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# Alternative Uses of Cavitating Jets

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## 1. Introduction

Cavitation is a phase transformation occurring in a fluid system under certain conditions. If the dynamic alteration of the absolute static pressure reaches or drops below the vapour pressure of the liquid, vapour bubbles are formed inside the liquid and can collapse as they move to a high-pressure region [1]. When the vapour bubbles collapse, shock waves are produced that propagate at the speed of sound through the liquid [2]. So, cavitation can produce undesirable effects such as noise, vibration, pressure fluctuation, erosion and efficiency loss in a hydraulic system.

The pressure difference due to the dynamic effect of the fluid motion is proportional to the square of the relative velocity. This can be written in the form of the usual pressure coefficient ( $C_p$ ), presented in the Equation 1 [3]:

$$C_p = \frac{(p - p_o)}{\rho v_o^2 / 2} \quad (1)$$

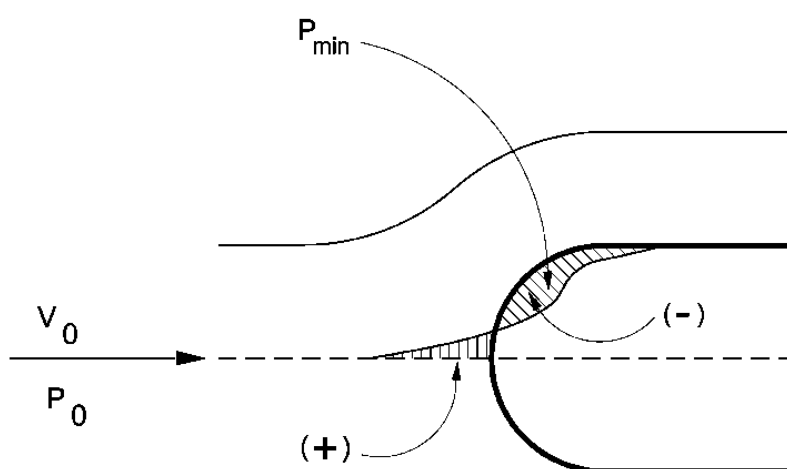
where  $\rho$  is the density of the liquid;  $v_o$  and  $p_o$  are the velocity and pressure of an undisturbed liquid, respectively, and  $(p - p_o)$  is the pressure differential due to dynamic effects of fluid motion.

If pressure  $p$  reaches a minimum,  $p = p_{\min}$  (see Figure 1), the pressure coefficient will be minimum, and a set of conditions can be created so that  $p_{\min}$  drops to a value where cavitation can begin. This can be accomplished by raising the relative velocity  $v_o$  for a fixed value of the pressure  $p_o$  or lowering  $p_o$  with  $v_o$  remaining constant. If surface tension is ignored, the pressure  $p_{\min}$  will be the pressure inside the cavity. This pressure will be the bubble pressure.

If we consider that cavitation will occur when the normal stresses at a point in the liquid are reduced to zero, then the bubble pressure will assume the value of the vapour pressure,  $p_v$ . Then, the cavitation index ( $\sigma$ ) is the theoretical value of the negative pressure coefficient, Equation 2:

$$\sigma = \frac{p_o - p_v}{\rho v_o^2 / 2} = -(C_p)_{\min} \quad (2)$$

The cavitation index can designate the probability of a system to cavitate and establish different intensity levels of cavitation in this system.



**Figure 1.** Pressure distribution in a submerged body [4].

As the pressure is increased, the bubble diameter decreases from the original size reaching a minimum size. The process takes place until the bubble diameter becomes microscopic. If the bubble collapses, then shock waves form with celerity equal to the speed of sound in water. If a boundary is close to where the bubble imploded, it will deform into a microjet. The velocity of this microjet is high and the shockwave produces high pressure responsible for the cavitation damage of a surface [5]. The collapse of the cavities formed by the cavitating jet generates high-pressure waves, estimated to be approximately 69.00 MPa [6] and high-speed microjets (above 100 m/s), all of which have a significant amount of destructive power [7].

Flow conditions leading to the onset of cavitation are generally conservative in predicting damage. The severity of the damage may be related to both intensity of cavitation and exposure time [8].

In hydraulic structures, as the high velocity flow passes over the many irregularities that exist in the concrete surface, cavitation can commence and consequently, damages may occur. Therefore, the material properties of the surface have to be improved to provide adequate resistance either during the construction phase or when the substitution of the eroded concrete is required.

Particularly of interest, in developing countries, hydropower will continue to play a significant role in supplying energy. Therefore, as energy demands are continuously increasing, new hydropower plants (dams and appurtenances) are being constructed. Nevertheless, the operation and maintenance of these structures, which include the spillways and tunnels under high velocity flows, are a great issue. Therefore, the material properties have to be improved to provide adequate resistance, either during the construction phase or substitution phase. For example, the substitution of a great area of eroded concrete was required in the case of Porto Colombia hydropower spillway and dissipation basin in the Grande River, Brazil [7].

An additional complexity is observed in hydraulic structures due to the simultaneous effect of cavitation and high impact of the flow [9,10,4]. Evaluation of the concrete resistance erosion in hydraulic structures is essential to guarantee adequate operation. It was suggested by [11] defining a methodology to appropriately test the materials, when submitted to cavitation, to be used in hydraulic structures.

In this chapter the authors discuss the use of high velocity cavitating jets to determine the erosion in high performance concretes for hydraulic structures. Moreover, two alternatives uses for cavitating jets are presented: 1) the inactivation of *Escherichia coli*, and, 2) the decomposition of persistent compounds in water.

