CAV2021
11th International Symposium on Cavitation
May 10-13, 2021, Daejon, Korea

Hydraulic Performance of Cryogenic Cavitating Orifices: can it be predicted after isothermal testing?

Claudia Esposito [1,3]*, Laura Peveroni[1], Jean-Baptiste Gouriet[1], Johan Steelant [2] and Maria Rosaria Vetrano [3]

[1] von Karman Institute for Fluid Dynamics,Waterloosesteenweg 72 , Sint-Genesius-Rode, Belgium

[2] Aerothermodynamics and Propulsion Analysis Section, ESTEC-ESA, Keplerlaan 1, 2200AG Noordwijk, The Netherlands

[2] KU Leuven, Celestijnenlaan 300A – postbus 2421, B-3001 Heverlee, Belgium

Abstract: Cryogenic cavitation can be easily encountered in the liquid propulsion systems at the very initial phase of the launch due to the propellant passing through orifices and valves. This leads to flow instability, performance degradation, and even damages to the structures. Hence, the design of the propulsions systems cannot overlook cavitation phenomena. Despite the relevance of the topic, its accurate prediction is still hampered by the difficulty in modeling the high non-equilibrium phenomena involved. From an engineering point of view, the main interest is to design such restrictions present in propellant systems and, hence, to predict the maximum flow rate they can reach. This work questions the possibility to design orifices for cryogenic applications on the basis of purely isothermal testing. To do that, cavitation experiments were performed with both water and liquid nitrogen by considering two orifices hydraulically similar. This implies a geometric similitude in terms of the orifice characteristic ratio (β) and its dimensionless thickness (th). The results show that this hydraulic similitude is not exhaustive to correctly predict the orifice behavior in cryogenic flow. A key role is the level of liquid subcooling (ΔT_{sub}) upstream of the orifice.

Keywords: cryogenics, liquid nitrogen, subcooling, orifice, geometric similitude

1. Introduction

Cryogenic cavitation is a well-known issue during the activation of the propulsion systems in liquid rocket engines. However, the thermal properties of cryogenic fluids hinder an adequate prediction of cavitation occurrence and intensity. Consequently, the design of orifices or valves constituting the feeding system becomes more difficult. As extensively reported in the literature [1,2], the fluid properties profoundly change the nature of cavitation with respect to isothermal fluids, like water. Nevertheless, from an engineering point of view, is it possible to design a hydraulic system for cryogenic applications based on tests performed in isothermal conditions? To answer this question, we study cavitation through an orifice configuration and, specifically, we evaluate its hydraulic performance, i.e. the flow rate variation as a function of the applied differential pressure. Two main formulations exist in the literature to describe the hydraulic performance of an orifice in an isothermal environment, and they read:

$$\textbf{[a]} \quad Kv = \frac{Q_{v,w}}{\sqrt{\Delta P}} = Q_v \frac{\sqrt{\rho/\rho_w}}{\sqrt{\Delta P}} \quad \left[\frac{m^3/h}{\sqrt{bar}}\right] \qquad \textbf{[b]} \quad Q_{v,chok} = F_L Kv \sqrt{\frac{P_{up}-P_{min}}{\rho/\rho_w}} \tag{1}$$

In fully liquid conditions (Eq.1[a]), the volumetric flow rate (Q_v) linearly grows with the square root of the pressure drop through the orifice ($\Delta P = P_{up} - P_{dw}$). This proportionality is commonly expressed by the flow coefficient Kv, which physically represents the volumetric flow of water passing through a restriction with a pressure drop of 1 bar. Even if the use of Kv is quite spread and very convenient to quantify the flow capacity of an orifice, it is not dimensionless. Besides, it depends on the orifice area. Therefore, as suggested by Tullis [3], to have meaningful comparisons between similar geometries of different sizes, we

* Corresponding Author: Claudia Esposito, espoclau4@gmail.com

will use a new coefficient which, in this work, we will call SF, obtained by dividing the Kv by the orifice area (Ao), i.e. $SF = Kv/A_o$ [m/h/ $\sqrt{\text{bar}}$]. In Eqs. 1.[a][b], ρ is the density, and the subscript w refers to water. The ratio ρ/ρ_w is the specific gravity of the liquid, introduced to extend the use of these correlations to liquids different from water. Regarding the choked flow (Eq.1[b]), this corresponds to that regime where the pressure downstream of the orifice does not recover. For isothermal fluids, this minimum pressure (P_{min}) is well approximated by the saturated vapor pressure at the working temperature. Finally, the choked flow rate also depends on F_L [4], which is the ratio between the overall pressure drop through an orifice ($P_{up} - P_{dw}$) and the drop between the static pressure at the inlet (P_{up}) and the one at the *vena contracta* (P_{vc}), i.e. $F_L = \sqrt{(P_{up} - P_{dw})/P_{up} - P_{vc}}$.
By looking at Eqs.1[a][b], it can be concluded that, if two orifices have the same SF and F_L, they will show the same hydraulic performance in both linear and choked conditions. Such a hydraulic similitude depends on a geometrical one since SF and F_L are functions of the orifice diameter ratio ($\beta = d/D$) and the dimensionless thickness ($th = s/d$) [3,4,5]. The geometrical dimensions involved in their definitions are shown in Figure 1. A previous numerical study conducted at VKI observed such a similitude by means of numerical simulations [6].

