CAVITATION EROSION TESTS IN CENTRIFUGAL PUMPS

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Abstract. *The prediction and monitoring of cavitation erosion in hydraulic machines has been a challenging task for engineers, technicians, and machine designers working in industrial processes. Characterization of the cavitation effects on solid surfaces has generally been achieved through testing performed on standard specimens in cavitation test chambers and rotating disk devices. However, experimental cavitation tests performed on prototypes of industrial machines are very rare. This work deals with an experimental study of the cavitation erosion on commercial centrifugal pump brass impellers operating under stringent conditions. An experimental setup, which is based on a 15 hp hydraulic pump running at 3520 rpm, is specially devised for this work. The pump inlet and outlet pressures, the pump flow rate and the acoustic emission signal from the pump case are monitored by using transducers properly installed on the experimental setup. The acoustic emission signal shows clearly the occurrence of cavitation in the pump regime analyzed. The mass loss in the process is monitored periodically during the tests. Images of the impeller surface, before and after the cavitation erosion tests, are generated by using a scanning electron microscope. The experimental results show that the mass loss rate experienced by the brass impeller prototype is larger than the rate obtained through cavitation traditional tests in brass specimens.*

Keywords*: Centrifugal pumps, cavitation erosion, acoustic emission*

1. INTRODUCTION

Knapp *et al.* (1970) define "cavitation as the condition when a liquid reaches a state at which vapour cavities are formed and grow due to dynamic-pressure reductions to the vapour pressure of the liquid at constant temperature". Many research works have been done on the description of the fluid dynamic problem associated with cavitation, however a thorough understanding of the mechanisms of cavitation erosion is still a technical challenge for the scientific community (Liu and Chen, 2010). Basically, the erosion associated with cavitation is explained by the action of fluid micro-jets, which are generated by abrupt periodical pressure variations, provoking micro pits on the material surface (Coelho (2006) and Miranda (2007)). In metallic materials, the fluid cavity collapse close to the material surface can cause erosion due to the local plastic deformation (Kristensen et al. (1978)). In hydraulic pumps, the bubble collapse can generate several micro pits on the pump impeller, spiral case, and inlet pipes. In pumping systems, the cavitation occurs mainly in the pump suction pipeline, where the pressure reaches values below the liquid saturation pressure.

The determination of the cavitation onset levels for machines and equipments, such pumps , turbines, valves, and pipes, at different flow regimes can only be performed through experiments. There are also technical difficulties to establish a good correlation between the cavitation erosion tests carried out on standard specimens and the surface erosion of full scale systems and prototypes (Avellan, 2004). Furthermore, a relationship between the bubble formation frequency and the mass loss associated with cavitation erosion is still a technical challenge for researchers working on this subject. Ball *et al.* (1975) present a classification of the cavitation stages from the fluid dynamics standpoint. In hydraulic centrifugal pumps, when the intense cavitation takes place, the average pressure downstream reaches the sub-ambient liquid saturation pressure, causing high levels of vibration and noise. A special condition for centrifugal pumps occurs when the pump flow rate is smaller than the 50% of the nominal flow rate, generating a pulsating cavitation (Ball *et al.* (1975)). The pulsating cavitation usually has a high potential for great material damage and economical losses.

Nowadays there are many standard cavitation test methodologies, as for example the the rotating disk devices, the cavitation tunnels, and the ultrasound techniques. However, all the standard cavitation tests are performed on ideal flow conditions and use small test specimens. In the technical literature, there is no report about cavitation erosion tests carried out on commercial brass pump impellers at real operating conditions. Furthermore, the vast majority of the industrial acoustic emission (AE) techniques have been applied in the study of static failures, mainly in pressure vessels and pipes, and on the failures of gears and rolling bearings. Alfayez *et al.* (2005) present a work developed to monitor exclusively the cavitation phenomenon on hydraulic pumps using AE techniques. They show that the AE signals are very efficient to identify the flow conditions at which the cavitation occurs.

