# Numerical simulation of the micro-jet velocity and cavitation-erosion on an axisymmetric nozzle

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**Abstract.**
The present study deals with the numerical study of the micro-jet velocity and the cavitation - erosion on an axisymmetric nozzle, which presents high flow unsteadiness and aggressiveness. The proposed model is based on energy conservation for the micro-jet velocity prediction, and assumes the potential and kinetic energies, at the start and at the end of the cavity collapse, respectively. The mass transport between liquid and vapor is closely related to Rayleigh Plesset's equation. Results have been obtained with a numerical scheme assuming homogeneous mixture flow, implicit LES and Zwart-Gerber-Belamri cavitation model. The 3D unsteady flow simulation has been solved using OpenFOAM, whilst for the micro-jet estimation, Python language coupled with OpenFOAM's calculator have been used. Results clearly show that the implemented model captures adequately the phenomenon and enables to identify attacked areas. Outcomes agree reasonably with the experimental results obtained by Franc in the Laboratoire de Écoulements Géophysiques et Industriels. Furthermore, results of the implemented Zwart-Gerber-Belamri cavitation model with adaptive time step, showed more details related to the cavitation shedding and detachment, which are important factors to predict erosion.

**Keywords:** cavitation-erosion; micro-jet velocity; OpenFOAM; axisymmetric nozzle

## 1. Introduction

To study cavitation-erosion is important not only to prevent the damage on hydraulic machinery components as blades and guide vanes, but also for optimized designs [1, 2].The basic ideas of the aforementioned topic are based on the work carried out by Hammitt [3, 4], who proposed that the energy contained in a cavity is released as a water shock, which can be higher than the material threshold strength. Kubota, Kato and Yamaguchi [5] proposed that the cavity collapse must be in a trajectory close to the walls. Bark et al. [6] and Patella et al. [7] proposed that potential energy stored in cavities is released during their collapse in cascade with the consideration of an effective trajectory. Dular et al. [8, 9] proposed a numerical modeling of cavitation erosion using the concepts of potential energy liberated in cascade and the high speed micro-jet [10]. The model explains that the bubble collapse located in a specific layer releases energy as a wave, which can re-energize bubbles close to hydrofoil walls. The collapse of the bubbles cluster generates a high speed micro-jet and an impact load on the material similar to a water hammer.

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Bearing in mind these aspects, Hidalgo [11] proposed a cavitation-erosion model using OpenFOAM and python language, which joined the potential energy in cavities with the kinetic energy in the micro-jet. In this context, the proposed model has been applied to study cavitation-erosion on a nozzle due to the highest aggressiveness of the phenomena, which was observed on Franc's studies [12].

## 2. Model description

Homogeneous mixture flow assumption, implicit large eddy turbulence model (ILES) and the Zwart-Gerber-Belamri cavitation model (ZGB) have been used for the numerical simulation of unsteady cavitating flow, which is based on previous research [13].

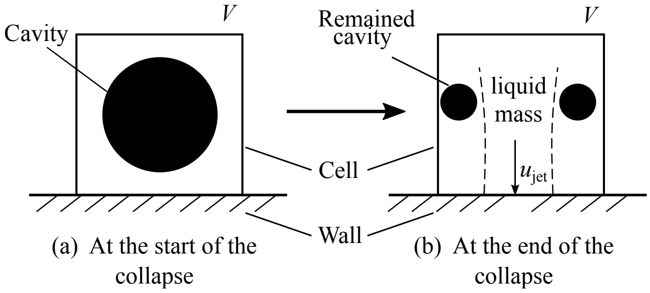


Figure 1: Collapse of a vapor cavity structure for one cell located over the solid wall

The model considers the collapse of a vapor structure in one cell of volume $V$ as indicated in figure 1. The dimensionless micro-jet velocity, $c_{\text{flow}}$, is expressed in (1) as a function of the micro-jet velocity, $u_{\text{jet}}$, and the undisturbed flow velocity, $U_\infty$ (31 m/s).

$$c_{\text{flow}} = \begin{cases} 8.97\gamma^2\sqrt{\left(\dfrac{p-p_{\text{v}}}{\rho_{\text{l}}U_\infty^2}\right)\left(\dfrac{\alpha_{\text{o}}-\alpha_{\text{f}}}{\alpha_{\text{o}}}\right)} & , \text{ if } (\alpha_{\text{o}}-\alpha_{\text{f}})>0 \text{ and } (p-p_{\text{v}})>0 \\ 0 & , \text{ if } (\alpha_{\text{o}}-\alpha_{\text{f}})<0 \text{ and } (p-p_{\text{v}})<0 \end{cases}, \qquad (1)$$

where $\gamma$ is a dimensionless distance from the bubble centre to the wall [8], $p$ is the static pressure, $p_{\text{v}}$ is the water saturation pressure, $\rho_{\text{l}}$ is the density of the liquid water, $\alpha$ is the vapor volume fraction, and $_{\text{o}}$ and $_{\text{f}}$ are subscripts for the initial and final instant of the cavity collapse.

