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DEVELOPMENT OF A PROTOTYPE EQUIPMENT FOR CAVITATION TESTING

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Abstract. *The purpose of this work was to construct a prototype for cavitation test and use it to analyses the damage created by the cavitation phenomenon on a test piece. Throughout this work, a prototype was proposed, assembled and adjusted in order to allow evaluate the effects of cavitation in hydraulic (water) medium. This prototype was used to test small samples of engineering materials, focusing on metals, and to obtain parameters for the construction of the final test equipment. Comparing the results before and after the cavitation tests, became possible a discussion and quantification of cavitation impact on the material integrity as well its performance on usage.*

Keywords: *Cavitation erosion, Hydraulic machines, Materials performance*

1. INTRODUCTION

Cavitation is a hydraulic phenomenon associated with the formation and collapse of vapor bubbles in a liquid, as illustrated by Fig. 1. According Macintyre (2008), high values of pressures are reached on the surfaces or by the action of the percussion of the condensed particles or by the shock waves caused by the self-collapse of the bubbles.

Although, it is not intense enough to produce immediate rupture, cavitation produces erosion of internal parts of hydraulic systems, such as pumps impellers, that may lead to failure. Santos (2007) highlights that cavitation is a recurrent concern in the area of hydraulic machines, and can occur in the entrance of centrifugal pumps, in the output of the rotors of hydraulic turbines and other situations involving fluid handling in confined spaces.

Therefore, there are a great importance, for Engineers and Operators, to obtain precise information about the effects of cavitation on materials, so that its effect be properly considered in practice, especially during the design and operation phases of hydraulic equipment. Thus, in that scenario, the objective of this work is to construct a prototype of a cavitation test module to analyze the wear and pittings caused by the phenomenon in a test piece installed inside a hydraulic pipe. After the module is operated in a certain time, the test body can be collected for analyzes, such as metallography, roughness and tensile tests, allowing the discussion of the results.

