ASSESSING CAVITATION EROSION ON SOLID SURFACES USING A CAVITATION JET APPARATUS

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ABSTRACT

This study is dedicated to the examination of cavitation-induced erosion, a critical factor in optimizing the efficiency of hydraulic systems, including hydropower plants and pumping systems. To accomplish this, we conducted a sensitivity analysis utilizing a cavitation jet apparatus (CJA) and an experimental configuration that featured a vertical cylindrical test tank, a submerged nozzle, and an aluminum sample (specifically, alloy 6351 T6). The study maintained a consistent standoff distance of 5 cm and an orifice diameter of 2×10^{-3} m. Two distinct nozzle geometries were tested to assess their influence on cavitation erosion. The outcomes revealed that the 20° conical sharped-edges nozzle resulted in the highest erosion rates, while the commercial nozzle (MEG 2510) caused comparatively less erosion. By standardizing the test duration to 1200 seconds and using a cavitation index of 0.14, the researchers avoided overlapping pits. In summary, the CJA, with these adjustments, demonstrated its effectiveness as a tool for evaluating the resistance of solid surfaces to cavitation.

KEYWORDS: Cavitation; Cavitation Erosion; Submerged Cavitation Jet; Nozzle Geometry; Cavitation Jet Apparatus (CJA).

AVALIAÇÃO DA EROSÃO POR CAVITAÇÃO EM SUPERFÍCIES SÓLIDAS USANDO UM APARATO DE JATO DE CAVITAÇÃO

RESUMO

Este estudo é dedicado ao exame da erosão induzida por cavitação, um fator crítico na otimização da eficiência de sistemas hidráulicos, incluindo usinas hidrelétricas e sistemas de bombeamento. Para isso, realizamos uma análise de sensibilidade utilizando um aparelho de jato de cavitação (CJA) e uma configuração experimental que apresentava um tanque de teste cilíndrico vertical, um bico submerso e uma amostra de alumínio (especificamente, liga 6351 T6). O estudo manteve uma distância consistente de 5 cm e um diâmetro de orifício de 2×10^{-3} m. Duas geometrias distintas de bicos foram testadas para avaliar sua influência na erosão por cavitação. Os resultados revelaram que o bocal cônico com bordas afiadas de 20° resultou nas maiores taxas de erosão, enquanto o bocal comercial (MEG 2510) causou comparativamente menos erosão. Ao padronizar a duração do teste para 1.200 segundos e usar um índice de cavitação de 0,14, os pesquisadores evitaram a sobreposição de poços. Em resumo, o CJA, com esses ajustes, demonstrou sua eficácia como ferramenta de avaliação da resistência de superfícies sólidas à cavitação.

Palavras chave: Cavitação; Erosão por Cavitação; Jato de Cavitação Submerso; Geometria do Bocal; Aparelho de jato de cavitação (CJA).

1 INTRODUCTION

Cavitation is a complex phenomenon encompassing both hydrodynamic and material aspects, known to lead to disastrous consequences like cavitation erosion (Arabnejad et al., 2020; Franc & Michel, 2006; Genovez & Dalfré Filho, 2008; Gualtieri & Chanson, 2021; Peng et al., 2020; Soyama et al., 2020). Hydrodynamically, it involves the formation of vapor structures in low-pressure regions of cavitating flow, which violently collapse upon entering areas of pressure recovery, resulting in erosion of solid surfaces (Arabnejad et al., 2020; Franc & Michel, 2006; Genovez & Dalfré Filho, 2008; Gualtieri & Chanson, 2021; Peng et al., 2020; Soyama et al., 2020). Materially, cavitation erosion is characterized by material loss due to aggressive cavity collapses near surfaces, subjecting adjacent surfaces to high mechanical loads and stress levels that surpass the material's yield or fatigue stress, ultimately leading to material removal (Arabnejad et al., 2020; Genovez & Dalfré Filho, 2008).

