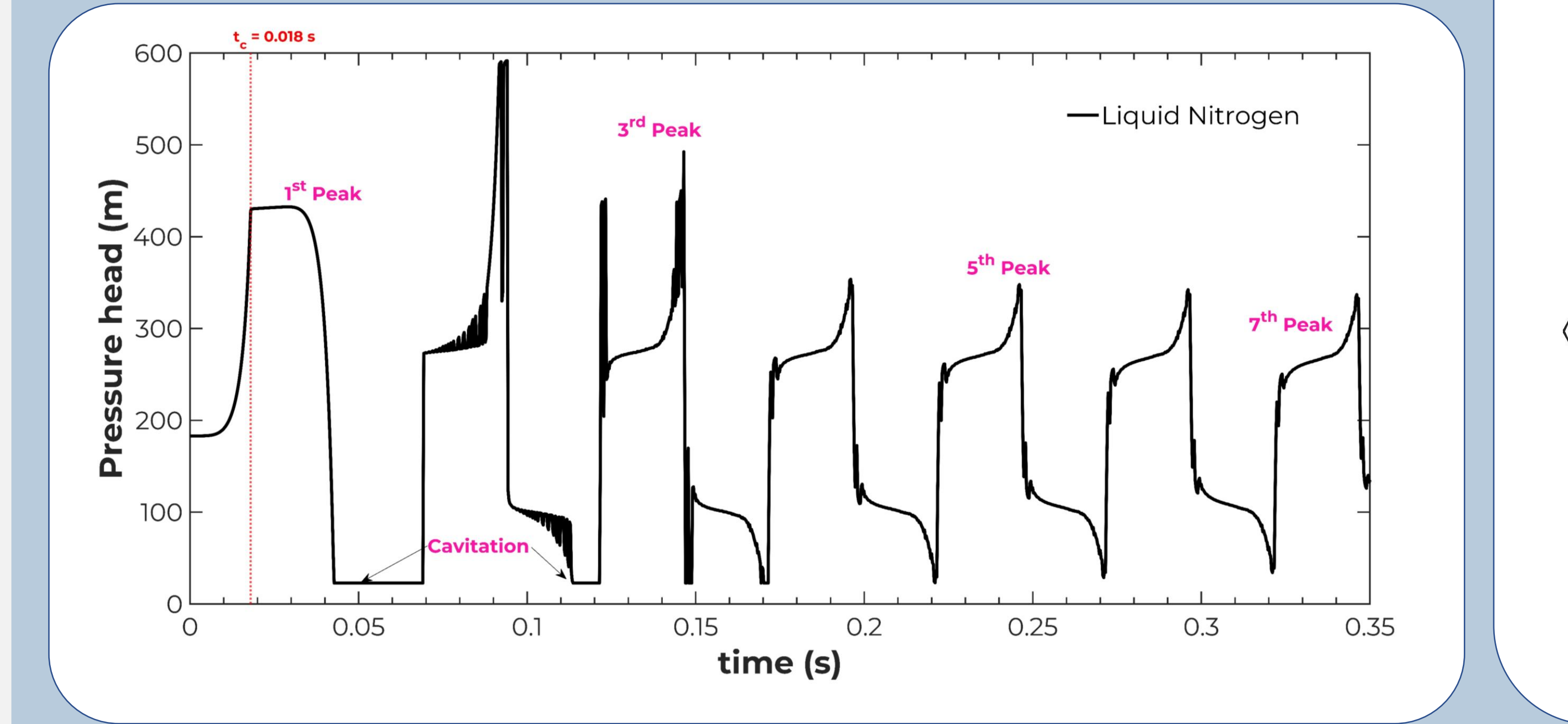
4. RESULTS

Parameters	H2O	LN2
Pipe length L (m)	9.29	
Pipe diameter D (m)	0.019	
Reservoir pressure (kPa)	1394	
Valve closure time (s)	0.018	
Velocity u (m/s)	1.375	3.25
Young's Modulus E (GPa)	190	
Pipe roughness Є(m)	2 x 10⁻⁶	
Temperature (K)	293- 423	87

