Cavitation erosion resistance of high-strength fiber reinforced composite material

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Abstract. Cavitation erosion tests were performed using a cavitating jet apparatus inspired by the ASTM G134 standard on a high-strength fiber reinforced composite material named Vectran. These tests were also performed on metallic materials, namely Al, SUS304 stainless steel and AlBC, to determine the effect of their elastic modulus and acoustic impedance on the erosion. The effects of the jet parameters, the standoff distance and cavitation number were also observed. Using a high speed-pressure sensor, a measure of accumulated impact energy was made: the number of high amplitude force counts decreased with the standoff distance, while the optimal erosion distance was negatively proportional to the cavitation number. The higher the intensity, the higher was the maximal mean depth of erosion rate (MDER) for all materials. The erosion rate decreased with the young modulus, but it was observed to be linearly dependent on the material’s acoustic impedance.

Keywords: Cavitating Jet, Erosion rate, Cavitation erosion resistance, Accumulated impact energy, Equivalent impedance, Composite materials, Metallic materials.

1. Introduction

As fluid machinery such as pumps and water wheels are ever more compact and made to operate at higher speeds, various problems relating to cavitation can occur. Among them, the erosion of materials by cavitation remains an ever-present problem: it is difficult to predict, causes significant mass loss and increases the necessity of down-time for maintenance [1]. One way to increase the cavitation erosion resistance of turbomachinery is to select different materials according to the fluid machinery’s intended use. Recently, evaluations of cavitation erosion resistance were carried out for composite materials such as glass fiber reinforced plastics and particle reinforced plastics. Metallic materials are mostly used in this context, but plastics offer several advantages [2-5]: low density, small acoustic impedance leading to smaller impact pressure caused by shockwaves, etc. Plastic blades can even change shape under certain conditions, improving performance and preventing cavitation occurrence [6].
For this reason, we studied the cavitation erosion of a composite material reinforced with high-strength fibers, known as Vectran manufactured by Kuraray Co. Ltd., using a cavitating jet. This jet is comparable to the ASTM standard G134 [7-9], but the present results cannot be compared directly because the sample size differs from this standard. Then, the composite material’s erosion resistance was compared with conventional metallic materials used in fluid machinery. A high-speed pressure sensor manufactured by Muller was also used to get an estimation of the accumulated impact energy, a measure of the aggressiveness of the jet. The erosion rate of materials was measured as a function of jet operating conditions and material properties, in the hopes of finding useful correlations.

List of symbols

\[ A \quad \text{Test piece cross-sectional area} = 176.22 \text{mm}^2 \quad \text{(diameter} \quad d = 15 \text{mm)} \]
\[ l_c \quad \text{Accumulated impact energy} \]
\[ W_t \quad \text{Cumulative mass loss [mg]} \]
\[ M \quad \text{Cumulative volume loss} = W_t / \rho [\text{m}^3] \]
\[ \text{MDE} \quad \text{Mean depth of erosion} = M / A [\text{mm/s}] \]
\[ \text{MDER} \quad \text{Mean depth of erosion rate} = \text{MDE} / t [\text{mm/s}] \]
\[ d_e \quad \text{Nozzle diameter} = 0.4 \text{mm} \]
\[ t \quad \text{Elapsed time [s]} \]
\[ \rho \quad \text{Material density} [\text{kg/m}^3] \]

2. Experimental methodology

2.1. Cavitation erosion jet
The cavitation erosion test was carried using a cavitating jet based on the standard ASTM G134-95 [7]. By injecting a high-speed jet into a water vessel using a small size nozzle, cavitation bubbles are generated, travel to the sample then implode close to the surface, causing pits and erosion.

Soyama et al. reported on the relationship between the cavitation number and the optimal standoff distance among other results in [10]. In addition, Hattori et al. investigated the influence of the flow rate and cavitation number on the erosion rate using a cavitating jet: the erosion rate of pure Al increases to the 3.9~4.6th power of the flow rate and standoff distance [8]. To confirm these effects on the mass loss, the standoff distance and the cavitation number were also changed in this study. As recommended by the ASTM G134 standard [7], the optimal erosion distance was first found using these measurements.