The adverse effects of cavitation erosion significantly influence the design of hydraulic structures and machinery, such as spillways, hydropower plants, and pumping systems, leading to reduced operating lifetimes and increased maintenance costs (Asnaghi et al., 2021; Gavidia, Chinelatto, et al., 2023; Gensheng et al., 2005; Jahangir et al., 2021; Nikeghbali et al., 2014; Back et al., 2023). Conversely, cavitation's destructive capabilities find valuable applications in industries like wastewater treatment, marine pipe cleaning, and petroleum well drilling (Descovi et al., 2023a; Franc & Michel, 2006; Gavidia, Mohammadizadeh, et al., 2023; Fonseca, et al., 2017; Soyama, 2020a). Additionally, it is utilized in medical applications, including microbubble-enhanced high-intensity focused ultrasound for tumor ablation (Descovi et al., 2023b; Ma et al., 2021; Murillo Bermudez et al., 2023; Peng et al., 2020; Sierra et al., 2023; Soyama, 2020b, 2020a, 2020b; Soyama et al., 2011).

Researchers have explored various experimental methods to address cavitation's impact on solid surfaces and identify suitable materials for coatings and polishing (ASTM G134-17, 2017; Zhao et al., 2020). For instance, Zhao et al. proposed a cavitation rotary abrasive flow polishing method using multiple venturi cavitation channels (Zhao et al., 2020). However, existing test methods may not be ideal for evaluating the wear of nonmetallic aerospace materials (ASTM G134-17, 2017). Nozzle geometry significantly influences erosion rates, leading to experiments being conducted with various nozzle types and parameters (El Hassan et al., 2021; Hutli et al., 2016, 2017; Yamauchi et al., 1995). Nonetheless, some equipment limitations hinder full compliance with testing standards (such as ASTM G134), necessitating improvements in standoff adjustments and pressure utilization (ASTM G134-17, 2017; Hutli et al., 2016, 2017; Yamauchi et al., 1995).

In this study, the authors aim to conduct a sensitivity analysis of cavitation erosion using a cavitation jet apparatus (CJA) and varying nozzle geometries. The objective is to achieve steady-state wear in a shorter time using lower-cost, weaker positive displacement pumps and to evaluate cavitation erosion in free-surface tank flow scenarios, which holds practical relevance for hydraulic structures (S. Mohammadizadeh et al., 2021; Soyama et al., 2020; Yan et al., 2015). Given the limited focus on low-pressure tests and short durations in previous studies, further investigation into different nozzle geometries is deemed necessary.

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2 METHODOLOGY

This study employs a submerged cavitating jet test technique, wherein a jet of liquid undergoes cavitation and impacts a stationary solid sample submerged in the liquid. The impact of the cavitation bubbles on the solid sample leads to erosion. To assess the cavitation erosion of solid surfaces, we utilized a specialized experimental apparatus known as the cavitation jet apparatus (CJA), as shown in Figure 1. It comprised several critical components, beginning with a positive displacement pump (1) generating an operating pressure of 14.50 MPa and a flow rate of 4.84×10^{4} m^3/sec. This pump was powered by an electric motor (2) with a power output of 12.33 hp at 1200 rpm, operating on 220 V/3 phase. A pipe (3) connected to the pump outlet led to a nozzle (4) positioned inside a vertical cylindrical test tank with a diameter of 0.68 m and a height of 0.74 m. The tank was equipped with two circular glass windows (5) of 0.12 m diameter for observation purposes. A top drain (6) with a diameter of $\Phi = 6.35 \times 10^{2}$ m facilitated liquid discharge, while a bottom drain (7) of $\Phi = 1.27 \times 10^{2}$ m allowed for maintenance operations. At the bottom of the tank, a solid sample (8) composed of Aluminum alloy 6351 T6 was carefully placed. The tank was filled with tap water through the top drain, maintaining a constant temperature of 26 ± 1 °C.