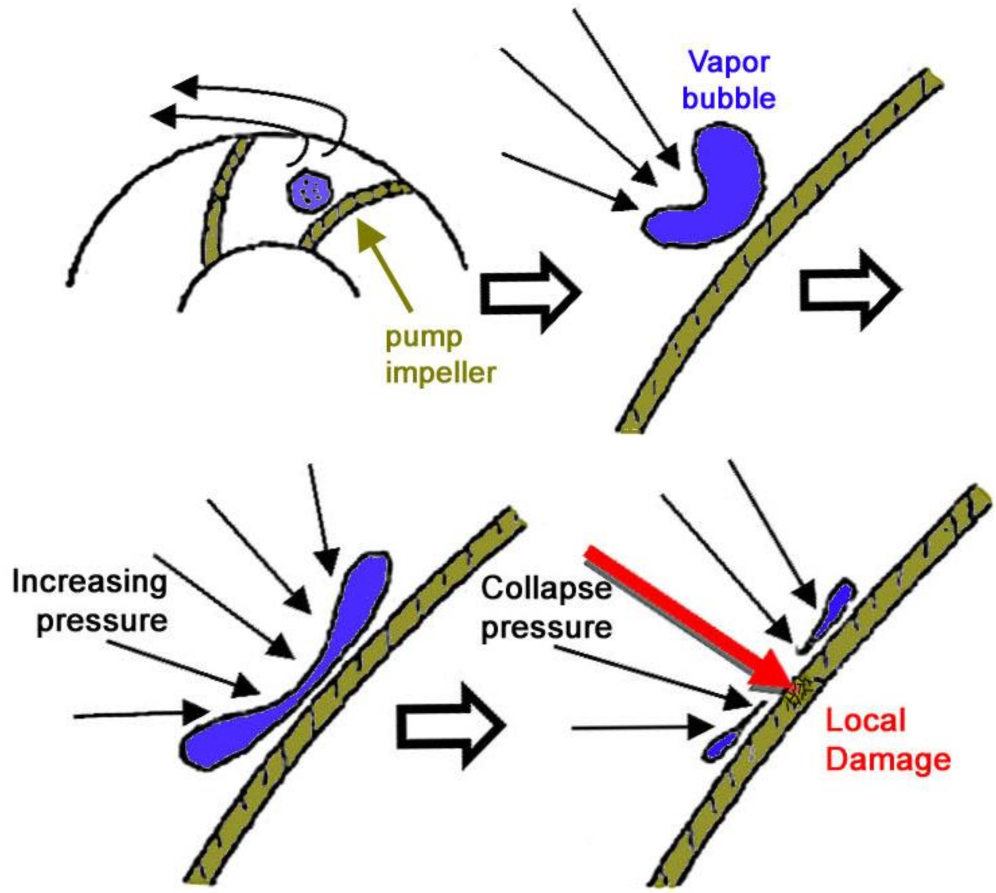

Figure 1. From left to right and from up to down: sequence of damage formation by cavitation on impeller surface. Adapted from Santos (2007).

2. BIBLIOGRAPHIC REVIEW

Brunetti (2008), defines that if the pressure of a stream equals or falls below the vapor pressure of the liquid at the flow temperature, there will be formation of vapor and this phenomenon of formation of steam in tubing or hydraulic machines is called cavitation. Cavitation becomes acting and damaging when vapor bubbles, as showed in Figure 1, reach higher pressure points, abruptly condensing and imploding with great energy release. This collapse with the respective release of energy can cause vibrations and a particular type of erosion due to the agitation and shocks of the particles of the liquid on the solid walls generation local damage, as illustrated by the last part of Figure 1.

Santos (2007) considers cavitation as the vaporization of the fluid that happens when the pressure of a flow decreases, for any reason, and reaches the vapor pressure corresponding to its temperature. Many interpret the consequences of cavitation as a severe erosion of the internal parts of the pump.

The vaporization of the fluid can be aborted by the concept of vapor pressure. The fluid vaporizes when the pressure of a flow decreases, for any reason, and reaches the vapor pressure, corresponding to its temperature. The Eq. (1), shown by Brunetti (2008), describes the necessary condition to occur the phenomenon of cavitation:

$$P_e \leq P_v \qquad (1)$$

Where: P_e - Pump Inlet (admission) Pressure; P_v - Vapor pressure of the fluid.

Figure 2 shows an abacus relating pressure and velocity with temperature change for better understanding the conditions for cavitation occurrence. Table 1 shows the variation of Vapor pressure (P_v) of water with temperature.

Table 1. Variation of P_v as a function of temperature for Water (Brunetti, 2008).

T [°C]	0	10	20	30	50	100
P_v [10^3 Pa]	0,617	1,225	2,313	4,204	12,25	101,2

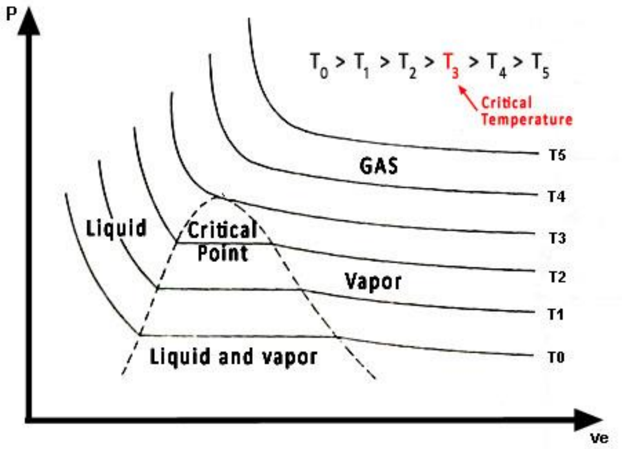

Figure 2. Conditions for Variation on temperature (T), pressure (P), and velocity (v_e)
for vapor formation inside a liquid (Mattos and Falco, 1998).

If the absolute pressure of the liquid, at any point in the pumping system, is less than or equal to its vapor pressure (Eq. 1), at the pumping temperature, part of this liquid will vaporize (Liquid and vapor region on Fig. 2), forming cavities within the liquid mass. The cavitation process will begin there (Fig. 1) damaging mainly the impeller surfaces.