This work deals with an experimental study carried out to investigate the cavitation erosion in commercial centrifugal pumps. A pump testing bench is specially devised to develop this work. Instead of using standard specimens of small dimensions, full scale commercial brass impellers are employed in the cavitation erosion tests performed. The experimental apparatus includes some transducers to monitor the suction line pressure, the discharge pressure, the flow rate, and the AE signal at the pump case. The impeller mass loss caused by the erosion is measured at several times along the cavitation tests. Moreover, AE signals are acquired during the tests to help the identification of the pump cavitation regimes. Images of the impeller surface are obtained by a scanning electron microscope before and after the tests, in the attempt to enlarge the knowledge about the cavitation erosion in water pumping systems. The experimental results show that brass impeller prototype suffers mass loss greater than that observed in standard cavitation test brass specimens.

2. EXPERIMENTAL APPARATUS AND METHODOLOGY

Figure 1 shows a schematic drawing of the experimental setup employed in this work. The pump suction headwater is positive. The brass impeller diameter of the single stage centrifugal pump is equal to 198mm. The pipeline has diameter of 2in at the suction and diameter of 4in the discharge. A section of transparent tube is installed at the inlet pipeline near to the pump spiral case to allow the visualization of the bubble formation and movement during the cavitation. The motopump used is a Schneider BC23R and is driven by an electric motor Weg of 15hp at 60Hz. The electric motor is commanded by a frequency inverter Weg CFW09. All cavitation erosion tests are carried out at the pump nominal speed of 3520rpm.

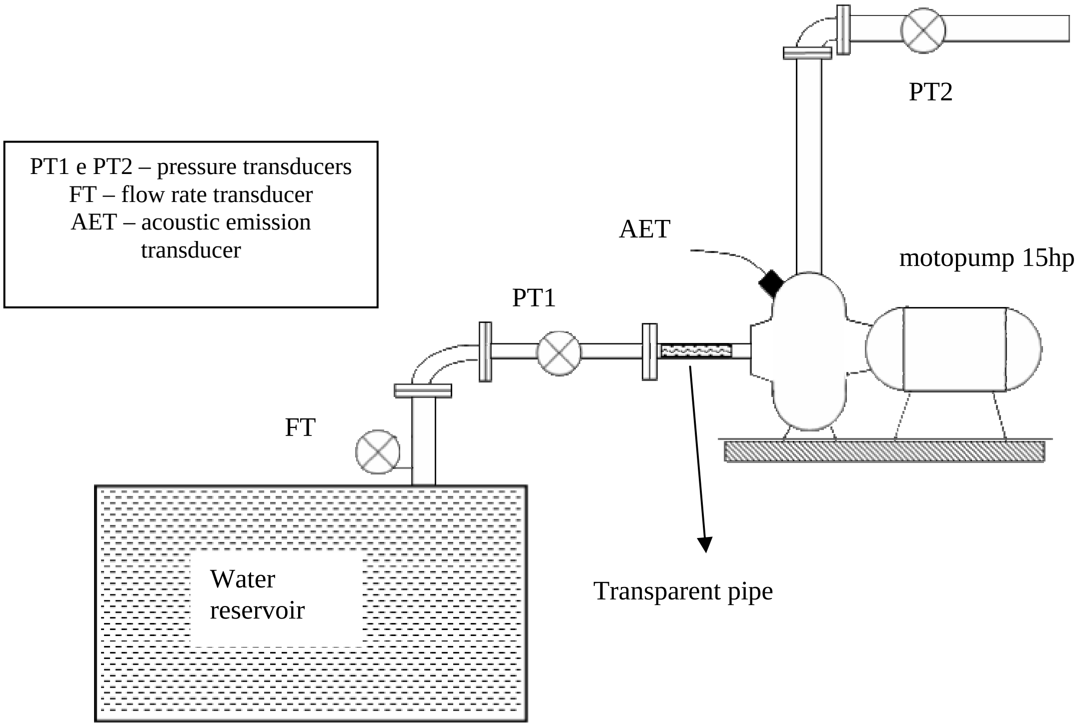


Figure 1. Schematic drawing of the pumping system used in the cavitation tests.

The instrumention system mounted on the pump testing bench includes two piezeletric pressure transducers, one electromagnetic flow rate transducer, and one acoustic emission transducer. The data acquisition system for pressure and flow rate measurements is based on the multifunction device PXI-8106 from National Instruments. Analog pressure meters are also mounted on the suction and discharge lines to facilitate the direct observation of the pressure measurements. At some time intervals along the cavitation tests, the pump spiral case is dismounted and the impeller is placed in an oven to dry off. Afterwards, the pump impeller is placed on a precision electronic scale to estimate its mass.