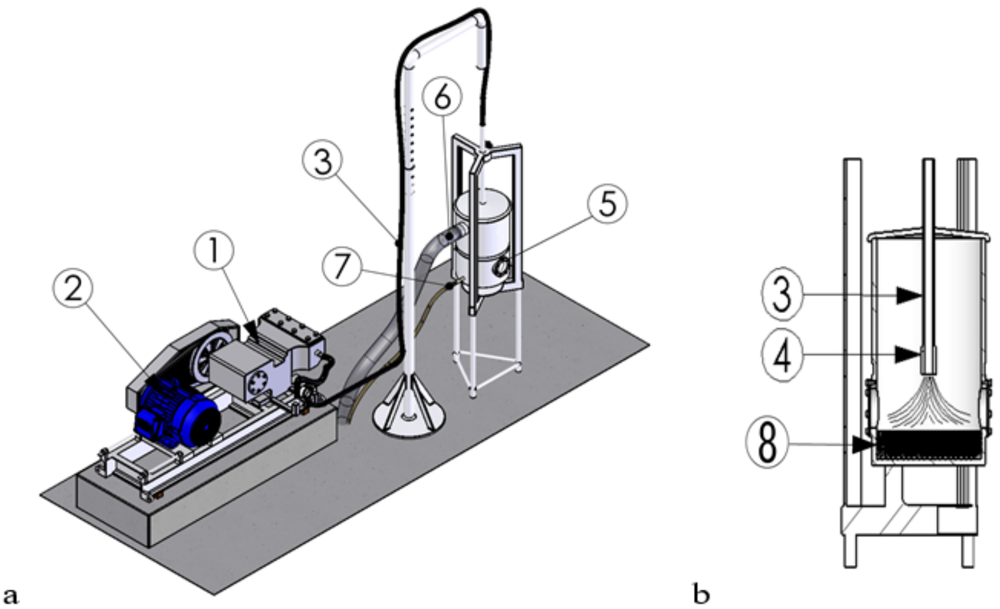

Figure 1: CJA;(a) Scheme of cavitating jet apparatus, (b) Cylindrical test tank detail (dimensions not to scale)

One significant advantage of the CJA setup was the adjustability of the nozzle's orifice diameter, nozzle geometry, and standoff. This feature allowed precise control over the cavitation process, enabling various experimental conditions and enhancing the accuracy of results.

The intensity of cavitation erosion is influenced by several crucial parameters, namely the cavitation index (σ), the orifice diameter of the nozzle (D), the standoff (S), and the nozzle geometry. According to Falvey's research (Falvey, 1990), cavitation index values (σ) within the range of 0.10 to 0.20 indicate developed cavitation, with the presence of small bubbles in the liquid. In light of this study and to reduce the test duration, a suitable cavitation index value of 0.14 was chosen for evaluating cavitation erosion.

To investigate the impact of nozzle orifice diameter on erosion quantity, five different diameters (2×10^{-3}, 2.5×10^{-3}, 3×10^{-3}, 3.25×10^{-3}, and 3.50×10^{-3} m) were employed in previous studies (Filho & Genovez, 2009; Genovez & Dalfré Filho, 2008; S. M. Mohammadizadeh et al., 2023). The results demonstrated that using an orifice diameter of 2 ± 0.05 mm resulted in the highest erosion quantity compared to the other diameters, thus it was adopted for this research.

The standoff (S) denotes the distance from the downstream of the nozzle orifice to the sample surface. In this study, the standoff was set at 0.05 m (± 0.005). However, this parameter requires further investigation in future research to determine the most susceptible standoff.

Furthermore, to achieve maximum cavitation erosion, two distinctive nozzle geometries were tested to identify the most vulnerable one. These encompassed a 20° conical nozzle with sharped edges and a commercially available nozzle known as MEG 2510 WASH JET SPRAY NOZZLE, as shown in Figure 2.