2.1 Symptoms of cavitation

The characteristic symptoms of cavitation are all due to the collapse of bubbles generated from vaporized fluid inside the pump (Fig. 1), according conditions exemplified by Fig. 2

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- the first symptom is the characteristic noise: cavitation produces a noise similar to the passage of sand grains or stones by the pump. The noise level is lower or higher according to a more or less severe cavitation, respectively. It is the main symptom;
- the second symptom is the characteristic vibration: bubble collapse produces so-called random excitations which are characterized by exciting the natural frequencies of the pump support structure;
- the third symptom is the drop in efficiency of pump system (η), and change in its characteristic curve: performance reduction can be attributed to the specific volume difference between the liquid and the vapor, as shown in Fig. 3, which gives as an example the case of a centrifugal pump in the state of cavitation;
- the fourth symptom is the need to increase the pump shaft power to compensate its great loss of performance due to cavitation.

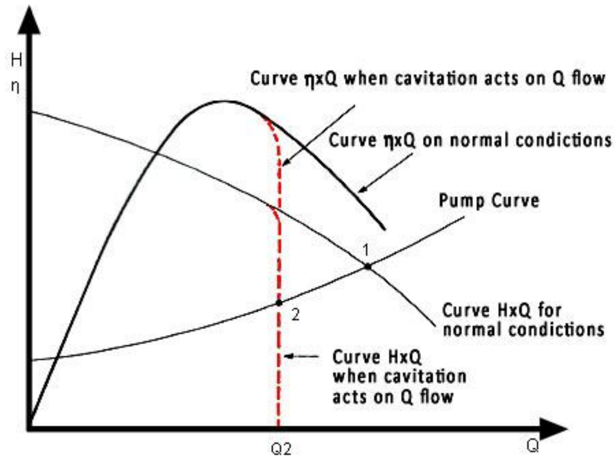

Figure 3. Normal characteristic curve (manometric height and efficiency versus flow, H and $\eta\times$Q)
and its alteration by cavitation as shown by dashed lines (Mattos and Falco, 1998).

2.2 Consequences of cavitation

The effects of cavitation are visible in the long- and short-term, both of which are measurable.

- In the short term, the cavitation phenomenon compromises the performance of pumps, with a drop in pump efficiency, a not characteristic vibration of the considered pump and noises, caused by the "implosion" of the liquid (Fig. 1).
- In long term, the mobile parts of a hydraulic system, typically the rotors, present considerable losses of mass, compromising the performance of complete system, mainly the pump that be able to be lead to its rupture.

Cavitation occurs in addition to the rotor. It can be manifested at the pump inlet, in the suction line, in the volute and in the directional blades of the diffuser. Continuous operation of a pump in the cavitation condition result in serious damage or even destruction of its components due to formation and collapse of vapor bubbles on its internal surfaces. The shock of the bubbles and its collapse (Figure 1) disintegrate the materials surface localized, forming holes that with the continuity of the phenomenon will evolve into an aspect of severe erosion. This type of wear can progress until the disintegration of pieces of the impeller, as shown in Fig. 4.

Figure 4. Damaged aspect of a pump impeller after use under severe cavitation conditions (Pricast, 2009).

Bearing damage will also occur: high frequency vibrations caused by cavitation, if they persist, for a long period, will produce shocks resulting from the collapse of the bubbles in the pump bearing that will produce high point loads that will lead the bearings to premature wear. Over time, the bearings can also suffer severe damages such as pittings (small cavities), plucking of materials, etc.

In addition, on mechanical seals: the strong instability generated by bubble collapse and the resulting vibrations will produce impacts between the stationary and rotating faces of the mechanical seal. Due to the required hardness characteristics, these faces tend to be fragile, not resisting impact forces that cause them to break and, consequently, to leak the mechanical seals.

2.3 Practical conditions for cavitation occurrence

According to Mattos, Falco (1998), modifying some variables can completely change the occurrence of cavitation and its effect consequently. Therefore, it is important to analyze the influence of the following factors:

- Static suction height;
- Altitude at installation site;
- Liquid pumping temperature;
- Type of pumped liquid;
- Flow rate;
- Pressure in the suction vessel;
- Length of the suction pipe;
- Roughness of the pipe walls and load losses locally induced by parts inserted in the installation.