Figure 1 shows a photograph of the vessel and a schematic that better illustrates the standoff distance. The distance from the upstream end face of the nozzle to the test piece is defined as the standoff distance, hereinafter referred to as SOD. The nozzle shape conforms to the ASTM standard: its diameter is 0.4 mm.

Figure 1. Standoff distance definition.
In the experiments, the upstream pressure $P_1$ was set to 20MPa, while the cavitation number and SOD were changed. The previously mentioned cavitation number $\sigma$ is a dimensionless number representing the generation of cavities and can be calculated as follows [11]:

$$
\sigma = \frac{P_2 - P_v}{P_1 - P_v} \approx \frac{P_2}{P_1}
$$

with $P_1$: upstream pressure (absolute pressure in the nozzle), $P_2$: downstream pressure (absolute pressure in the vessel), $P_v$: water saturated vapor pressure (absolute pressure).

The lower this number is, the more cavitation bubbles are generated, in general. Tap water was used as the test liquid, and its temperature was kept in the interval $25 \pm 5^\circ C$.

2.2. Test materials

A commercially available polyallylate fiber, registered as "Vectran", manufactured by Kuraray Co. Ltd. was studied [12]. It exhibits high strength, low water absorption and abrasion resistance properties. Its performance was compared to metal materials used for fluid machinery such as pumps and water wheels: Aluminium, AlBC 3C (or known as CAC703 by the Japanese Industrial Standards Committee, or JISC [13]) and SUS304 stainless steel. Figure 2 shows the shape of the specimen: their diameter is 15 mm regardless of the material, which does not comply with the ASTM G134 standard.

Table 1 shows the basic physical properties of the test materials and test water used in the experiments. We note that SUS304 steel possesses the highest density, elastic modulus as well as acoustic impedance. The composite material Vectran though has a density value half of the very light Al, with comparably low impedance and elastic modulus, while AlBC has middling values of elastic modulus and impedance.

The chemical composition of the tested metallic materials is shown in table 2. The SUS 304 steel owes its corrosion resistance to its high chromium content. Its use in hydraulic machinery is explained in part by this property as well as its ease of formability. This grade of AlBC (CAC703) and others are commonly used for marine applications like propellers and valves because of its corrosion and abrasion resistance, easily recognizable to its slightly brown gold tint [13]. The values put in table 2 for the
composition of the AlBC were given by the manufacturer, and fit in the previously mentioned JISC standard’s specifications.

Table 2. Chemical composition of metallic materials.

| Materials | Si  | Cu  | Mn  | Cr  | Fe  | Mg  | Zn  | Ti  | Ti+Zr | C   | P   | S   | Ni  | Al  |
|-----------|-----|-----|-----|-----|-----|-----|-----|-----|-------|-----|-----|-----|-----|-----|
| Al(A7075) | 0.09| 1.60| 0.04| 0.19| 0.20| 2.50| 5.70| 0.01| 0.02  | RE  |     |     |     |     |
| SUS304    | 0.32|     |     |     |     |     |     |     |       |     | 0.05| 0.37| 0.29| 8.44|
| AlBC      | 80.5| 1.0 |     |     |     |     |     | 4.3 |       |     |     |     | 4.7 | 9.3 |

Table 3 shows the combinations of the standoff distance and the cavitation number that were used in this paper. For each cavitation number, the relationship between bubble collapse position and the SOD changes, and accordingly the erosion amount is influenced by both parameters [7].

Table 3. Tested jet parameters(○: tested, ×: not tested).

| SOD [mm] | σ  | 0.009 | 0.020 | 0.030 |
|----------|----|-------|-------|-------|
| 8.5      | ×  |       |       | ○     |
| 13.5     | ○  | ○     |       | ○     |
| 21.0     | ○  | ○     | ○     |       |
| 28.5     | ○  | ○     |       | ×     |

3. Results and Discussion

3.1. Optimal standoff distance selection

The cumulative mass loss as a function of the SOD and cavitation number was recorded for AlBC to determine the optimal SOD, as recommended by the ASTM G134 standard. The results after 3 hours of erosion are presented in figure 3.