2. Materials and Methods

To understand if such geometric similitude is exhaustive to predict cavitation through an orifice for any working fluid, experiments were carried out both with two different but geometrical similar orifices with water (isothermal case) and LN_2 (thermosensitive case). Of course, more constraints on the specific parameters to choose come from the tests in cryogenic, especially from the need to chill down the line before testing. In practice, two thick cylindrical orifices with $th = 1.19$ and $\beta = 0.17$ were selected, which, applying the theoretical model proposed by Chisholm [7,8], give a $SF_{th} = 4.4 \cdot 10^4$ [m/h/ $\sqrt{\text{bar}}$].

Figure 1 presents the main elements of the isothermal and thermosensitive test sections used in this work. Both are mounted upwards with the cylindrical orifice between two transparent modules to allow flow visualizations. These are square blocks with a traversing hole having the same diameter as the test section, i.e. (a) D=15 mm and (b) D = 40 mm. Concerning the measurements, an electromagnetic and a Coriolis flowmeter provide the flow rate for the water and the cryogenic setup, respectively. Flush-mounted pressure sensors measure the pressure upstream and downstream of the orifice. In the cryogenic setup, the temperatures are measured sufficiently close to the pressure ports via cryogenic silicon diodes. Simultaneous pressure and temperature measurements allow defining the temperature drop through the orifice, and the subcooling degree, i.e. the proximity to the saturation curve of the fluid at the inlet, ($\Delta T_{sub} = (T_{sat}(P_{up}) - T_{up})/T_{cri}$). T_{cri} is the LN_2 critical temperature, equal to 126.19 K. On the contrary, for the experiments with water, only two thermocouples are installed along the loop to monitor the working temperature. A detailed description of the isothermal and thermosensitive cavitation facility can be found in [9] and [10], respectively.

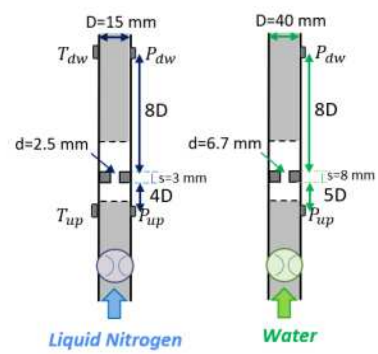


Figure 1. Sketch of the two test sections with their characteristic dimensions.

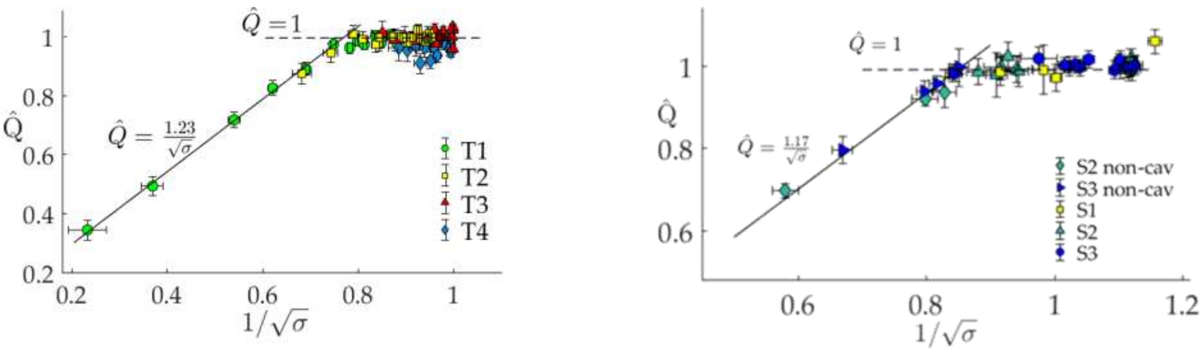
3. Results

Figure 2 shows the dimensionless characteristic curves for the two tested orifices. The volumetric flow rate is scaled by the choked flow rate ($\hat{Q} = Q_v/Q_{chok}$), while σ is the cavitation number ($\sigma = (P_{up} - P_{min})/(P_{up} - P_{dw})$) quantifying the strength of cavitation. Different symbols in the isothermal curve