The presence of cavitation is avoided through the proper design of the suction line minimizing the appearance of low pressures. The geometric suction or suction height of a pump is defined as the vertical distance from the center of the pump axis and the level of the liquid in the suction vessel. Typically, in drowned pumps, i.e. where suction height is located above the pump axis, cavitation is practically eliminated. The suction line of a pump is where the pressures are generally low. Therefore, it is exactly in the suction or suction line that care must be taken that during pumping of liquids, the pressure does not reach the vaporization pressure at the temperature the liquid is in.

3. MATERIALS AND METHODS

To development this work it were used: bibliographical research based on books of centrifugal pumps, hydraulic facilities, industrial hydraulics; analysis of scientific articles; use of the on former standard ABNT NBR 6400 MB 1032: 1989; and consultations with hydraulic and mechanical practical assembly specialists.

The standard ABNT NBR 6400 MB 1032: 1989 prescribes performance and cavitation testing methods for hydraulic pumps (centrifugal, axial and mixed), being that its test method are valid for a Venturi tube, whose construction is specified by this standard. But, the internal part of the Venturi tube, in which the fluid is under cavitation conditions, can be used to expose specimens for analysis of resistance to cavitation.

Thus, based on the ABNT NBR 6400 MB 1032: 1989 and on the use of the inner part of the Venturi tube, a prototype was designed, whose diagram is showed in Fig. 5.

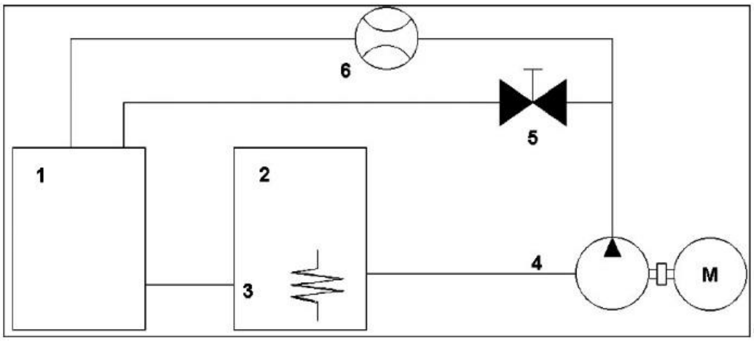

Figure 5. Prototype schematic drawing. (1) discharge tank; (2) suction tank; (3) electrical resistance; (4) centrifugal pump; (5) flow control valve; (6) Venturi tube.

Additionally, in Fig. 6 is showed a photograph of the prototype assembled as projected in design phase of this work