## 2. Use of the cavitating jet to test erosion in surfaces

### 2.1. Introduction

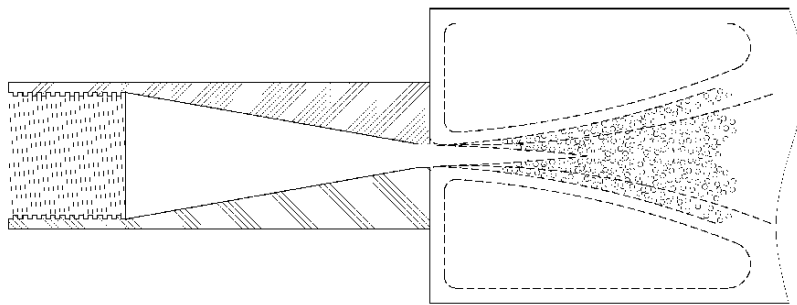
Evaluation of the concrete erosion resistance in hydraulic structures is essential to guarantee adequate operation, and tests should be performed under the same operation conditions. Various techniques can be used to induce cavitation, such as, ultrasonic methods, hydrodynamic methods, and high-speed/high-pressure homogenization. In the hydrodynamic cavitation, pressure variations are produced using the geometry of the system, while in the acoustic cavitation pressure variations are effected using sound waves.

Concrete resistance to cavitation damage was investigated by [12-14] using a Venturi device. A chamber was used by [15] to test concrete samples subjected to short-duration cavitation. An alternative test for erosion evaluation uses water cavitating jet technology [16,17] to achieve short test time. A flow cavitation chamber was used by [18-20] to test concrete and different rock samples subjected to short-duration cavitation. Water cavitating jet technology was firstly used to clean surfaces. For example, [21] compared the efficiency of conventional non-cavitating jets to cavitating jets.

Regardless several researchers have worked with the cavitation jet apparatus, to test concretes submitted to the erosive effect of cavitation, the appropriate nozzle specifications and sample dimensions must be experimentally determined.

## 2.2. The cavitating jet apparatus

The cavitating jet apparatus uses a nozzle specially designed to produce cavitation, combining high-velocity flows and cavitation (with an appropriate cavitation index). Because the collapse of bubbles is concentrated over a microscopic area, localized stresses are produced, providing the cavitating jet with a great advantage over steady non-cavitating jet operating at the same pressures and flow rates [22]. Figure 2 shows a schematic of the formation of a cavitating jet. As the high velocity flow leaves the orifice nozzle, eddies are formed between the high velocity layer of the jet and the surrounding liquid. If a nucleus in the water is captured in one of these eddies and the pressure inside the eddy drops to vapour pressure, then the nucleus will begin to grow. However, if the pressure remains near the vapour pressure long enough for the nuclei to reach the critical diameter, then it begins to grow almost by vaporization. As long as the size of the vapour cavity increases, the strength of the eddy is destroyed and the rotational velocity decreases. Then, the surrounding bubble pressure is no longer the vapour pressure. Inside the cavity the pressure remains at vapour pressure and cavity surroundings at hydrostatic pressure. Consequently, the cavity becomes unstable and it collapses inward.



**Figure 2.** Schematic flow of a submerged jet [6].

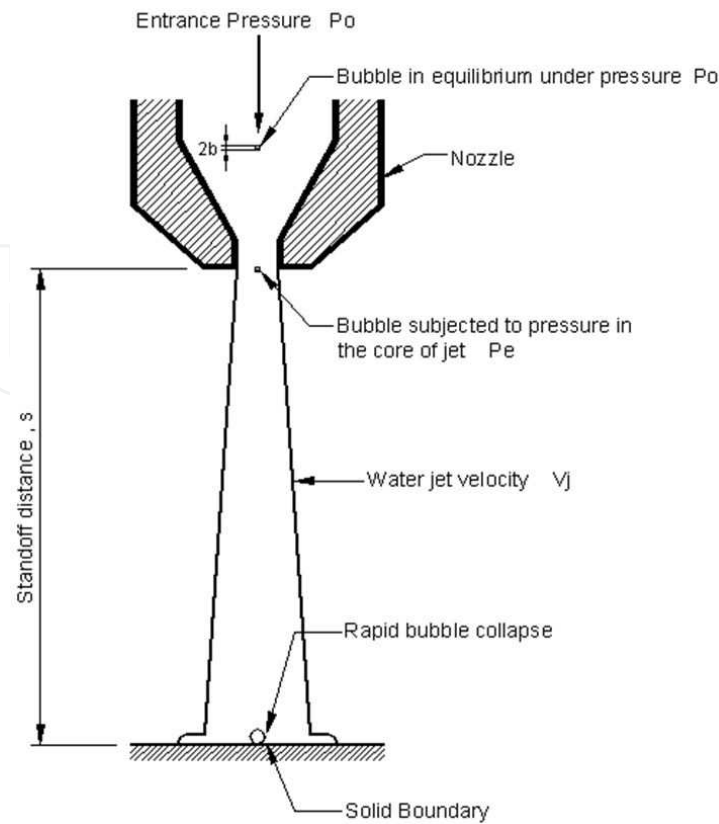
Now, consider in Figure 3 a spherical vapour bubble of initial radius  $b$  and internal pressure  $P_o$ . Later on, the bubble acquires the radius  $r_e$  at pressure  $P_e$ . If a small amount of air is in the liquid, such that the cavities are filled exclusively by vapour, the bubble growth and collapse is intense and causes severe damages to the vicinity [6].