Firstly, some tests are performed on the pump testing bench for characterization of the cavitation phenomenon. The flow discharge is restricted through a valve installed at the discharge pipeline and the measures of flow rate, pressure and AE levels are taken. The AE signal is used to identify the cavitation in the centrifugal pump. Then the cavitation erosion tests on a brass impeller are started. The impeller mass loss along the tests is monitored. The cavitation erosion tests last 1357 hours. The impeller mass loss is evaluated using a precision digital balance. Practically, the impeller is subjected to pulsating cavitation along the 1357 hours of pump operation. Two impellers are used in the tests –one is installed in the pump for the erosion tests and the other one is new and kept out of use as a reference for comparison. After the 1357 hours of operation, the pump impeller is removed from the spiral case for the metallographic tests. Metallographic specimens are obtained from the two impellers for the analysis of the alloy structure. Micrographs from the eroded and new impellers are compared to evaluate the surface characteristics of eroded materials in order to bring some insights into the erosion mechanisms in centrifugal pumps. Some details of the experimental apparatus are shown on Fig. 2. Figure 2(a) shows a photograph of the transparent pipe installed at the pump suction line, while Fig. 2(b) depicts the place chosen to mount the AE transducer on the pump spiral case.

(a) (b)

Figure 2. Photographs of the suction pipeline and the motopump: (a) transparent pipe installed at the pump suction line (b) AE transducer mounted on the motopump spiral case.

The AE transducer is mounted on the spiral case using a magnetic supporting block and adhesive tape. In the interface between the transducer and the case surface it is used mineral grease. The data acquisition system for the AE signal includes a wideband acoustic sensor PAC S9208, a pre-amplifier 20/40/60 dB, a circuit PXI-6115 from National Instruments, and an electronic circuit for signal conditioning. The software used in the data analysis is the Labview®. The acquisition system is previously tested following the norm ASTM E 2075. The optimal value for the AE signal threshold for the cavitation erosion tests is 40 dB.

The brass impellers are selected from a single manufacturing lot. According to the pump manufacturer, the material employed in the impellers is a copper base alloy BZ81-3-7-9 ASTM 84400. The datasheet provided by Schneider for the chemical composition of the impeller material is reproduced on Tab.1.

Table 1. Chemical composition of the impeller material.

Alloy	Norm ASTM	Cu (%)	Sn (%)	Pb (%)	Zn (%)	Fe (max %)	Ni (max %)	Al (max %)	Mass density (g/cm^3)
CB-21 (BZ81-3-7-9)	84400	78-82	2.5-3.5	6-8	7-10	0.35	1.00	0.005	8.73

The impellers have six blades. In order to perform the comparative metallographic analysis of the eroded and new impellers, an impeller is separated from the manufacturing lot for reference and receives an X mark. It is assumed that the specimens cut from the reference impeller would practically present the same characteristics of specimens obtained from all impellers manufactured in the same lot.

The choice of a brass impeller for this study is based on the availability of technical data in the literature (Bazanini *et al*. (2008); Coelho (2006); Miranda (2007)). It is expected to observe wear rates in brass impellers due to the cavitation higher than those observed in cast iron ones. Furthermore, cast iron impellers are subjected to oxidation and consequently their mass can vary along the cavitation tests. In the equilibrium phase diagram of the alloy Cu-Zn, an alloy containing weight 20.51% Zn is considered. The alloy consists of a substitutional solid solution of face-centered cubic crystalline structure, ductile, and has tensile stress limit in the range of 20 kgf/mm^2.

The metallographic tests employ four samples, which are analyzed using a scanning electron microscope. Two samples are obtained from the reference impeller, which has been marked with X, denominated XA and XB. Two samples are extracted from the eroded rotor and they are called 1A and 1B. All samples are cut from similar positions on the impellers. Figure 3 shows a photograph of the samples used in the metallographic analysis. After the extraction, the samples are cleaned by ultrasound in a sodium hypochlorite solution (5%), washed in distilled water, immersed in ammonium persulphate (25% solution), again washed in distilled water, immersed in alcohol 88% hydrolyzed, and, finally, dried off using filtered air.