Modified Ehrlich and Murdock

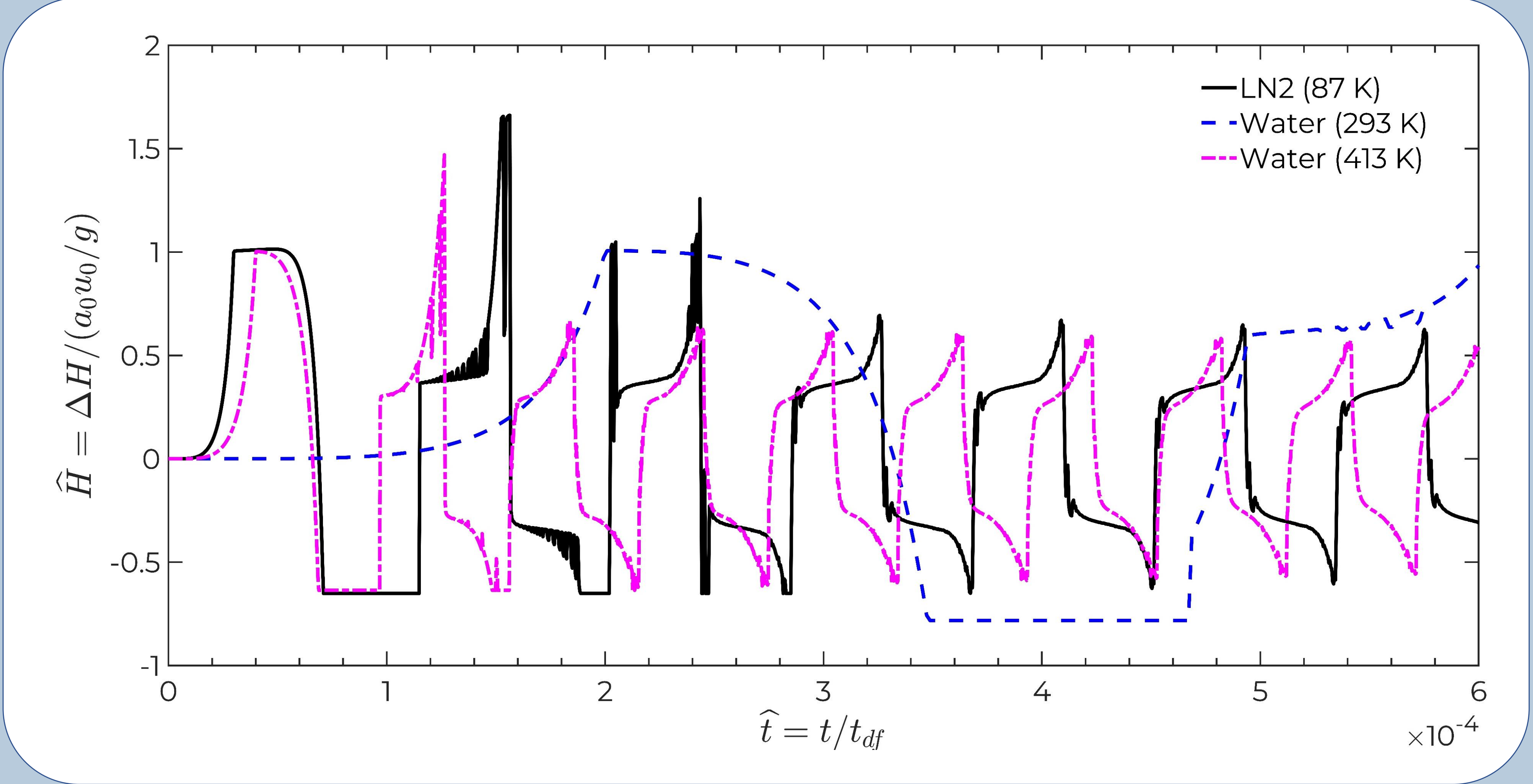
$$DB=\frac{\rho_l^2 C_{pl} T_0\sqrt{\alpha}\,u^{3/2}}{\rho_{go}^2 h_{fg}^2\sqrt{r}}$$