The pressure magnitude generated at the solid boundary is expected to be a main factor in estimating the erosion efficiency of a cavitating jet impinging on a solid boundary as shown in Figure 3.

For a steady water jet ( $v_j$ ), the generated pressure magnitude ( $P_s$ ) can be estimated from the stagnation pressure, as in Equation 3:

$$P_s = \frac{1}{2} \rho v_j^2 \quad (3)$$

A moderate level pressure would be inappropriate for testing erosion rates. Depending on the standoff distance, water droplets formation can occur and the impact pressure can be larger



**Figure 3.** Cavitating jet formation and bubble collapse (Adapted from [23])

than  $P_s$ . It was indicated that the transient pressure ( $P_a$ ) between the cavity implosion and the solid boundary could be approximated by the “water hammer” equation, as in Equation 4:

$$P_a = \rho c v_j \quad (4)$$

with  $c$  as the sound velocity in water.

However, the pressure magnitude generated with the impact of a cavitating jet ( $P_b$ ) is different from that generated by the impact of distinct droplets. According to [21] the maximum pressure  $P_b$  develops if a bubble collapses in an incompressible flow, under isothermal conditions, resulting in equation (5):

$$P_b = \frac{P_s}{6,35} e^{\left(\frac{1}{\alpha}\right)} \quad (5)$$

where  $\alpha$  relates the gas pressure inside the bubble in the beginning of collapse under the pressure  $P_s$ . Therefore, the cavitating jet erosion efficiency  $R^*$  is related to  $P_b$  and  $P_a$  in Equation (6):

$$R^* = \frac{P_b}{P_a} \quad (6)$$

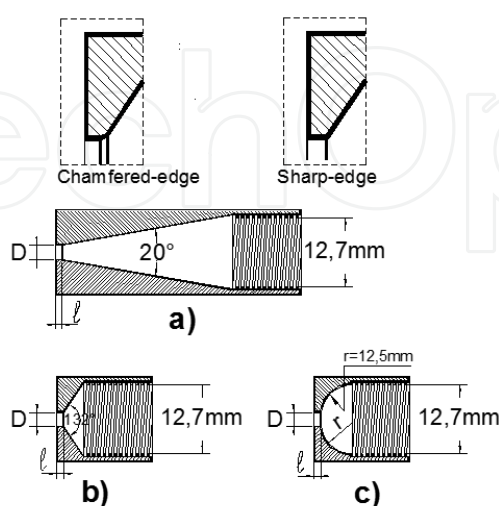
Equation (5), however, does not take into account the geometry and finishing of the nozzle. It was verified by [10] that the finish and the geometry of the nozzle influence the erosion performance of the equipment. The author accomplished a series of tests with a cavitating jet apparatus, verifying the influence of these two variables in aluminium and concrete samples. Therefore, in Equation (7) a geometric efficiency factor  $\eta$  was introduced in the cavitation erosion efficiency [7] to calculate the total efficiency  $\varepsilon$  :

$$\varepsilon = \eta R^* \quad (7)$$

### 2.3. Experimental setup

To simulate the cavitation phenomenon and to evaluate the erosion in samples, a cavitating jet apparatus was constructed [10] in the Laboratory of Hydraulics and Fluid Mechanics at the State University Campinas, Brazil. Figure 5 and 6 shows a schematic representation and a photo of the test facility. A high-pressure displacement pump (kept at pressure 12.00 MPa) conducts water to the facility and to the metallic chamber provided with two windows for visualization of the tests. A pressure-regulating valve guaranteed safe operation. At the end of the high-pressure pipe and inside of the inactivation chamber, the nozzle with a hole (diameter of  $2.00 \times 10^{-3}$  m) was positioned at the end of the high-pressure pipe.

The nozzle specifications must be established according to its use and they are determined experimentally. The researcher [10] used three nozzle geometries (20° conical, 132° conical and circular) with both shaped and rounded edges (Figure 4).

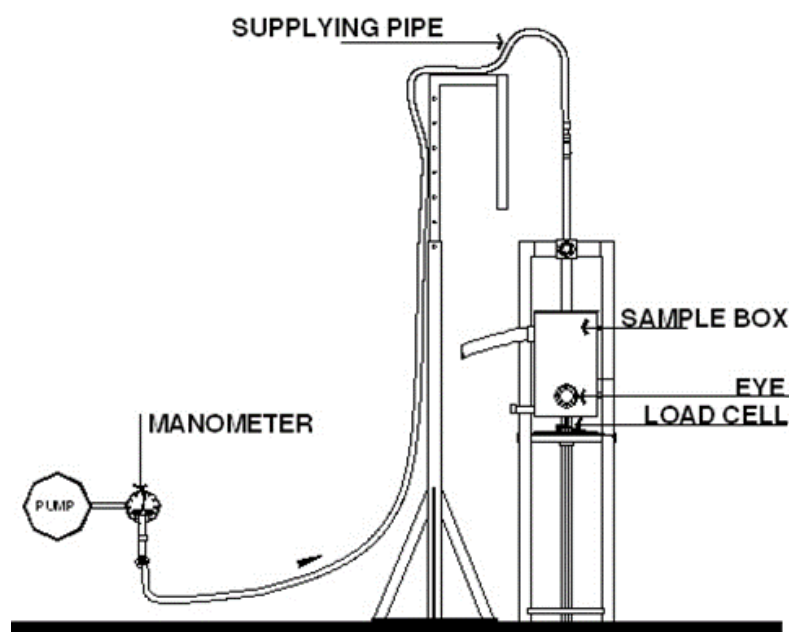


**Figure 4.** Nozzle geometries (a) conical 20°, (b) conical 132°, (c) circular [7].



The facility is supplied with no re-circulated water. The samples are placed in the chamber subjected to the cavitating jet, that is, the jet is impinging onto the sample surface. The chamber is filled with water in order to allow the occurrence of the bubbles implosion. The damaged area was measured, the pits number were counted and the samples were photographed every 60 seconds until 300 seconds of time test. Then, the test continued more 900 uninterrupted seconds, achieving a total test time of 1200 seconds.