* Corresponding Author: Claudia Esposito, espoclau4@gmail.com

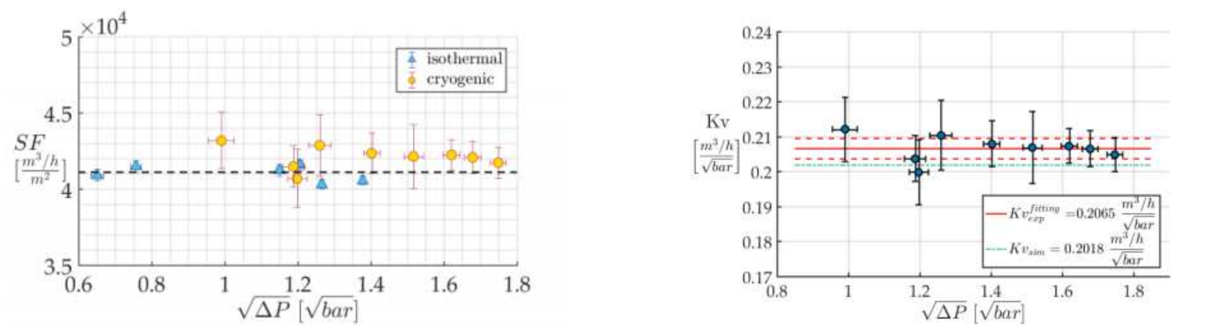
(Fig.2.a) refer to four sets of tests, each produced fixing the downstream pressure (P_{dw}) and gradually increasing the upstream one (P_{up}). On the contrary, different symbols in the cryogenic curve (Fig.2.b) refer to the subcooling degree. Specifically, S1 corresponds to $\Delta T < 0.020$, S2 groups the data with $0.020 < \Delta T < 0.050$ and, finally, S3 includes the cases with $\Delta T > 0.050$.

Cavitation starts with the intermittent appearance of tiny bubbles downstream of the orifice at $\sigma = 1.34$ (isothermal case) and $\sigma = 1.2$ (cryogenic case). By increasing $1/\sqrt{\sigma}$, bubbles grow and coalesce, forming clouds that periodically shed downstream of the orifice. The flashing regime presents the highest vapor production and, in the cryogenic environment, it goes together with significant temperature drops through the orifice.



(a) **(b)**

Figure 2. Dimensionless hydraulic curve for the two similar orifices with water (**a**) and LN_2 (**b**).



(a) **(b)**

Figure 3. (**a**) Experimental SF calculated from the fitted *Kv*-water (dashed line) compared to the SF for each data point in fully liquid from the isothermal case (triangles) and from the cryogenic case (circles). (**b**) Comparison between the experimental and the theoretical *Kv* for the cryogenic case.

Once the hydraulic performance has been computed, the procedure to seek whether the hydraulic similitude applies to any tested fluid consists of four steps. First, the values of Kv and F_L are computed from the isothermal testing. The *Kv-water* is derived by fitting the data points for water in fully liquid conditions, and it resulted equal to $Kv_w = 1.480 \pm 0.021$ *[m³/h/* $\sqrt{bar}$*]*. $F_{L-water}$, instead, is computed from the measured choked volumetric flow rate (Eq.1[b]), leading, hence, to $F_{L-water} = 0.82$. Second, $SF = 4.11 \cdot 10^4$ [m/h/ $\sqrt{\text{bar}}$] is derived from *Kv-water* and the A_o of the cryogenic setup. Fig.3.a shows the SF calculated from *Kv-water* as a dashed line together with the experimental SF for each fully liquid point from the isothermal case (triangles) and the cryogenic case (circles). The calculated SF deviates about 6.6% from the theoretical SF_{th} [3]. Third, the equivalent Kv for LN_2 is derived, i.e. $Kv_{sim} = 0.202$ [m³/h/ $\sqrt{\text{bar}}$]. Fig. 3.b compares the Kv_{sim} with the Kv of each fully liquid point from the cryogenic case and with the fitted $Kv_{fitting,exp}$, which is equal to 0.206 ± 0.003 [m³/h/$\sqrt{\text{bar}}$].