Figure 3. Relationship between SOD and total mass loss for 3 hours of erosion, using AlBC.

As the cavitation number decreases, the optimal SOD lengthens. The optimal SODs are 21.0, 13.5, 8.5 mm, in increasing order of cavitation number. The dimensionless nozzle diameter, equal to SOD/de, computed for the optimal SOD are plotted in figure 4 as a function of the cavitation number, such as is shown in Hattori [11] and the ASTM standard [7].
Figure 4. Relationship between dimensionless nozzle diameter $SOD/d_e$ and cavitation number.

As can be observed in figure 4, the present dimensionless nozzle diameter is shifted downwards compared to the ASTM standard, while data from Hattori’s paper is shifted upwards [7].

3.2. Erosion comparison: metallic materials and composite Vectran

Table 4 and table 5 show photographs of the erosion state of the surface of the test pieces after one hour, for both the AIBC material and Vectran under different jet conditions. Both materials’ erosion progress is similar at the optimum SOD. The shape of the eroded portion is of toroidal shape with a radius whose relationship with the SOD cannot be clearly established with these pictures. The radius appears inversely proportional to the cavitation number, with notable exceptions.

Table 4. Pictures of the eroded AIBC surface after 1 hour of erosion.

| SOD  | $\sigma = 0.02$ | $\sigma = 0.009$ |
|-------|----------------|-----------------|
| 13.5 mm | ![Picture](image1.png) | ![Picture](image2.png) |
| 21.0 mm | ![Picture](image3.png) | ![Picture](image4.png) |
| 28.5 mm | ![Picture](image5.png) | ![Picture](image6.png) |
Table 5. Pictures of the eroded Vectran surface after 1 hour of erosion.

| SOD (mm) | | |
|----------|----------|----------|
| 13.5     | ![Image](image1.png) | ![Image](image2.png) |
| 21.0     | ![Image](image3.png) | ![Image](image4.png) |
| 28.5     | ![Image](image5.png) | ![Image](image6.png) |

$\sigma = 0.02$

$\sigma = 0.009$

Figures 5 (a) and figure 5 (b) show the total mass loss for each material with the optimal SOD = 13.5 mm for $\sigma = 0.02$. When the mass loss is divided by the material density, the approximate volume loss is obtained, an erosion value some argue more representative of the actual erosion [11]. The Al (A 7075) had the highest erosion rate, followed by Vectran, SUS 304 and finally AlBC. These results for the metallic materials show a tendency similar to [14]. It is interesting that the temporal change in volume loss of Vectran is close that of Al (A 7075), with the most resistant material being AlBC.

![Figure 5](image7.png)

**Figure 5.** Comparison of the erosion rate of metals with the composite Vectran (SOD = 13.5mm, $\sigma = 0.02$).

3.3. Force count data and its relationship with the standoff distance

As was mentioned before, the cavitation jet method’s aggressiveness is greatly influenced by the cavitation number $\sigma$ and standoff distance SOD. One way to quantify this aggressiveness is to measure the pressure applied on a surface unit in time and compute the accumulated impact energy $I_C$, defined below in equation (2).

By using a high-speed impact pressure sensor manufactured by Muller Instruments, high pressure amplitudes could be measured. The sensor’s sensitive diameter = 1.0 mm, its dynamic range = -3 to 40 MPa and its rise time = 60 ns. The impact pressure sensor was attached to a dedicated jig and inserted into the vessel just like a sample would be. A sampling frequency of 102.4 kHz (10µs) was used, and the force applied was recorded for 10 seconds then counted, producing the histogram presented in figure 6. With this method, the total number of counts is equal to the number of points recorded in the 10s total measurement interval.
As shown in [15], this sampling rate is too long to properly visualize impacts, but it gives a random sampling of the force applied by impacts. From this, the accumulated impact energy can be computed by equation (2) [16,17]. Some other parameters of importance exist, such as the cavitation intensity, the instantaneous power applied on a unit of surface [18].

\[
Ic = \sum F_i^2 \times n_i
\]

with \( F \) the measured force and \( n \) the number of points in the binning interval \( i \).