Apparatus test parameters can be adjusted to obtain optimal efficiency. In this experiment, pressure and velocity of the system were adjusted to reach a cavitation index of 0.14, which is considered to cause damage in hydraulic structures [11]. The three different geometry nozzles were used to evaluate the efficiency of cavitating jets.



**Figure 5.** Schematic of experimental setup for erosion tests.

Concrete is a heterogeneous material, which poses difficulties to test and evaluate optimal conditions based on comparison test. Thus, aluminum samples were used to establish the nozzle efficiency because the metal is homogenous and allows a comparison among tests in order to evaluate the differing optimal erosion conditions, and damages. Cavitation erosion rates can be analyzed in terms of number of pits by time in order to obtain quantitative and qualitative information on the erosion intensity variation. A binocular magnifier 160x was used to count pits in the surface of the aluminum samples through the tests

First, the apparatus tests were run with the different nozzles presented in Figure 4. The typical value of  $\alpha=1/4$  used by [21] was adopted and maintained for comparison purposes. The sound velocity  $c$  in water at  $20^{\circ}\text{C}$  was assumed to be  $1482\text{ m/s}$  and water density as  $998.2\text{ kg/m}^3$ . Given the value of the jet velocity  $v_j$ , calculations were done for all the data and the efficiencies  $\eta$  were calculated. It was presented by [7] the efficiency results for the nozzles (Table1).





**Figure 6.** Photo of experimental setup in the Laboratory.

Nozzle	Sharp-edge ( $\epsilon$ )	Chamfered- edge ( $\epsilon$ )
132°Conical	0.43	0.17
Circular	0.33	0.12
20°Conical	0.16	0.12

**Table 1.** Total erosion efficiency ( $\epsilon$ ) [7]

According to Table 1, better results were observed for sharp-edged nozzles than for chamfered-edge ones. The best total efficiency was obtained for the 132° conical nozzle ( $\epsilon=0.43$ ). Also, the time intervals required to accomplish the same erosion rate were observed to be 300 seconds for 132° conical sharp-edged nozzle, and 1200 seconds for the chamfered-edge nozzle. Therefore, not only the entrance pressure, but also nozzle geometry and finish are important for optimizing the apparatus efficiency. The authors pointed out that obtuse-angle nozzles with sharp-edge are preferable to perform cavitation erosion tests.

Using cavitating jet apparatus ( $\sigma=0.14$ ) and the 132° conical sharp-edged nozzle, three special concrete samples were tested to obtain the cavitation erosion rate. The procedure of making samples begins by separating, cleaning and stocking the aggregates in the laboratory the day before. The next day, samples were molded in agreement with the Brazilian Standard NBR 5738. Table 2 presents samples compositions and compressive resistance obtained.

Sample	Cement and Aggregates (Relation)	Water and Cement (Relation)	Aggregate	Addition	Compressive Resistance (MPa)
A	1:4	0.3	Limestone	-	55.00
B	1:4	0.3	Granite	-	63.00
C	1:4	0.3	Granite	Silica *	83.00

\* 8% the mass of cement

Table 2. Characteristics of the concrete samples.

Figure 7 shows the erosion comparison between concrete samples in terms of volume erosion in time.