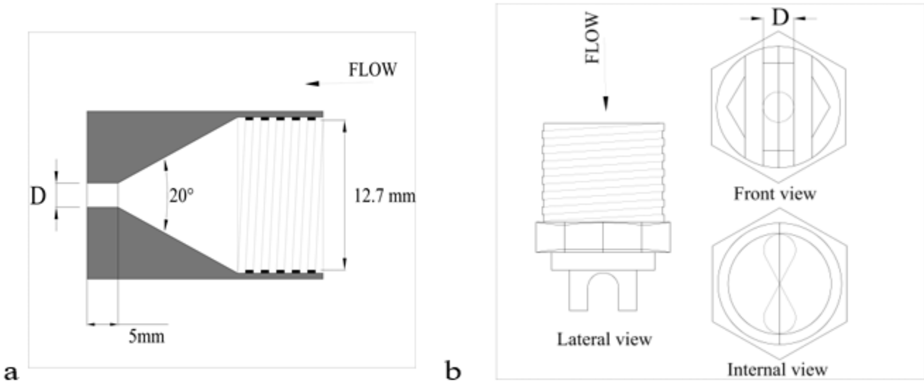

Figure 2: Nozzles' scheme used in cavitation jet apparatus; (a) 20°conical nozzle, (b) MEG 2510 WASH JET SPRAY NOZZLE

Previous studies have consistently used aluminum samples to assess pitting and measure cavitation erosion (Kadivar et al., 2021; Lv et al., 2018; Nagalingam et al., 2019; Soyama et al., 2020; Takahashi et al., 2018). Aluminum was chosen not as the subject of erosion evaluation, but rather as a means to record the intensity of cavitation bubble collapses. Any implosion causing sufficient damage to the material would lead to permanent deformation in the aluminum. In this research, an aluminum sample (alloy 6351 T6) with a diameter of 0.15 m and a thickness of 6.5×10^{-3} m was placed at the tank's bottom as the solid sample. Tables 1 and 2 list the mechanical and physical as well as chemical properties of the aluminum sample.

Table 1: Mechanical and physical properties of the sample

Mechanical and physical properties of Aluminum (alloy 6351	
Density (g/cm^3)	2.71
Hardness Brinell	95
Hardness Knoop	130
Modulus of Elasticity (GPa)	68.9
Fatigue Strength (MPa)	89.6
Poissons Ratio	0.33
Tensile Strength, Ultimate	310
Tensile Strength, Yield (MPa)	283
Elongation at Break (%)	14
Shear Modulos (GPa)	26
Shear Strength (MPa)	200
Thermal Conductivity (W/m−K)	176

Table 2: Chemical properties of Aluminum sample

Component element properties of Aluminum (alloy 6351	
Aluminum, Al	95.9 - 98.5 (%)
Copper, Cu	<= 0.10 (%)
Iron, Fe	<= 0.50 (%)
Magnesium, Mg	0.40 - 0.80 (%)
Manganese, Mn	0.40 - 0.80 (%)
Other, each	<= 0.05 (%)
Other, total	<= 0.15 (%)
Silicon, Si	0.70 - 1.3 (%)

Cavitation erosion was evaluated by creating a concentric ring with two distinct regions, one exhibiting intensive cavitation and the other showing moderate cavitation, around a central damaged area of the sample. Using a Trinocular Stereoscopic Microscope (OPTON Microscope) with zoom capabilities (1X to 4X) and magnification range (10X to 160X), the number of pits on the intensely cavitated surface of the polished aluminum sample was counted for visual examination. The quantification of cavitation erosion (wear) involved calculating the number of pits per square centimeter within the region characterized by intensive cavitation.