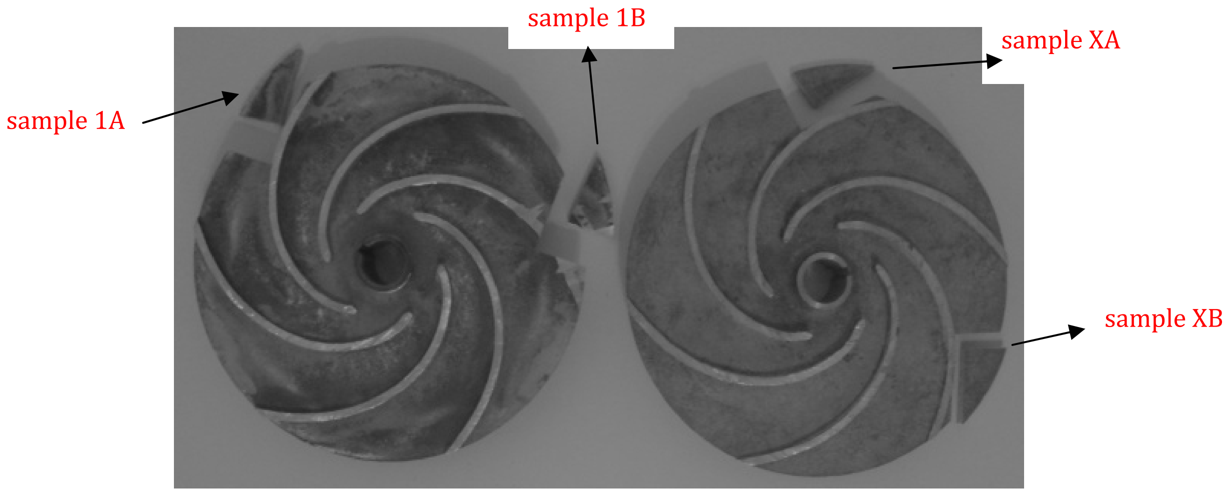


Figure 3. Samples cut from the eroded and new impellers.

3. EXPERIMENTAL RESULTS

For convenience, the presentation of the results obtained in this work is divided in three items– characterization of the cavitation using AE signals, impeller mass loss estimate, and metallographic analysis of the brass specimens – as follows.

3.1. Characterization of the cavitation using AE signals

The cavitation tests are carried out with the pump suction line fully open. At the discharge pipeline, there is a valve to restrict the pump outlet flow. Then the discharge valve is closed to induce higher levels of cavitation in the suction line. Through the transparent pipe installed at the pump suction line, it is possible to observe the bubble formation when the discharge valve is closed. When the discharge valve is fully open, the manometric discharge pressure is equal to 1,0kgf/cm^2. For the discharge valve partially closed, the discharge pressure reaches the level of 2,4kgf/cm^2. At this condition, the AE signals are monitored. The pump average flow rate is about 22m^3/h when the discharge valve is partially closed.

There are basically three different methods of analyzing the AE signals. The RMS value of the AE signal, in volts, is a classical method of depicting the time variation of the acoustic emission. The other two methods are the number of hits, which are the number of times that the signal crosses a reference value, and the amplitude of the emission signal (dB). The curve of the AE signal amplitude versus time shows clearly the occurrence of cavitation. Figure 4 shows the AE signal amplitude rendered from the acoustic emissions measured on the pump case during 600 seconds.

Figure 4 shows the occurrence of the cavitation phenomenon in the centrifugal pump at two stages – incipient cavitation and intense cavitation. The incipient cavitation stage represents the pump nominal operating conditions with the suction and discharge valves fully open. The transient regions between the incipient cavitation stages and the intense cavitation stage represent the times when pump discharge valve is partially closed. The first and last regions of the curve of the AE signal amplitude represent the pump startup and shutdown operations. At the intense cavitation regime, the noise generated by the bubbles hitting the pump case and impeller is noticeable. The measured flow rate in the cavitation tests is about 22m^3/h, which represents about 40% of the pump nominal capacity according to the manufacturer. That means that the pump operates at a very special condition when the pulsating cavitation predominantly occurs. The observation of the transparent pipe installed in the pump suction line can show qualitatively the bubble formation frequency. The results presented on Fig. 4 indicate clearly that the AE signal can be employed to characterize the cavitation regimes in the pump operation. Unfortunately, the 1357 hours of cavitation erosion tests were not enough to allow the variation on the AE signal associated with the impeller mass loss. Longer testing times must be used to evaluate the influence of the impeller erosion on the acoustic emission signal.