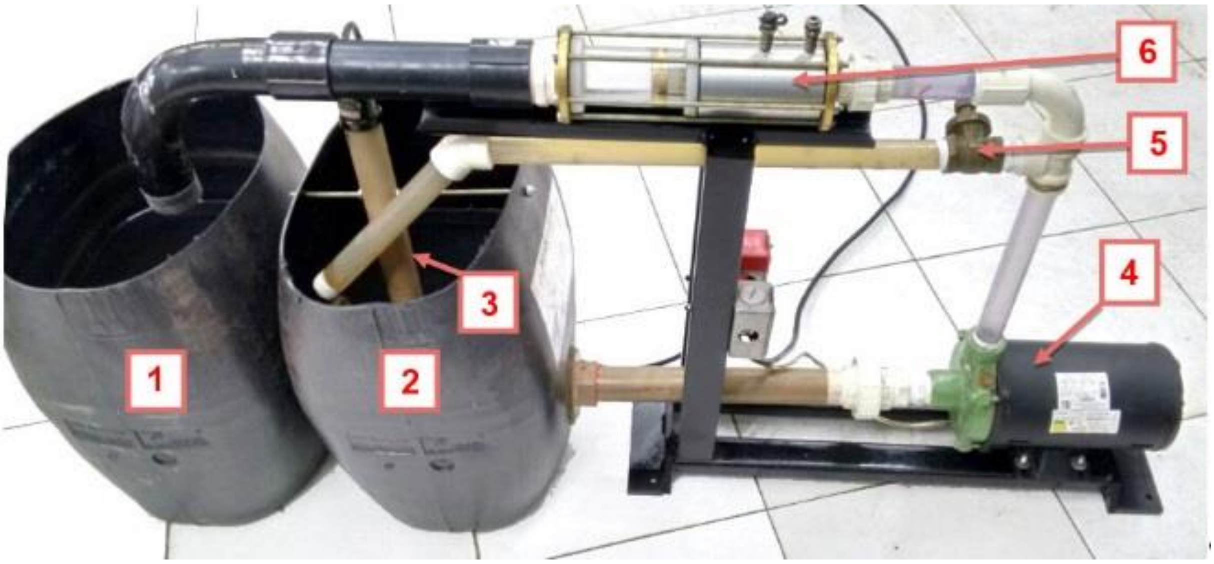

Figure 6. Prototype assembled. (1) discharge tank; (2) suction tank; (3) electrical resistance; (4) centrifugal pump; (5) flow control valve; (6) Venturi tube.

In the equipment, cavitation is induced by the combination of a Venturi tube, which varies pressure and speed, with an electric resistance, which heats the fluid. These two accessories combined becomes possible to induce a suitable combination of temperature and pressure that leads to generate bubbles. These bubbles will be collapsed against the surface of the test sample, positioned in a transparent chamber at the exit of the Venturi tube, as showed by Fig. 7(4).

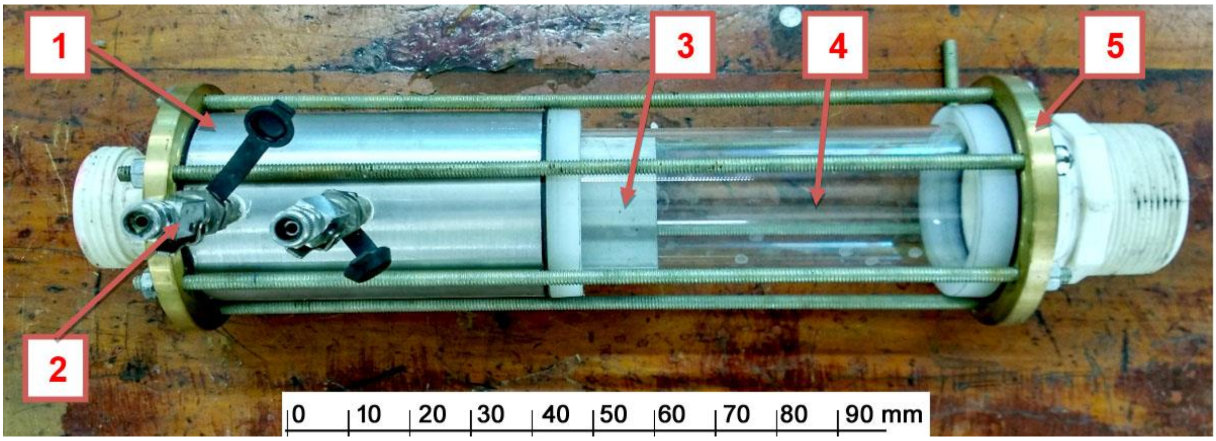

Figure 7. Test chamber of the prototype: (1) aluminum Venturi tube; (2) pressure outlet; (3) sample position; (4) acrylic tube; (5) brass gasket.

3.1 Venture tube calculations

The calculations for the construction of the Venture tube was made according to the characteristics of the pump and the fluid (water) used in the equipment. The centrifugal pump chosen presents the following features: flow rate of 7.6 m³/h, maximum pressure of 2.35 MPa (2.4 kgf/cm²) and a 0.0254 m (1-inch) diameter outlet.