Furthermore, a qualitative value of flow aggressiveness, $\overline{c}_{\text{flow}}$, can be estimated using (2) to predict the affected region in relation with its maximum value after one characteristic cavitation cycle. Where $_i$ is the subscript for each affected cell, and $t_o$ and $t_f$ are the initial and final time of the characteristic cavitation cycle respectively.

$$\overline{c}_{\text{flow}} = \frac{\left[\sum_{t_o}^{t_f} c_{\text{flow}}\right]_i}{\max\left(\left[\sum_{t_o}^{t_f} c_{\text{flow}}\right]_i\right)}. \qquad (2)$$

## 3. Computational domain and boundary conditions

The computational domain and boundary conditions indicated in figure 2 were based on the experimental studies carried out by Franc [12], and the numerical studies carried out by Koukouvinis et al. [14]. Structured mesh with a mean $y^+$ equal to 1.3 and $4.7 \times 10^5$ cells was used for the numerical simulation, which is in accordance with previous research [11, 15]. Furthermore, the mesh was refined close to the bending part, walls and the possible erosion target.

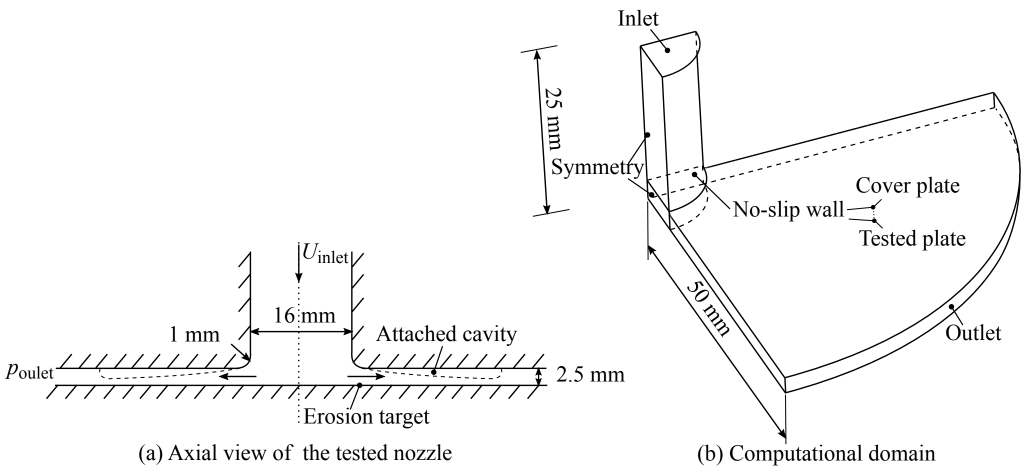


Figure 2: View with dimensions of the quarter part of the simulated nozzle

## 4. Results and discussion

Figure 3 (a) shows the comparison of erosion results between Franc's studies [12] and the proposed numerical simulation for the axisymmetric nozzle. The numerical result matched fairly well the affected region of the experimental result, which is between radius of 19 mm and 32 mm with a maximum $\overline{c}_{\text{flow}}$ between these two radius. A small region was selected from the numerical part for a better understanding of the phenomenon and it is indicated in figure 3 (b). From that region, a point called 1 was selected to study the $u_{\text{jet}}$ and to compare with the critical velocity that the material can absorb, $u_{\text{cri.}}$, which is based on Lush's observations [16].