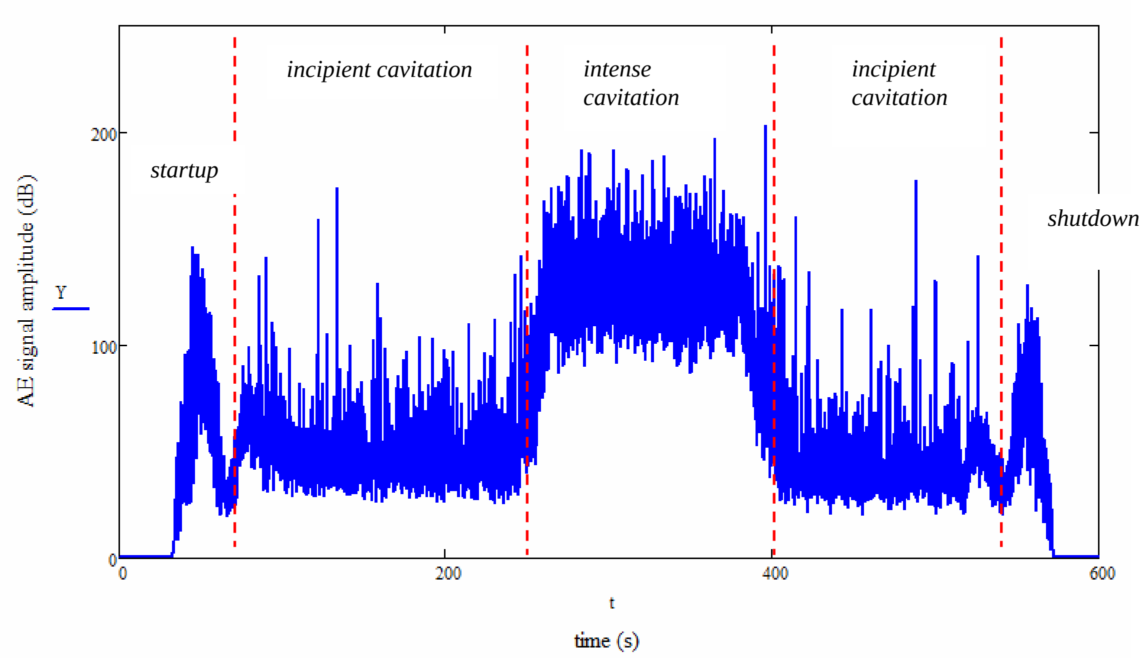


Figure 4. Curve of AE signal amplitude versus time.

3.2. Impeller mass loss estimate

The cavitation erosion tests are carried out with the pump operating at discharge pressure of 2,4kgf/cm^2 and average flow rate of 22,4m^3/h. The valve installed in the pump suction line is kept fully open during the tests. The pump suction absolute pressure is about 0,24kgf/cm^2. The motopump speed is 3520 rpm. Along the 1357 hours of tests, the hydraulic performance of the pumping system practically does not vary. The pulsating cavitation is characterized by oscillations in the bubble formation and collapse, but the suction and discharge pressures basically are kept constants.

The impeller mass loss after 1357 hours of cavitation represents 0.39% of its total mass. Even though the mass loss rate observed in the prototype is larger than the rates observerd in standard specimens used in cavitation tests, the impeller mass loss is too small and does not affect the hydrodynamic performance of the pumping system. Table 2 presents the estimates of the brass impeller mass losses during some stages of the cavitation tests. In Tab. 2, column 1 shows the moment when the impeller is removed from the pump and column 2 depicts the mass loss estimated at each time interval. After 1357 hours of operation, the total mass loss is 14.7g, which represents 0.39% of the impeller mass. The average mass loss rate in these tests is equal to 11.2mg/h.

Table 2. Mass loss measured in the brass impeller during the cavitation erosion tests.