3 RESULTS AND DISCUSSION

The role of nozzle geometry in influencing the intensity of cavitating jets has been a subject of considerable interest in the field, with various studies by researchers like Gensheng (2005), Soyama (2020b, 2020a), Soyama et al. (2020), and Hulti (2016, 2017) shedding light on its significance. To delve deeper into this area, we conducted an experimental investigation aimed at comprehending the impact of employing two distinct nozzle geometries while maintaining a constant standoff distance of 0.05 meters (with a tolerance of ± 0.005). The orifice diameter was fixed at 2×10^{-3} meters, and the cavitation index was set at σ = 0.14. Each experiment was rigorously repeated a minimum of three times, utilizing identical samples to ascertain measurement precision. The standard deviation of the measurements can be observed in Figures 3 and 4.

The core objective of this study was to measure the diameter of the intensely cavitated region, which we found to be 0.04 meters with a precision of ± 0.002 meters. Subsequently, we probed the effects of cavitation erosion on an aluminum sample over a duration of 1200 seconds, with observations made at 60-second intervals up to the 1200-second mark. The outcome of our investigations unveiled that the utilization of a nozzle with a 20° conical and sharp-edged design resulted in the most significant erosion within the Cavitation Jet Apparatus (CJA). Erosion rates were documented as 27.67 pits/cm^2 in the initial 60 seconds, followed by 48.54, 72.81, 95.19, 178.88, and 258.55 pits/cm^2 at the 120, 180, 240, 300, and 1200-second marks, respectively.

This research sheds light on the profound impact of nozzle geometry in cavitating jet dynamics and offers critical insights into the erosion effects, which can have wide-ranging implications for industrial applications and engineering design. Further studies in this domain may yield valuable information for optimizing cavitating jet systems.

Furthermore, Figure 3 indicated that when MEG 2510 was used during different test periods, the measured erosion was less than half of the same scenario using the 20° conical sharped edges nozzle. Additionally, it is evident that erosion is directly linked to the passage of time up to t = 1200 seconds. The commercial nozzle (MEG 2510) exhibited the least amount of wear, indicating its worse performance. This observation suggests that the 20° conical sharped edges nozzle results in a more rapid decline in pressure and a simultaneous increase in velocity compared to MEG 2510. These factors significantly contribute to the increased erosion seen with the 20° conical shaped-edges nozzle.

Moreover, it's worth noting that all the curves exhibited a distinct knee-shaped pattern, conspicuously appearing within the time range from t = 180 to t = 300 seconds. This knee-shaped region corresponded to a sudden and substantial surge in erosive activity. Following this initial spike, there was a gradual amelioration in erosive behavior that extended until the culmination of the exposure period at t = 1200 seconds. This particular behavior aligns closely with the findings detailed in ASTM G134 (2017), a standard which extensively discusses this knee-shaped pattern and the subsequent gentle slope in the erosion rate.

In consonance with the insights provided by ASTM G134 (2017), which meticulously elaborates on the knee-shaped pattern and the gradual decline in the erosion rate, our ongoing research harmonizes with these observations. This confirmation lends credibility to the notion that an exposure time of t = 1200 seconds is indeed the optimal duration for achieving wear stability and evaluating erosion in the context of the CJA. Extending the test beyond this 1200-second threshold not only provides a substantial period for observation but also serves the purpose of enhancing the clarity of individual pit formations. This approach effectively mitigates the risk of potential pit overlap, allowing for a more accurate and detailed assessment of the erosive effects, which is crucial for a comprehensive understanding of cavitation-induced wear phenomena. Consequently, adhering to this recommended exposure time facilitates a more thorough and precise investigation into the behavior of materials subjected to cavitation, with applications spanning various fields, including materials science, engineering, and industrial equipment design.

Figure 4 in the study provides a comprehensive analysis of erosion, taking into account both the quantity of pits and the density of pits per unit area (pits/cm²) within a highly cavitated region, in relation to two distinct nozzle geometries. The data is specifically presented at a fixed time point, t = 1200 seconds, which marks the conclusion of the testing period.