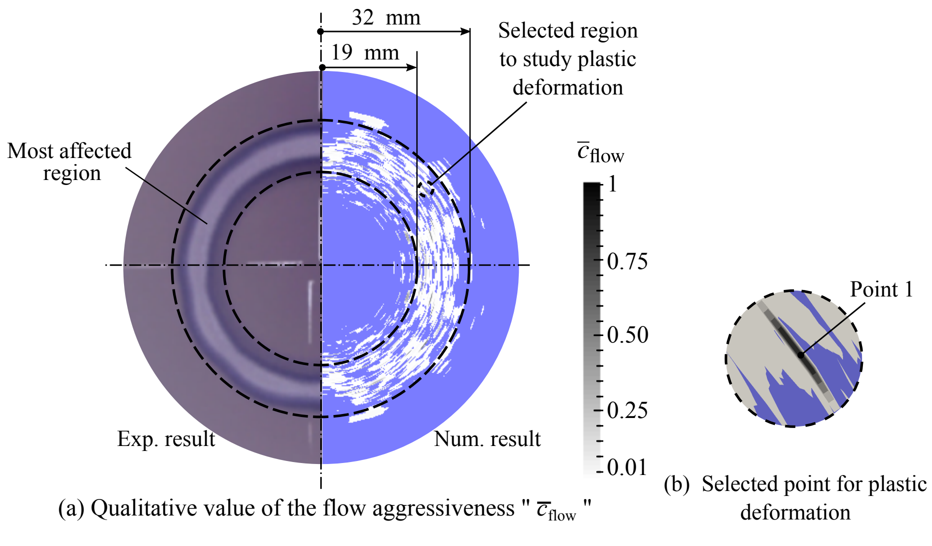


Figure 3: Comparison of erosion results between experimental studies and numerical simulations

Moreover, the pressure coefficient, $C_p$, and the dimensionless time, $\xi$, were estimated using equations (3) and (4) respectively.

$$C_p = \frac{p - p_\infty}{0.5\rho U_\infty^2} = -\sigma + \frac{p - p_{\text{v}}}{0.5\rho U_\infty^2}, \tag{3}$$

$$\xi = \frac{t - t_o}{t_f - t_o}, \tag{4}$$

where $\sigma$ is the estimated cavitation number, which is equal to 0.9 [11, 12] and $p_\infty$ is the undisturbed pressure [13]. Bearing in mind these aspects, $c_{\text{flow}}$, $\alpha$ and $C_p$ have been plotted in function of $\xi$ as indicated in figure 4.

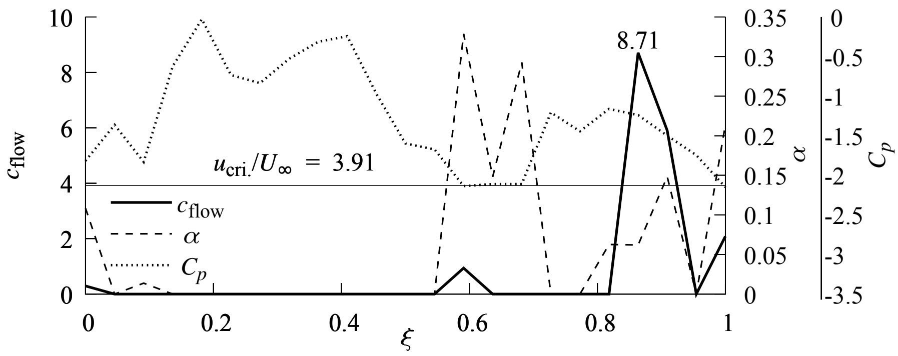


Figure 4: $c_{\text{flow}}$, $\alpha$ and $C_p$ in function of $\xi$ for point 1

The aforementioned figure shows that $Cp$ fluctuates between -2 and 0 up to $\xi = 0.6$ mainly due to the nozzle configuration and the turbulence [13]. In this range $\alpha$ is small and hence it is not significant for cavity collapses. The maximum $c_{\text{flow}}$ is given after $\xi = 0.8$, which is mainly relates to the fall of $C_p$ with a value close to $-\sigma$ and the presence of $\alpha$. Furthermore, the maximum $c_{\text{flow}}$ is two times higher than the $u_{\text{cri.}}/U_\infty$ for steel, which was estimated based on Lush [16]. In this context, the tested plate of figure 3 can be eroded in a short period of time, which agrees with the experimental data [12].

## 5. Conclusions

Results of the present research show that the proposed model can reproduce the cavitation-erosion problem on an axisymmetric nozzle with enough accuracy compared with experimental data. The model can be applied to study the induced erosion by cavitation on industrial applications. Moreover, the maximum $c_{\text{flow}}$ of 8.71 found in the assessment is equivalent to $u_{\text{jet}} = 270$ m/s, and it highlights the necessity of compressible correlations for further analysis.

## Acknowledgments

The authors gratefully acknowledge the financial support provided by Escuela Politécnica Nacional for the development of the project PIMI 14-03.

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