Time(h)	Mass (g)	Loss(g)	% of loss	Time interval(h)	Mass loss rate (mg/h)
0	3793.8				
25	3793.8	0		25	0
158	3793.8	0		133	0
240	3793.8	0		82	0
480	3788.6	5.2	0.14%	240	10.8
698	3785.8	2.8	0.28%	218	12.8
992,25	3782.2	3.6	0.31%	294.25	12.2
1357	3779.1	3.1	0.39%	364.75	8.5

Figure 5 depicts the curve of the brass impeller mass loss versus time obtained from the cavitation erosion tests. It can be noticed that in the first 240 hours of tests, it is not possible to register any mass loss. Two explanations for this behavior can be provided. Very small values of mass loss may be out of range of the weighting scale used to estimate the impeller mass. Secondly, there may exist a miminum energy level to start the removal of material after a certain period of test. However, Coelho (2006) describes a very well behaved mass loss rate in the cavitation tests of brass specimens using a rotating disk device. In this work, after the first 240 hours of the cavitation erosion tests, the mass loss rate becomes practically uniform.

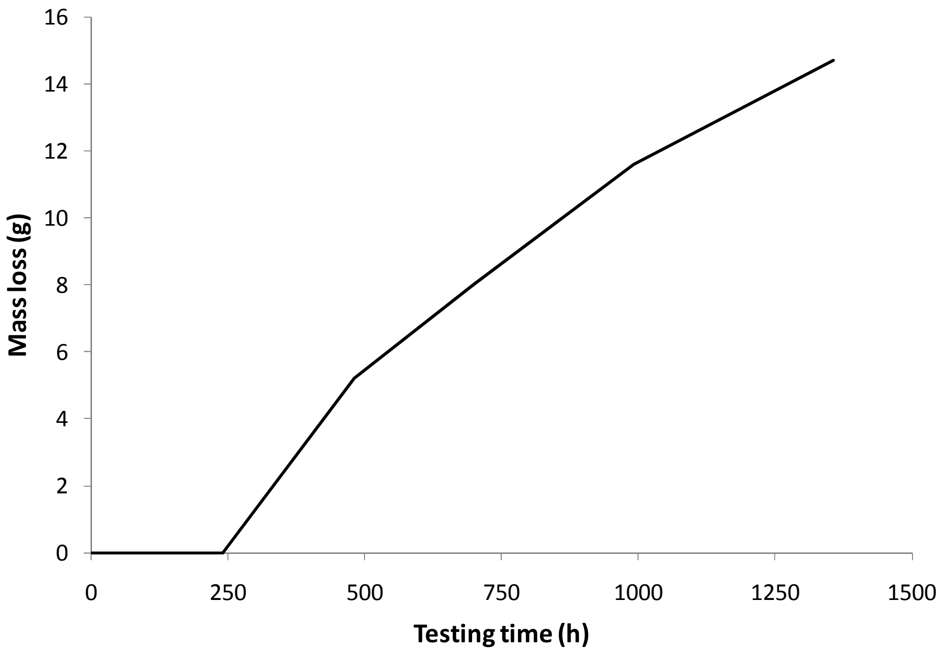


Figure 5. Curve of the brass impeller mass loss.

3.3. Metallographic analysis of the brass specimens

Table 3 presents a series of micrographs of the brass specimens extracted from the eroded and new impellers obtained by a scanning electron microscope. The new impeller used as reference is called impeller X. The micrographs of the eroded impeller are rendered after 1357 hours of operation under cavitation. The reference impeller surface is irregular due to the casting of the monophasic solid solution Cu-Zn. It can be highlighted the existence of very clear contours in the micrographs of the specimens from impeller X. In the eroded impeller, there are many pits with a very well defined circular contour that indicate the action of collapsing bubbles near to the surface. Moreover it is shown the presence of several material impurities in the specimens, which can be a natural constitutive part of the copper alloy used in the manufacturing process or can have been included in the material structure during the specimen treatment. The spongy aspect of the specimen from the eroded impeller is typical from cavitation wear.