The outcomes of the analysis demonstrate that the 20° conical sharp-edged nozzle yields the highest erosion rates, in stark contrast to the commercial nozzle (MEG 2510), which results in relatively less erosion. As a result, the CJA proves to be a suitable and precise method for evaluating cavitation erosion on solid surfaces. It's worth noting that the use of a 20° conical sharp-edged nozzle, an orifice diameter of 2×10^{-3} meters, a standoff distance of 0.05 meters, and a cavitation index of 0.14 are identified as the optimal experimental conditions for this evaluation. This information establishes valuable insights into erosion mechanisms and highlights the importance of nozzle geometry in cavitation erosion studies.

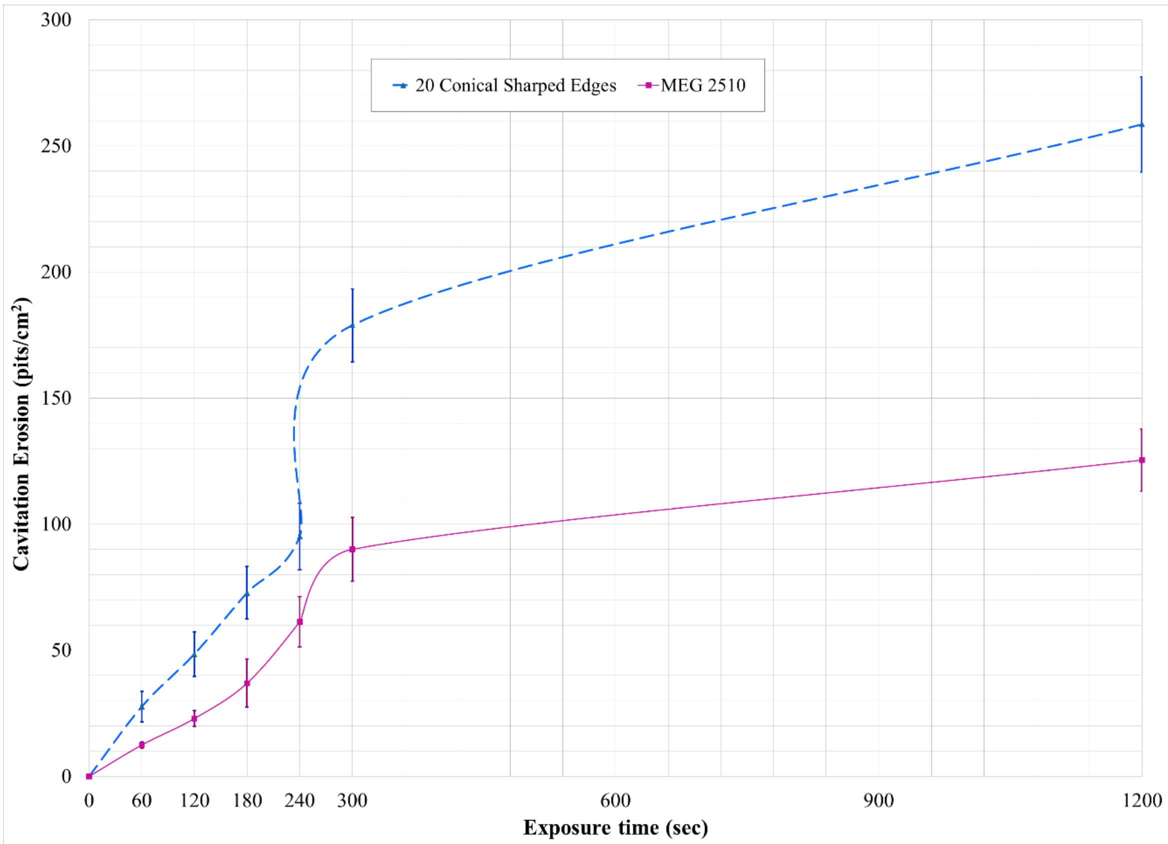

Figure 3: Effects of different nozzle geometries on Cavitation Erosion respect to Exposure time (nozzle orifice diameter = 2 mm, standoff = 5 cm, and intensively cavitated diameter of sample = 4 cm). Error bars present Standard Deviation.