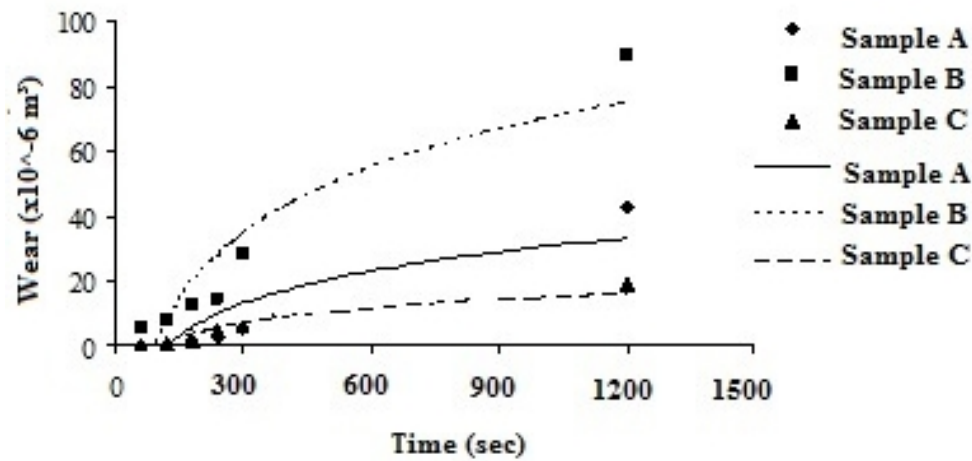
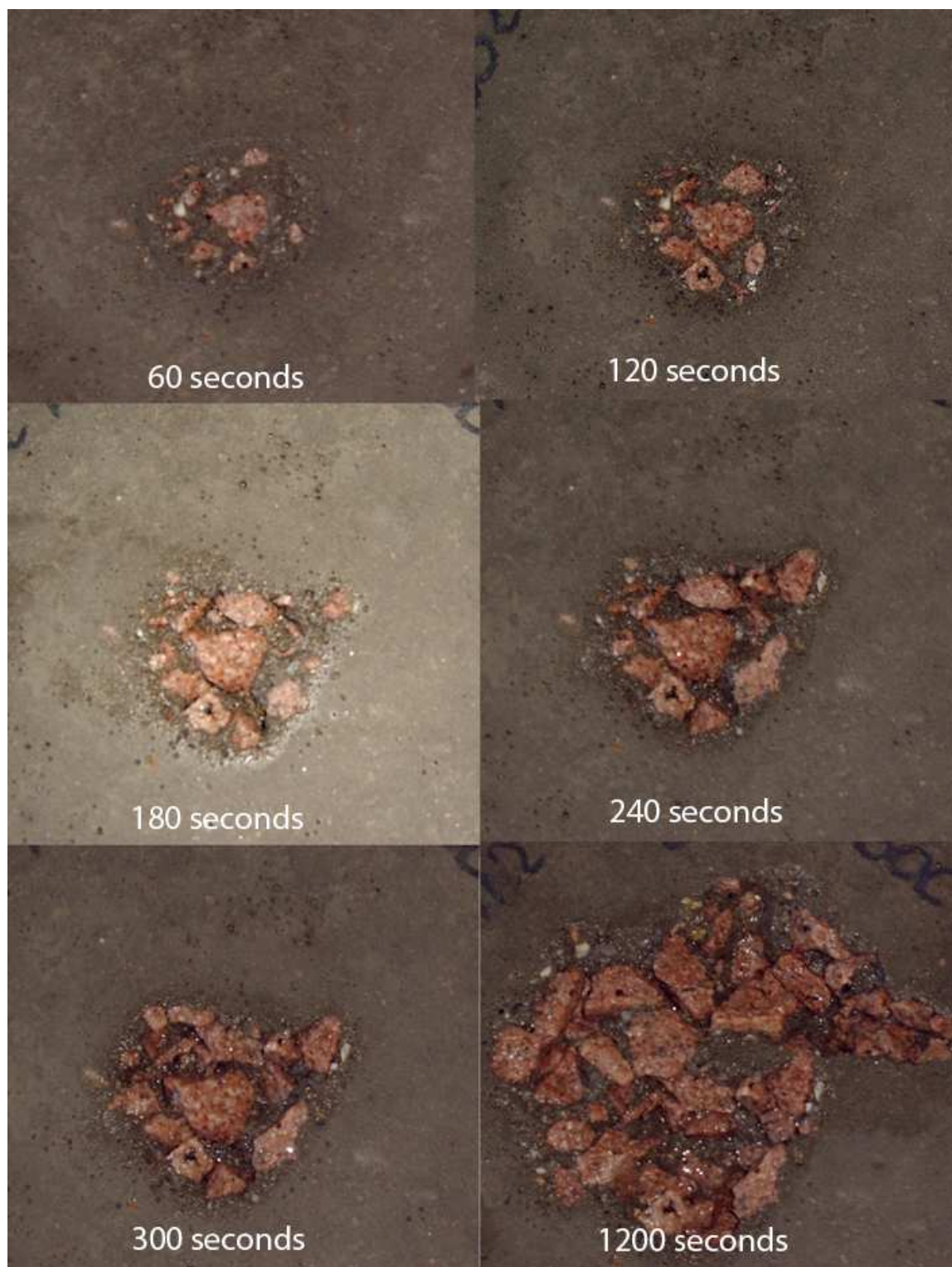
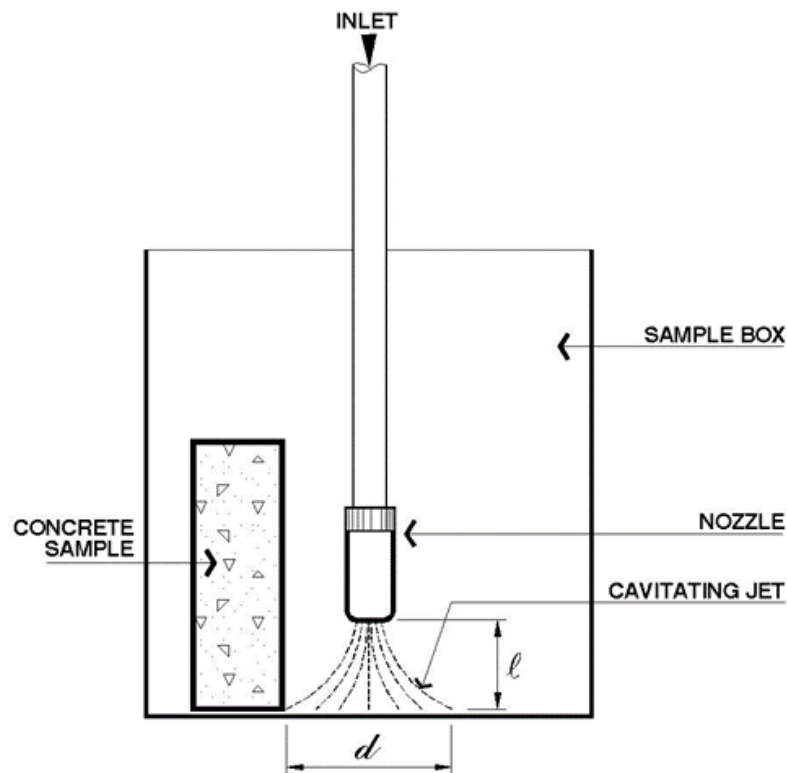


Figure 7. Concrete erosion over time.