4. DISCUSSION OF THE RESULTS

Alfayez *et al.* (2005) investigate the bubble collapse as a source of acoustic emission and discuss the changes observed in the AE signal amplitude associated with the bubble collapse intensity. A conclusion from their work is that the increase in the RMS value of the AE signal may be caused by the increase in the cavitation intensity. This conclusion can be also drawn from Fig. 4, which depicts the variation of the AE signal amplitude related to the variation of the cavitation regime. Moreover they analyze the phenomenon called “visible bubble cloud” that is capable of provoking a drop in the AE signal amplitude when the cavitation regime is intense and there is a noticeable decrease in the flow rate. Alfayez *et al.* (2005) also talk about the generation of AE signals during the bubble collapse and the reduction in the AE signal in intense cavitation regime, when the “bubble cloud” is present. A final and important conclusion of their work is that the acoustic emission techniques are very efficient to detect the cavitation onset and to determine the optimal pump operating condition under cavitation. A relationship between the AE signal pattern and the material wear magnitude must be experimentally obtained for each pumping installation, providing reliable technical data to build a database about the erosion caused by cavitation in industrial pumps.

To analyze the quality of the estimates computed for the brass impeller mass loss obtained in this work, the mass loss rates available in the technical literature for brass specimens tested using rotating disk devices can be used for comparison. Table 4 presents the mass loss rates rendered by some research works and the mass loss rate estimated in this work. The pump brass impeller is analyzed at real operating conditions, in which the body motion of the specimen is a particular feature. Only the results obtained by rotating disk devices are used for comparison because of the body motion described by the specimens, while in the cavitation tests performed by using ultrasound techniques and cavitation tunnels the specimens are kept steady. The body motion in the rotating disk devices can provoke the appearance of bubble clouds and water recirculation, similar to the test conditions in real pumping installation. The analysis of the impeller after 1357 hours of induced cavitation shows that its mass loss rate presents a significant value (11.2mg/h) in comparison with the mass loss rates available in the literature. However, the impeller total mass after 1357 hours of pump operation does not affect the hydraulic performance of the pumping system.

Table 3. Micrographs of the reference impeller (X) and the eroded impeller after 1357 hours of induced cavitation.

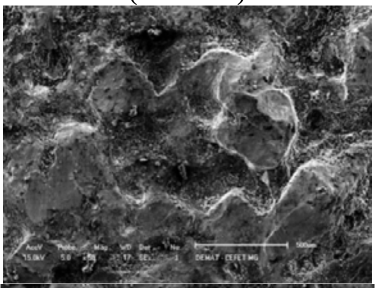
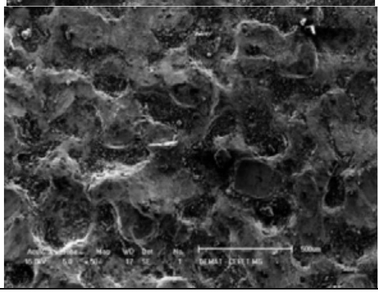
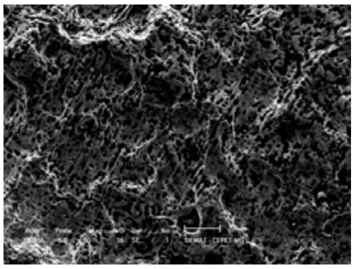
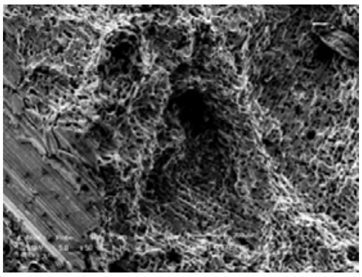
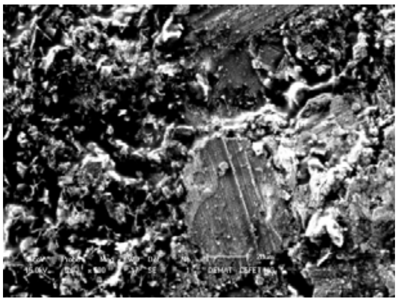
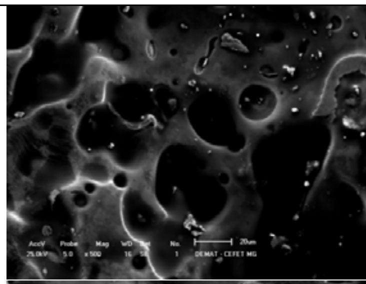
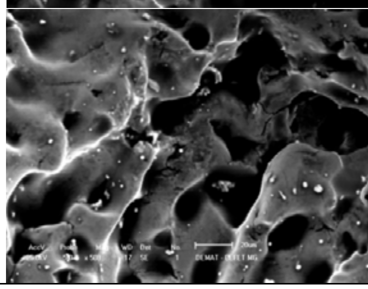
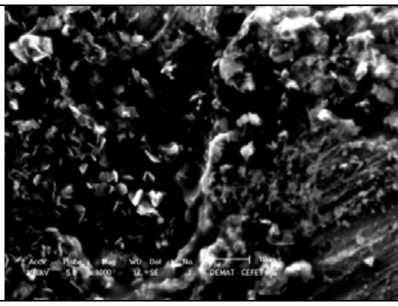
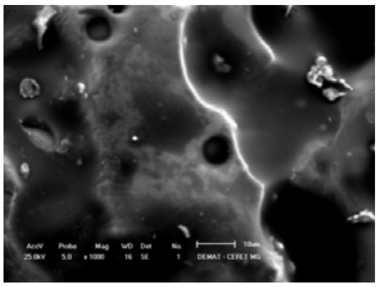
Magnification	Impeller X (reference)	Eroded impeller (1357 hours of cavitation)
50x	 	 
500x		 
1000x		