It is clear from figure 6 that the number of counts decreases exponentially with the measured force. Also, the number of counts at a low force changes only slightly, but the number of high force counts increases dramatically with the cavitation number. The accumulated impact energy was measured also as a function of the SOD, and its shape is compared with the accumulated impact energy as a function of the maximum erosion rate of all the materials in figure 7.

The total mass loss after 1 hour of erosion is proportional with the accumulated impact energy, in all cases. It is also interesting to note that the material mass loss ranking is generally conserved with the SOD: Al is the least resistant material, followed by Vectran, SUS304 and AlBC. The accumulated impact energy otherwise decreases with the SOD, as expected.
Figure 7. Relation between accumulated impact energy, standoff distance (SOD) and the mean depth of erosion rate (MDER) for $\sigma = 0.02$. Note: the MDER axis on the left graph is reversed.

The pressure $P$ generated when air bubbles collapse near a wall, or attached to it, is given by the following equations [19]:

$$P = Z_{eq} \cdot v$$

(3)

$$Z_{eq} = \frac{1}{\frac{1}{Z_1} + \frac{1}{Z_2}}$$

(4)

With $Z_i$: the acoustic impedance of substance $i$, which is equal to $\sqrt{E_i \cdot \rho_i} = c_i \cdot \rho_i$.

$1,2$: the liquid and material used,

$E_i$: the modulus of longitudinal elasticity of substance $i$,

$c_i$: the speed of sound in substance $i$,

$v$: the collision speed of the jet.

The impact pressure caused by the collapse of air bubbles is proportional to the equivalent impedance $Z_{eq}$, which depends on the impedance of the liquid and the material. The MDER for each material was determined and plotted as a function of the equivalent impedance in figure 8.

Only 4 materials where studied here, but it seems the MDER is linearly dependent on the equivalent acoustic impedance: the MDER decreases linearly as a function of $Z_{eq}$. The impact pressure is directly proportional to this parameter, which would lead one to expect the MDER to decrease with $Z_{eq}$, but the inverse relationship is observed. The composite material Vectran has very high MDER for a small acoustic impedance compared with metals, which have comparatively high acoustic impedance. One factor of important to a material’s impedance is its density: a higher density material has a higher acoustic impedance. As for other material properties: higher Young’s moduli or shear moduli also lead to higher acoustic impedances. Material properties are directly related to the acoustic impedance. One can then postulate that better material properties lead to higher impedance, and better cavitation erosion resistance.

A similar relationship is found between the volume loss and $Z_{eq}$: the high impedance materials have a lower total volume loss. In this case, Al is a notable exception because of its very high-volume loss. No such relation between the total mass loss and $Z_{eq}$ could be inferred from the present data. It seems that the impedance can serve as a first indicator of the cavitation erosion resistance of materials, or as an indirect measure of a material’s mechanical properties.
4. Conclusion
Cavitation erosion tests using a cavitating jet apparatus were performed to study a high-strength fiber composite material named Vectran. The cavitation erosion resistance of this composite material was compared with that of metallic materials used conventionally in hydraulic machines.

(1) The erosion rate of Vectran is close to that of Al (A 7075), but compared with SUS304 steel and AlBC, the erosion rate of the composite material is significantly larger.

(2) By counting the number of occurrences of a certain impact force on a high-speed pressure sensor in a time interval, changes in the accumulated impact energy as a function of standoff distance were evaluated. The accumulated impact energy was observed to abruptly increase when the SOD decreases, being maximal at 13.5mm. The MDER (mean depth of erosion rate) correlated directly with the accumulated impact energy for all materials: Al, Vectran, SUS 304 steel and AlBC (CAC703).