The best results were obtained for sample C which contains hard aggregate, superior axial compressive resistance and the addition of silica. However sample A (fck 55.00 MPa) presented better results than sample B (fck 63.00 MPa), despite of the greater compressive resistance, showing that an adequate concrete (resistant to cavitation erosion) is a combination of several factors such as aggregate type, size and shape, additions to cement and water cement relation. Figure 8 shows the evolution of erosion in the B concrete sample. Additional tests were performed with unsubmerged and submerged samples, showing that the formation of a high-velocity cavitating jet provoked high erosion rates in the sample as expected, according [7]. In [24] the authors compared the erosion generated by the cavitating jet imping directly in to and parallel to a concrete sample. In this last case, the sample is not subjected to the effects of the impact force of the jet. Comparing the results, a higher erosion rate was observed when the samples are positioned directly over to the cavitating jet (Figure 9).



**Figure 8.** Erosion evolution of concrete sample B over time.



**Figure 9.** Concrete sample placed parallel to the cavitating jet [24].

Fast, efficient and economic testing is needed. The use of the cavitating jet allowed significant reduction in testing times, [10] specially when compared to the Venturi device. In [12] the author took 30 hours to compare the cavitating wear among concrete samples. As concrete is a heterogeneous material, samples are necessary to be larger than a few millimeters, as used by [25] to test metal samples. [10] used samples 20 cm in diameter and 5 cm in height to test concrete samples. The cavitating jet apparatus used in this experiment is compact, low cost and has short test times. It can also be used to measure erosion for testing concrete use in hydraulic structures. The cavitating jet apparatus creates a force larger than the one generated by a simple jet of high pressure, and thus can simulate the combined effect of high-speed flows and cavitation normally experienced in hydraulic structures

### 3. Use of the cavitating jet to inactivate bacteria and to decompose persistent compounds in water

#### 3.1. Introduction

Water quality has deteriorated over the years due to industrial and agricultural pollution as well as an increase in the domestic sewage generated by a rapidly growing population. Pathogenic microorganisms in water pose a serious health and security threat to drinking water supply systems. The quality of water for human consumption can be improved by



controlling pollution and by increasing the efficiency of inactivation techniques, which involves the destruction of pathogens present in water at a reasonable cost.

The use of chemicals, such as chlorine gas, sodium hypochlorite, calcium hypochlorite, hydrated ammonia, ammonium hydroxide, ammonium sulphate, and ozone, is common during the water disinfection process in conventional water treatment systems [26]. Many problems arise when using chemical methods for disinfection, including the high maintenance demands of the associated facilities (corrosion, incrustation), the formation of toxic byproducts (chlorine addition may generate byproducts such as trihalomethanes) and environmental concerns (chemical effluents released into rivers compromise aquatic life) [27]. Therefore, the development of alternative techniques for inactivating pathogens in water is desirable. Inactivation based on the cavitation phenomenon appears to be a promising alternative or supplement to existing techniques [28].

Research using the phenomenon of cavitation to inactivate microorganisms has been performed in the United States, Russia, India, China, Japan, UK, South Africa, France, Mexico, among others, using different methods. The hydrodynamic cavitation method is the most studied and disseminated. This is because the best results are achieved. However, there is currently no standardized method to carry out inactivation with this technique with respect to the pressures and speeds testing.

The performance shown by the studies on the wear of concrete indicated that the cavitating jet apparatus could be adapted to test the inactivation of microorganisms and the decomposition of persistent compounds in water. However, tests are necessary to establish appropriate pressures and velocities for each study. The inactivation of microorganisms was performed with *Escherichia coli* that are microorganisms commonly found in the intestines of humans and other warm-blooded animals and indicate the presence of water contamination. The decomposition of persistent compounds was performed with methylene blue.