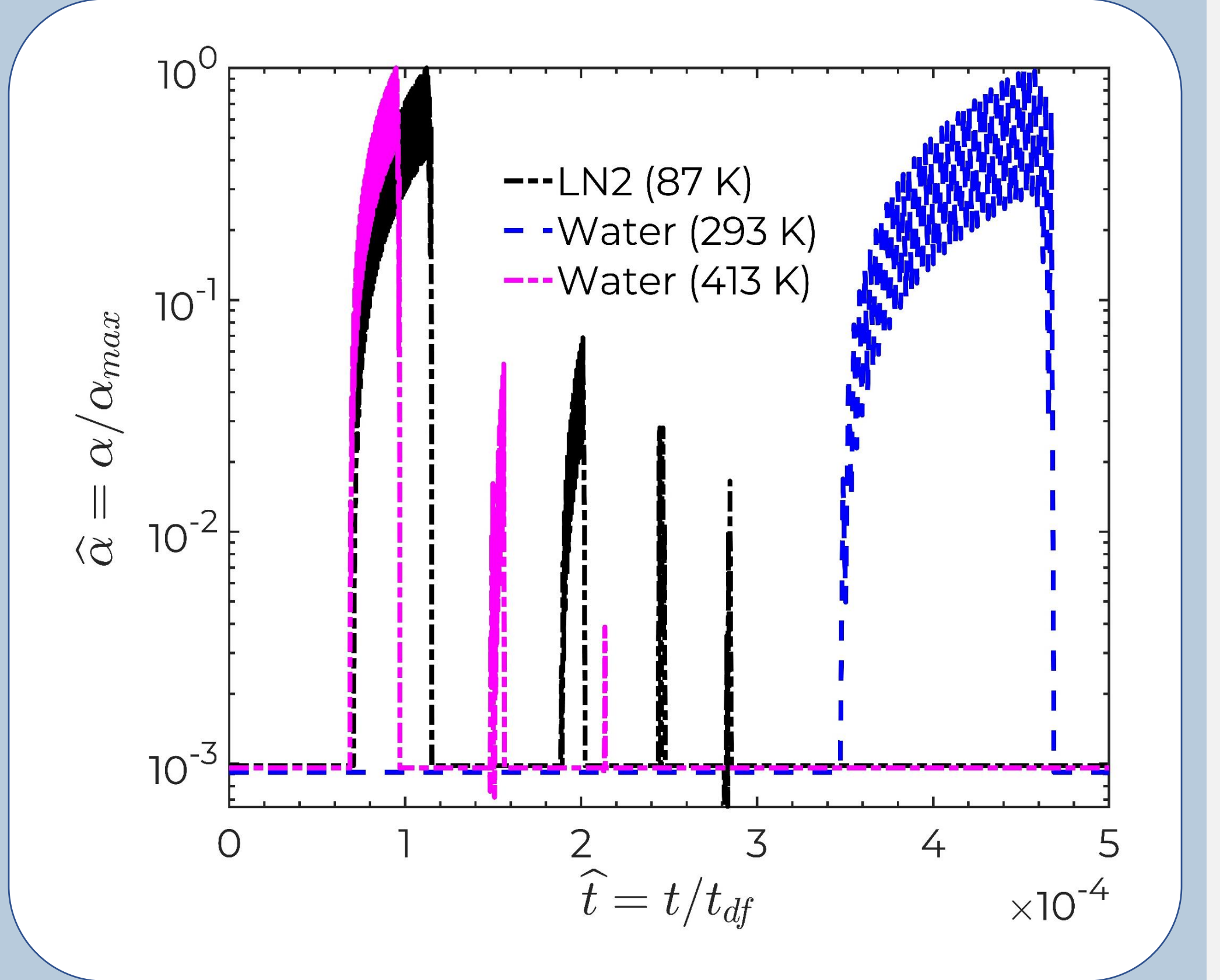
$DB_{H2O|\,293\,K}=4.24$
$DB_{H2O|\,313\,K}=0.55$
$DB_{H2O|\,333\,K}=0.093$
$DB_{H2O|\,353\,K}=0.021$
$DB_{H2O|\,373\,K}=0.005$
$DB_{H2O|\,393\,K}=0.001$



Pressure head oscillations obtained using the Method of Characteristics with DVCM

$$DB_{LN2|\,87\,K}=3.97\times10^{-4}=DB_{H2O|\,413\,K}$$





Comparison of pressure head oscillations and void fraction of liquid nitrogen at 87 K with water at room temperature (293 K) and elevated temperature (413 K)

5. CONCLUSION

- The study demonstrates the use of thermodynamic scaling for analyzing cavitation and fluid transients in cryogenic fluids, utilizing **hot water as an experimental surrogate.**
- **Method of Characteristics and discrete vapour cavity method** was formulated for accurate numerical simulations of fluid transients with cavitation.
- Scaling with **Modified Ehrlich and Murdock DB parameter** shows a good similarity in cavitation behaviour between **liquid nitrogen at 87 K and water at an elevated temperature of 413 K.**
- Phase difference & prolonged cavity were observed in room temperature water compared to liquid nitrogen.
- There is a need for further refinement of this scaling method to enhance precision.
- The improved scaling will help in designing a **thermodynamically scaled experimental setup.**

REFERENCES

1. Garva et al., 2022, IOP Conf. Ser.: Mat. Sci. & Engg (Vol. 1240, p. 012008).
2.Klein et al., 2023, Experiments in Fluids, 64(2), 30.
3.Brennen, E. Hydrodynamics of pumps. Cambridge University Press, 2011.
4.Ehrlich & Murdock, 2015, Jour. of Fluids Engg 137.4: 041103.

arjunggarva@gmail.com