(3) The equivalent acoustic impedance was observed to be inversely proportional to the maximal MDER. This suggests that the acoustic impedance of the material can give an indication of the cavitation erosion resistance of materials.

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References
[1] Singh R, Tiwari S K and Mishra S K 2012 Cavitation erosion in hydraulic turbine components and mitigation by coatings: current status and future needs J. Mater. Eng. Per. 21-7 1539-1551
[2] Nakamoto H, Yang X, Hattori S, Nohmi M and Hayabusa K 2012 Anti-cavitation erosion of fiber- and particle-reinforced composites for repairs (in Japanese) Turbomachinery, 40-2 85-90
[3] Hammond D A, Amateau M F and Queeney R A 1993 Cavitation erosion performance of fiber reinforced composites. J. composite mat. 27-16 1522-1544
[4] Hattori S, Hozawa K, Nakamoto H, Nohmi M and Hayabusa K 2014 Evaluation of cavitation erosion of glass fiber reinforced plastics based on eroded surface profiles (in Japanese) Turbomachinery, 42-2 627-632
[5] Hattori S, and Itoh T 2011 Cavitation erosion resistance of plastics Wear 271 1103-1108
[6] Saito S 1987 Cavitation Aspect and Flow Pattern in an Axial-Flow Impeller (in Japanese), Trans. Japan Soc. Mech. Eng. B, 53-492 2483-2491
[7] American Society for Testing and Materials G134-95 Standard Test Method for Erosion of Solid
Materials by cavitating liquid jet ASTM International West Conshohocken 1995
www.astm.org

[8] Hattori S, Maekawa N and Kuwahara M 2001 Comparison of cavitation erosion between cavitating jet and vibratory methods specified in ASTM standard Trans. Japan Soc. Mech. Eng. A, 67-655 470-475

[9] Lichtarowicz A 1979. Cavitating jet apparatus for cavitation erosion testing. In Erosion: Prevention and Useful Applications ASTM International

[10] Soyama H and Lichtarowicz A 1998 Useful correlations for cavitating water jet, Rev High Pres. Sci. Tech. 7 1456-1458

[11] Hattori S, Fukuyama T, Goto Y, Yagi Y and Murase M 2005 Influence of flow velocity and cavitation number on erosion rate by cavitating liquid jet method specified in ASTM standard Trans. Japan Soc. Mech. Eng. A, 71-709 1276-1282

[12] Yorimitsu S 2010 The Specific Character and the Use of Polyallylate Fiber (in Japanese) Sen'i Gakkaishi 66 386-90

[13] Japanese Industrial Standards Committee JIS 5210 Copper and copper alloy castings (in Japanese) Tokyo 2009 http://www.jisc.go.jp

[14] American Society for Testing and Materials STP474 Characterization and determination of erosion resistance ASTM Committee G-2 on Erosion by Cavitation or Impingement West Conshohocken 1970 www.astm.org

[15] Kim K-H, Chahine G, Franc J-P and Karimi A 2014 Advanced Experimental and Numerical Techniques for Cavitation Erosion Prediction (Fluid Mechanics and Its Applications vol 106) (Dordrecht: Springer)

[16] Hattori S, Mori H and Okada T 1998 Quantitative evaluation of cavitation erosion J. fluids Eng. 120-1 179-185

[17] Okada T, Iwai Y, Hattori S and Tanimura N 1995 Relation between impact load and the damage produced by cavitation bubble collapse Wear 184-2 231–239

[18] Patella R F and Reboud J L 1998 A new approach to evaluate the cavitation erosion power. J. of fluids eng. 120-2 335-344

[19] Hattori S, Itoh T and Mori H 2005 Cavitation erosion resistance of high polymer materials (in Japanese) Trans. Japan Soc. Mech. Eng. A, 71-705 838-843.