Thus, considering the following data:

- Requested temperature, T = 40 °C;
- Vapor pressure at 40 °C, P_v = 7,383.6 Pa (752,92 kgf/m²);
- Venture input pressure, P_{1p} = 235,359.6 Pa (24000 kgf/m²);
- Input (point 1) diameter, D_1 = 1" = 0,0254 m;
- Design flow (Pump), Q_p = 7,6 m³/h = 0,00211 m³/s.

Applying relevant design equations, as described by Macintyre (2008), Santos (2007) and ABNT NBR 6400 MB 1032: 1989, it is possible to calculate the fluid velocity at the Venturi inlet:

$$v_1 = \frac{4Q_p}{\pi \cdot (D_1)^2} = \frac{4 \cdot 0.00211}{\pi \cdot 0.0254^2} = 4.16\, {}^{m}\!/_{s} \tag{2}$$

With the input velocity, Bernoulli equation, for perfect steady state fluids, was used to find the velocity in the Venturi throat.

$$\frac{P_1}{\gamma} + \frac{(v_1)^2}{2 \cdot g} + Z_1 = \frac{P_2}{\gamma} + \frac{(v_2)^2}{2 \cdot g} + Z_2 \tag{3}$$

Where: P_1 - Liquid pressure at point 1 = 235,360 N/m²; P_2 - Liquid pressure at point 2 = 7,383.6 N/m²; v_1 - Speed at point 1 = 4.16 m/s (Found by Eq. 2); v_2 - Speed at point 2 (to be found), m/s; Z_1 - Height of the liquid column at point 1, m; Z_2 - Height of the liquid column at point 2, m; γ - Specific weight of the fluid = 10,000 N/m³; g - Acceleration of gravity = 9,81 m/s².

Since the dimensions are in the same plane, then Z_1 cancels Z_2, thus:

$$v_2 = \sqrt{\left\{\left(\frac{P_1}{\gamma}\right) + \left[\frac{(v_1)^2}{2 \cdot g}\right] - \left(\frac{P_2}{\gamma}\right)\right\} \times (2 \cdot g)} \tag{4}$$

$$v_2 = \sqrt{\left\{\left(\frac{235{,}360}{10{,}000}\right) + \left[\frac{(4.16)^2}{2 \cdot 9.81}\right] - \left(\frac{7{,}386.14}{10{,}000}\right)\right\} \times (2 \cdot 9.81)} = 21.55 \, \text{m/s} \tag{5}$$

As the Venturi throat velocity (v_2 = 21.55 m/s) was calculated, and with the pump flow (Q_p = 0.00211 m³/s), the throat diameter (D_2) was calculated as follows:

$$D_2 = \sqrt{\frac{4 \cdot Q_p}{\pi \cdot v_2}} \tag{6}$$

$$D_2 = \sqrt{\frac{4 \cdot 0.00211}{\pi \cdot 21.55}} = 0.0112 \, \text{m} \tag{7}$$

With these data it was consulted ABNT NBR ISO 5167-1 to obtain the complete dimensioning of the Venturi tube:

- the angle used at the Venturi entrance is 21°;
- the exit angle is 7 ° to 15 °, it was adopted 9°;
- the straight section of entry the length is equal to 1D;
- the length of the neck is equal to 1D, too.

The Venturi outlet diameter (D_3) will be equal to the inlet diameter (D_1). Finally, the pressure taps points are also defined in the Standard:

- the hole should be made in the middle of both the straight section of the inlet and the throat;
- the diameter of the tapping line should be 0.01D with a length of 2.5D from the hole (tap).

Table 2 shows the measures of the Venturi Tube, obtained with all the data analyzed and obtained.

Table 2. Dimensions calculated and used for the Venturi Tube used in this work (see Fig. 7).

Diameter (mm)			Angle	
Input (inlet)	Throat	Output (outfall)	Convergent	Divergent
29	10	28	21°	9°

For manufacture the Venture tube, was used a "Romi Imor – 3" lathe machine from the Mechanical Workshop at UNISANTA, that machine an aluminum billet to the calculated Venturi Tube dimensions and geometry. Figure 8 shows the final design of the Venturi Tube adopted for the test equipment.