### 3.2. Experimental tests for inactivation and chemical decomposition

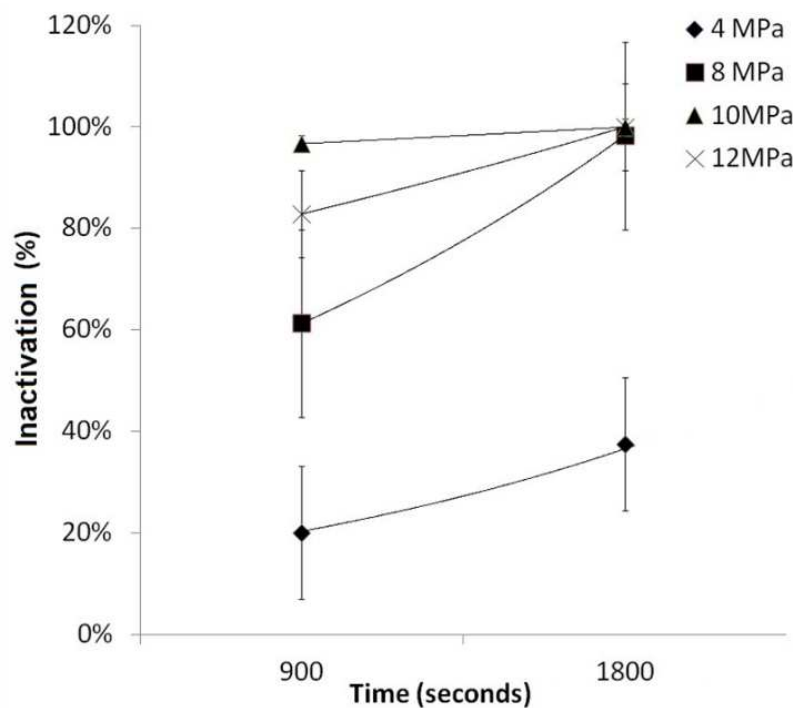
As illustrated in Figure 2 the cavitating jet apparatus with 132° conical nozzle was adapted to conduct the experiments to inactivate *Escherichia coli* and to decompose the persistent methylene blue compound. The chamber used was  $700.00 \times 10^{-3}$  m high with a diameter of  $300.00 \times 10^{-3}$  m. Part of the container was filled with  $40.00 \times 10^{-3}$  m<sup>3</sup> of contaminated water to be studied in a closed circuit. A low-cost refrigeration system was adapted to the apparatus. A  $12.70 \times 10^{-3}$  m diameter and  $19,500.00 \times 10^{-3}$  m long copper coil was placed inside of the inactivation chamber. This coil was connected to a reservoir with a capacity of  $750.00 \times 10^{-3}$  m<sup>3</sup> that was filled with clean water. The temperature of the tests was held constant at 33 °C, thus assuring that the inactivation was exclusively due to the cavitation phenomenon instead of an increase in the water temperature.

All of the microbiological, physical, and chemical procedures of this study follow the procedures described in the Standard Methods for Examination of Water and Wastewater Manual [19,20]. Non-pathogenic *Escherichia coli* (ATCC 25922) were used for the microbiological tests.

Viable cell counting was performed using the Colilert Method®. The presented results of the microbiological tests are the average of the results obtained in the dilutions.

The high-pressure displacement pump recirculated the water to be treated and was kept at a pressure of 4.00, 8.00, 10.00 and 12.00 MPa. First, the inactivation device was turned on without pressure to circulate the residue being treated. Samples were then collected at the initial time (T0) to obtain a control sample. Next, a vial of the sample was removed to measure the number of viable *Escherichia coli* cells. In addition to the control time point (T0), samples were collected every 900 seconds. All of the tests were repeated in triplicate, however, the results represent an average of the individual results.

Figure 10 shows that the higher the pressure, the higher the inactivation. At time test 1800 seconds, the following inactivation rates are observed: less than 37.50% for pressure test 4.00 MPa, 98.30% for test pressure 8.00 MPa, 99.96% for pressure test 10.00 MPa, and 100% for pressure 12.00 MPa,. Although the inactivation percentages are close to pressures 8.00, 10.00 and 12.00 MPa, the highest inactivation rate was achieved for test pressure 12.00 MPa.



**Figure 10.** Inactivation rate and pressure.

However, the optimum inactivation rate will be achieved by relating the inactivation rate to the energy consumption. The Energy Efficiency (*EE*) of the apparatus is calculated with Equation 8 and the experiment results are shown in Table 3.

$$EE = \frac{C_i - C_f \cdot V}{P \cdot T} \quad (8)$$

being:

Cf: Final Concentration of *Escherichia coli* (CFU/mL);

Ci: Initial Concentration of *Escherichia coli* (CFU/mL);

V: Volume (mL);

P: Power (W);

T: Time (seconds).

Parameters	Test pressures			
	4.00 MPa	8.00 MPa	10.00 MPa	12.00 MPa
t (s)		1800.00	1800.00	1800.00
V (mL)		40000.00	40000.00	40000.00
i (A)		25.00	29.00	31.00
U (V)		220.00	220.00	220.00
P (W)		5500.00	6380.00	6820.00
Ci (CFU/mL)		918425.00	141360.00	800013.00
Cf (CFU /mL)		574000.00	2410.00	337.00
Ci-Cf (CFU /mL)		344425.00	138950.00	799676.00
(Ci-Cf)/P(CFU /mL)/(W)		62.62	21.78	117.25
€€ (CFU /J)		1391.62	483.98	2605.66

**Table 3.** Energy Efficiency to inactivate *Escherichia Coli* at different pressure.

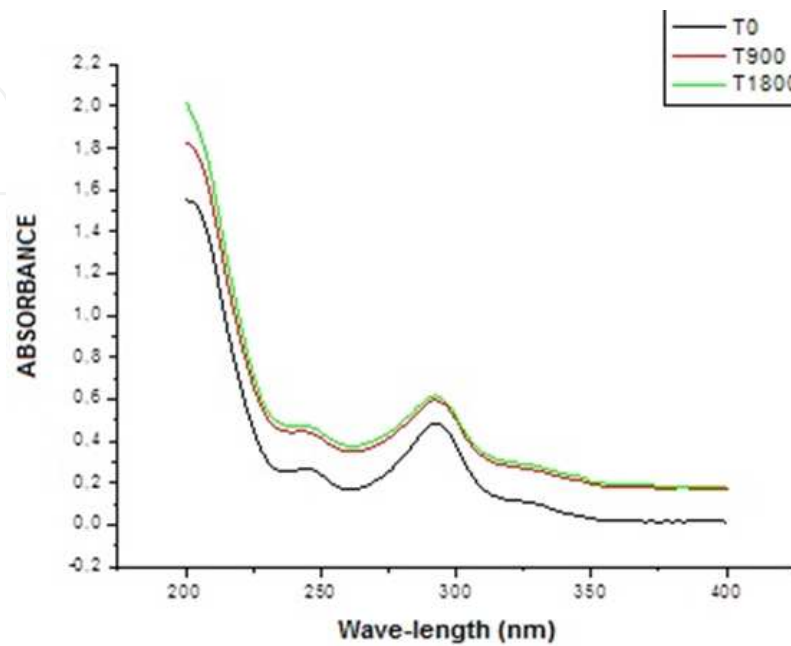
In order to compare the tests, a time test of 1800 seconds was standardized. Table 3 indicates that for the conical 132° nozzle, the most efficient operation pressure is 10.00 MPa, followed by pressure 4.00, 12.00 and 8.00 MPa.