Table 4. Comparative values of mass loss rate for brass specimens tested using rotating disk devices and for full scale brass impeller prototype.

Author	Cavitation test device	Impeller diameter (mm)	Tangential speed (m/s)	Chamber temperature (°C)	Mass loss rate (mg/h)
Bazanini *et al*. (2008)	Rotating disk	250	47.9	37	1.448
Rao *et al.* (1980)	Rotating disk	335	53.8	34	1.7
Zhyie (1983)	Rotating disk	350	43.2	26	1.38
Vivekananda (1983)	Rotating disk	335	38	32	1.5
Current work	Full scale prototype	198	38.8	23*	11.2

*Average temperature of the water in the reservoir

The works cited on Tab. 4 do not describe the copper alloy composition used in the specimens. Coelho (2006) states that an effective comparison of specimen mass loss values from diffent cavitation tests requires the same material composition and the same testing conditions for all specimens tested. The brass impeller mass loss results obtained in this work indicate that the pump operating conditions used in the cavitation tests are severe. It is noteworthy to say that the time intervals employed in this work to evaluate the mass loss are generally larger than the intervals used in the cavitation tests described in the technical literature. In the cavitation tests of commercial impellers, a large sample would be necessary to study the progressive surface degradation caused by cavitation erosion because the metallographic analysis requires the destruction of the pump impeller.

The transparent pipe installed at the pump suction line allows the visualization of the bubble formation during the cavitation erosion tests. It can be observed through the transparent pipe the relationship between the bubble formation frequency and the closure level of the valve at the suction line. The influence of the “bubble cloud”, described by Alfayez *et al.* (2005), on the attenuation of the AE signal has not been observed in this work.

Finally, it is important to emphasize that the technical literature lacks similar works developed for the cavitation erosion tests in commercial brass impellers. Furthermore, the AE signal in cavitation erosion monitoring and the specific norms for testing components of centrifugal pumps under cavitation also are rare matters in the literature.

5. CONCLUSIONS

The results presented in this paper show that the cavitation in commercial centrifugal pumps can lead to significant mass loss rates. The pump testing bench described in this work allows the development of cavitation erosion tests in brass impellers at real operating conditions.

It is shown that the AE signal can be employed to characterize the cavitation in industrial pumping installations. AE transducers can be very effective to detect the cavitation at different stages and intensity levels. However, the accurate evaluation of the wear magnitude associated with cavitation requires a very large number of cavitation erosion tests to build a broad database describing the mechanical component behavior. The application of AE techniques in the cavitation detection improves expressively the monitoring system reliability, mainly in industrial ambient where the noise levels are high. The high frequency AE signal can be distinguished from other source of sounds and noises and is out of the human frequency range of audibility.

The eroded surface presents a spongy aspect, typical of metallic surfaces that have suffered erosion by cavitation. In many works described in the literature, this spongy aspect is always present in metallic specimens tested using rotating disk devices or ultrasound techniques. The majority of surface pits observed in the micdrographs presents a circular form with different sizes, suggesting that the bubble formation and collapse near to the surface do not follow a fixed pattern.

6. ACKNOWLEDGEMENTS

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