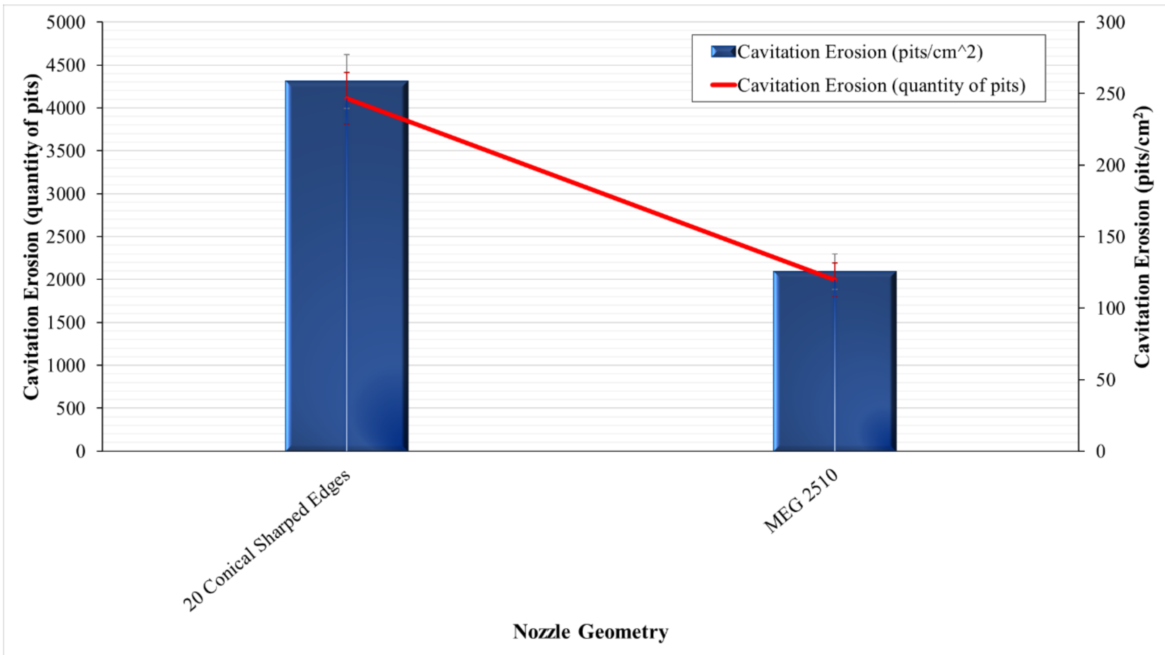

Figure 4: Effect of different nozzle geometries on Cavitation Erosion quantity at the particular moment of 1200 sec (standoff = 5 cm, orifice diameter of nozzle = 2 mm, and intensively cavitated diameter of sample = 4 cm).

4 CONCLUSION

To summarize, this research has elaborated on the utilization of a submerged cavitating jet test method for the assessment of cavitation erosion on solid surfaces. The cavitation jet apparatus (CJA) proved to be an indispensable tool in conducting these experiments. Its adaptability and modifiable components greatly enhanced the study's experimental capabilities. The insights gained through the application of the CJA have deepened our understanding of cavitation-induced erosion phenomena and their potential applications across engineering and material science disciplines.

The findings presented herein represent a substantial contribution to the comprehension of cavitation erosion and hold promise for driving advancements in numerous industrial applications where cavitation is a significant factor. The optimal experimental parameters for employing the CJA involve the installation of a 20° conical sharped-edges nozzle with an orifice diameter of 2×10^{-3} m, a standoff distance of 0.05 m, and a cavitation index of 0.14, with the tests conducted for a duration of 20 minutes. These recommendations are pivotal for ensuring the effectiveness of the CJA in assessing cavitation erosion.

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