A complementary study was conducted with natural waters retrieved from a lake at the University’s campus [28]. Given past studies by [29,30], high efficiency for the first 900 seconds of the test with an inactivation rate of 90% was obtained.

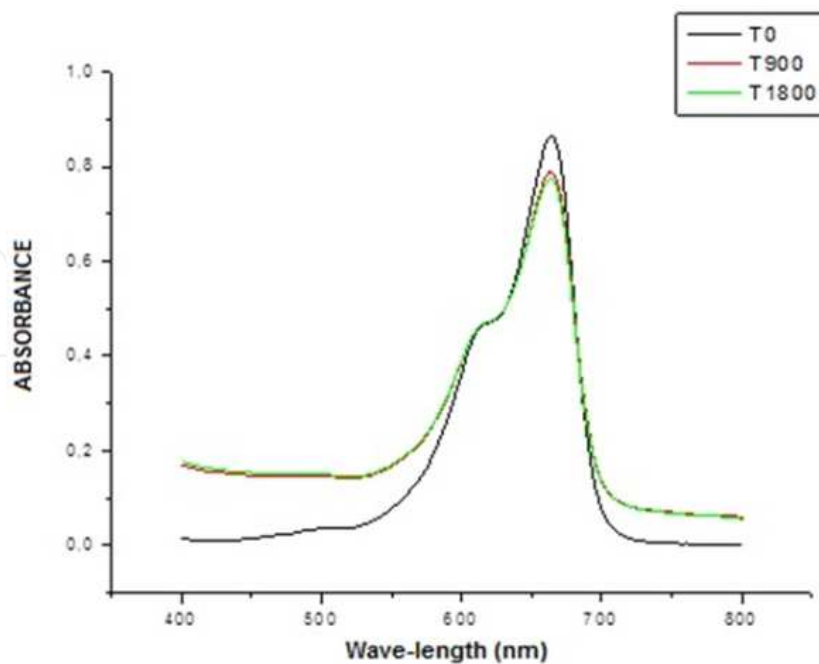
The substance methylene blue was used for testing degradation of persistent compounds. The results for each time and pressure test were analyzed using the spectrophotometer (Hach DR / 4000U Spectrophotometer) scan from 800 nm to 200 nm. To analyze the degradation of persistent compounds it is necessary to observe the decrease in absorbance at a given wavelength band over time. The absorbance is proportional to the concentration of the substance based on the law of Lambert-Bee. Changes in the molecule of methylene blue are then analyzed for two wavelength bands: the ranges from 200nm to 400nm, ultraviolet (UV), and the range from 400nm to 800nm, visible to the human eye.



The result of the degradation is shown in Figures 11 and 12 at a pressure of 12.00 MPa and time 1800 seconds. Figure 11 shows no significant reduction in absorbance. Figure 12 indicates a reduction of 10.5% in the final absorbance at the peak wavelength range of 664nm.



**Figure 11.** Decomposition of methylene blue, pressure 12 MPa, UV wavelength.



**Figure 12.** Decomposition of methylene blue, pressure 12 MPa, visible wavelength.

Comparing the results of Figures 11 and 12, the greatest difference in absorbance occurs in the visible band. Pressures lower than 12.00 MPa did not show any significant decrease in the absorbance. At the end of the tests, the residue was placed in translucent plastic bottles and exposed to sunlight. It was observed that the methylene blue dye was then degraded only by the peroxidation generated by the cavitation treatment.

The synergy between the cavitation process and the oxidative processes is a current and relevant research [31-33]. Recent work by [34-36] has been focusing on the degradation of persistent pollutants, such as pharmaceuticals, dyes, industrial effluents, pesticides, in addition to research with microorganisms.

#### 4. Final remarks

Cavitation is known for its undesired effects produced in hydraulic systems, namely, the noise, vibrations, pressure fluctuations, erosion and efficiency loss. In hydraulic structures, cavitation can be destructive. Many times, the materials to do repairs in the structure are used without the necessary laboratory tests. These tests can be onerous, showing the importance of previous studies to check the applicability, either for the project phase or for repairs.

Despite the undesirable effects of cavitation, this phenomenon showed to be an interesting alternative to inactivate bacteria in water. The use of chemicals, such as chlorine, is commonly used for water disinfection in conventional water treatment systems. Cavitation can be used as a “clean” treatment, as it can reduce the quantity of chemicals added to water in the conventional water treatments.

The cavitating jet equipment simulates cavitation and its efficiency can be improved by using different nozzle configuration that forms the cavitating jet. This work showed that the most efficient nozzle geometry was obtained using a sharp-edge 132° conical nozzle for different applications, erosion tests, bacteria inactivation and decomposition of compounds.

The cavitating jet apparatus proved to be efficient, low cost, low power consumption when used to test material erosion and to inactivate *Escherichia coli*. Furthermore, it can be adapted to operate at larger scale treatments.

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