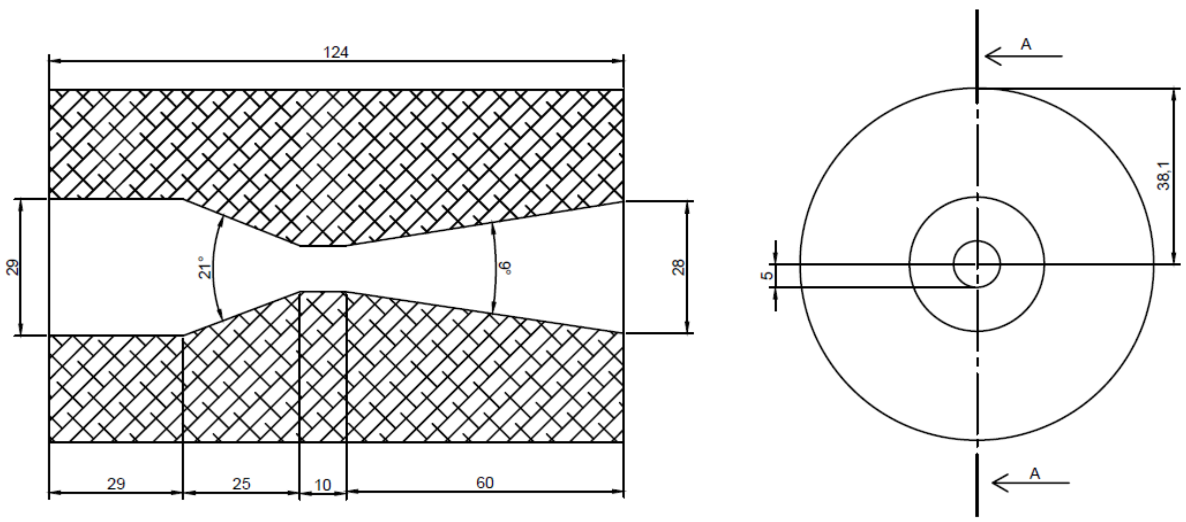

Figure 8. Drawing of the machined Venturi Tube adopted in the test equipment developed (all dimensions are in mm).

4. RESULTS AND DISCUSSION

Table 3 shows the materials and their initial conditions as well some test conditions and results. Figure 9 illustrates one of the points of a test piece with wear in a circular area with no sign of corrosion. This image shows a typical surface formed by the erosion caused by the vapor bubble collapse during cavitation test with the prototype.

Table 3. Sample and test conditions and some results.

Bronze (initial thickness 1.96 mm)			0 to 9h	9 to 15 h	Final results
Chemical composition (wt%)	Brinell Hardness	Roughness (two sides)	Total flow	Reduced flow	Roughness (two sides)
70%Cu; 20%Pb; 9%Zn; 4%Sn	76HB	1.51±0,5 μm 0.50±0,1 μm	Without loss of mass	0,0097% loss of mass	2.09±1,0 μm 0.65±0,2 μm

Figure 9. Cavitation damage after test registered on a sample surface. Optical magnification: 50X.

According Tab. 2 data, the prototype successfully induced a quantifiable damage by cavitation on the sample surface. This can be reinforced by a quantifiable loss of mass obtained when the sample was submitted to 9 hours of cavitation test. In addition, it is noted that the roughness measurements were well sensitive to cavitation actuation, becoming an important parameter to quantify the cavitation test. Microscopically examination can be used to describe better the type of macro damage on sample surface, as exemplified by Fig. 4.

5. CONCLUSIONS

The prototype equipment presented in this paper permits to test a sample under different cavitation conditions. These conditions can be obtained, in the equipment, varying the pressure, by its flow control valve, and the temperature, by its electrical resistance. The sample is positioned inside a tube of transparent acrylic, that was chosen in order to permit visualize the evolution of damage by cavitation on the sample surface, without stopping the test.

A definitive equipment will be built based on the prototype studied and on its operational results obtained. The prototype version showed the potential of such equipment to help carry out important researches on quantification of cavitation resistance, combining different materials and cavitation conditions.

6. ACKNOWLEDGEMENTS

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