* Corresponding Author: Claudia Esposito, espoclau4@gmail.com

Finally, $Q_{v,chok}$ is calculated from Eq.1[b] using the Kv_{sim} and the isothermal F_L. Firstly, the isothermal assumption $P_{min} = P_{sat}(T_{up})$ is considered (Fig.4.a). The comparison with the experimental choked volumetric flow shows that the $S3$ cases, high P_{up} and $\Delta T_{sub} > 0.050$, are the only ones where the similitude applies with a maximum error of 8.5%. This highest error corresponds to the data with the larger distance between the two-phase flow downstream of the orifice and the saturation conditions at T_{up}. Then, P_{min} is corrected according to the model proposed in [10], which accounts for the thermodynamic state of the fluid both at the inlet and outlet of the orifice. This correction, shown in Fig.4.b, guarantees a good prediction of the choked flow rate for all the experimental points, achieving an overall error below 1.6%.

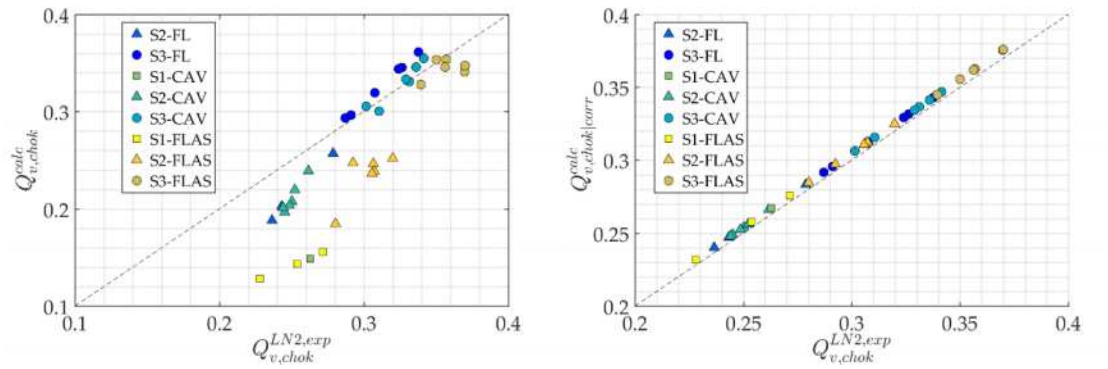


Figure 4. Comparison of the cryogenic experimental Qv at chocking with respect to the one computed from the hydraulic similitude: (**a**) $P_{min} = P_{sat}(T_{up})$; (**b**) $P_{min} = P_{sat}(T_{up}) \cdot f(\Delta T_{sub})$.

4. Conclusions

From the presented results, we can conclude that the hydraulic similitude applies only for the $S3$ test cases, i.e. high P_{up} and ΔT_{sub}. As the orifice inlet conditions get closer to the saturation curve, the thermodynamic state of the liquid must be necessarily considered and the hydraulic similitude corrected.

Acknowledgments: This work was supported by the ESA's Networking/Partnering Initiative (NPI) grant 4000117725/16/NL/MH/GM. The cryogenic experiments were performed in the framework of the ESA's General Support Technology Programme (GSTP) contract 4000118113/NL/KML coordinated by Safran AeroBoosters.

References

1. J. Hord, et al. Cavitation in liquid cryogens. 1: Venturi. *NASA CR-2054 (1972).*
2. J.-P. Franc and C. Pellone. Analysis of Thermal Effects in a Cavitating Inducer Using Rayleigh Equation. *J. of Fluids Engineering* 129.8 (2007), p. 974. doi: 10.1115/1.2746919.
3. J.P.Tullis. Cavitation guide for control valves. *Tech. rep. Nuclear Regulatory Commission*, Washington, DC (United States). Div. of Engineering; Engineering Consultants, Logan, UT (United States) 1993.
4. H.D. Baumann. The introduction of a critical flow factor for valve sizing. *ISA Transactions* 2.2 (1963).
5. G. Kojasoy, et al. Two-phase pressure drop in multiple thick-and thin-orifice plates. *Exp.Ther. and Fluid Science* 15.4 (1997), pp. 347–358.
6. J.Pinho, et al. Experimental and numerical study of a cryogenic valve using liquid nitrogen and water. *Aerospace Science and Technology* 93 (2019)
7. B. Ebrahimi, et al. Characterization of high-pressure cavitating flow through a thick orifice plate in a pipe of constant cross section. *Int. Journal of Thermal* Sciences 114 (2017),pp. 229–240.
8. M. Fossa and G. Guglielmini. Pressure drop and void fraction profiles during horizontal flow through thin and thick orifices. *Exp. Thermal and Fluid Science* 26.5 (2002), pp. 513–523.
9. Esposito, et al. Spectral and modal analysis of a cavitating flow through an orifice. *Exp. Ther. and Fluid Science*, 121, 110251.
10. Esposito, et al. On the influence of thermal phenomena during cavitation through an orifice. *Int. J. of Heat and Mass Transfer*, 164, 120481.

* Corresponding Author: Claudia Esposito, espoclau4@gmail.com