Chemical and Mechanical Aspects of the Cavitation Phenomena

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The paper endorses the necessity of treating cavitation erosion as a distinct process against corrosion. For this purpose, in a first section there is presented the cavitation phenomenon and are analyzed the occurring chemical, electrochemical and mechanical processes. In the second section there are presented the phenomena occurring during material degradation, when cavitation occur in neutral or chemical aggressive environments. Most of the results are obtained in Timisoara Hydraulic Machinery Laboratory but there are given also results obtained in other important scientific centers, which carried out cavitation studies.

Keywords: corrosion, cavitation erosion, eroded mass, eroded material, aggressive chemical environment, vibratory apparatus

For the specialists concerned with the supervision of technical systems, in which a moving fluid is implied, frequently becomes important to determine the way the wear of different parts it produced. For instance, it is important to establish if it is a result of a chemical reaction (corrosion), an effect of the presence of solid particles (abrasion), or because there are zones in which the pressure is sometimes lower than that of vaporization (cavitation). From these three distinct types of wearing, cavitation is a very complex phenomenon both from the physical point of view as well as from the aspects, which concern destroying of the solid surface guiding the flow.

The actual state of art in the studies of cavitation phenomenon

If corrosion and abrasion have been noticed for a long time, the first components affected by cavitation (ship propellers and hydraulic turbine runners) have been recorded around 1880 [2]. The wearing aspects present the following characteristics:

- the eroded area is selectively placed on the solid boundaries;
- if the repair work measures were delayed or if the wearing was not noticed in time, the detail can be pierced through;
- the individual wearing have the aspect of craters or grooves (disposed in parallel), with rugged surface.
- in some particular cases appear individual indentations (one till three), beyond the boundary of the eroded area; these indentations have the form of cones with shining surfaces.

The cavitation bubbles occur when in a point of a liquid flow the pressure decreases under a critical value (roughly it can be taken equal with the pressure of saturate vapors), which depends on the liquid physical characteristics as well as the number and mass distribution of microscopic vapour nuclei. When the bubbles reach a zone with higher pressure they suffer a violent collapse (frequently there is employed the term implosion) that determines important pressures increase, high temperatures, liberation of chemical substances and electrical phenomena.

Mechanical phenomena accompanying bubble implosion

Detailed observations of cavitation flows, lead to the conclusion that a great number of bubbles appears and collapse, their shape being more or less spherical. Even, if the bubble collapse does not respect a spherical symmetry, at the final stages of the implosion appear liquid jets with very high velocities, which at their turn produce mechanical deterioration of the material [5]. As a result, the solid boundary is loaded with numerous pressure impulses, having variable intensity and casual spatial distribution. The loading intensity of the collapses depends on the distance from the bubble to the solid boundary. Because this distance varies in large limits, it is possible that some collapses will produce individual craters and other collapses will produce only plastic or elastic deformations. As a result, the cavitation erosion will have also features of fatigue breakdown.

Thermal phenomena accompanying bubble implosion

Untilll now, there were identified two sources for the high temperatures:

- the gas compression in the collapsing bubble [1];
- the transformation in heat of the mechanical work developed during the metal deformation.

Because he thermodynamic phenomena manifest itself on extremely reduced areas and last a very short time, the results of both the theoretical and experimental approaches are not very reliable. At present, it is believed that 400°C is the most probable temperature.

Electrochemical phenomena accompanying bubble implosion

Foltyn [4] and Nechleba [10] considered that between the heated spot and the adjacent one a thermal gradient will appear, which in a conducting environment would produce an electric current followed by electrochemical corrosion. To prove that hypothesis, Foltyn performed tests by using cathode protection. Although, the complete elimination of erosions was not possible, the latter diminished considerably. G. T. Callis also confirmed this supposition, by connecting a specimen with 1 mm^2 area to an oscilloscope. He demonstrated that the collapse of bubbles determines associated anodic spots. At every collapse it occurs an increase of several milivolts, in the anodic direction [13 pp22]. If the deformation is permanent

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Table 1
PARAMETERS OF THE LABORATORY FACILITIES

Laboratory	Power [KW]	Vibration amplitude [µm]	Vibration frequency [Hz]	Specimen diameter [mm]	Type of the device	Reference
THML	500	94	7000±3%	14	vibratory	[2]
Michigan	200	12.5 -100	20000	14.3	vibratory	[6]

this increase is permanent, when the deformations are elastic the potential regain the initial value. As a result of these experiments in the years 1953-1960, numerous researchers considered cavitation an electrochemical phenomenon and consequently applied cathode protection in numerous situations with acceptable results. In 1960, M. S. Plesset [11] demonstrated that the reduction of the cavitation erosion occurs not as the result of the potential difference but simply while on the specimen surface is created and maintained a hydrogen cushion, which damps the mechanical stresses. F. L. La Que suggests the following idea: if the gas presence is the principal cause of cathode protection it will be desirable to undergo researches in which, the specimen is the anode but in the same time, for protection, to produce a gas cushion on the specimen surface. M. S. Plesset used an anodic specimen surface on which oxygen was produced . He discovered that for the same volume of gas, the protection against cavitation is the same, regardless if the specimen is cathode or anode. These results give the firm belief that the implosion of cavitation bubbles favors the corrosion through two mechanisms: the anodic jump and the local heating. As a consequence, the resistance to the complex cavitation-corrosion loading is substantially reduced.

In this work there are analyzed tests using liquid environments with both neutral and aggressive chemical behaviour and specimens manufactured from materials with different cavitation and corrosion resistance. The purpose was to put into evidence both mechanical and chemical aspects and to find out the specific differences between cavitation and corrosion. As analyzing parameter there were used the mass losses at different attack moments. There were used only vibratory test facilities while they have great erosion intensities and the test duration is sensibly reduced.

Experimental part

Researches regarding the effects of cavitation upon materials

The results subjected to discussions were obtained on specimens exposed to cavitation in vibratory devices. Such devices are characterized by a great intensity of cavitation damages [2, 5]. Most results were obtained in Timisoara Hydraulic Machinery Laboratory (THML) but there are presented also important results obtained in the Michigan University Laboratory [5, 6].

Figure 1 presents the nickel tube magnetostrictive device of THML, and figure 2 the shape of the used specimen. The method used on a large scale for tests is that recommended by the American standards ASTM G-32 [14]. It consists in realizing a specimen with a plane active surface (fig. 2) with as small as possible roughness in order to eliminate both the effect of the surface roughness (the top of the roughness (is easy detached) and of the metallic dust (the metallic dust is retained in the roughness valley and is also easly removed) upon the loss behaviour in the first moments of the attack. Customary this roughness is Ra = (0,2 – 1,6) µm.

A specimen is subjected to cavitation attack till the erosion rate receives an approximate stable value [2, 7, 8, 9]. The researches carried on in THML with the T1 device, showed that for materials with good or excellent mechanical properties, the total duration of the cavitation attack must be comprised in the interval 135…165 min.

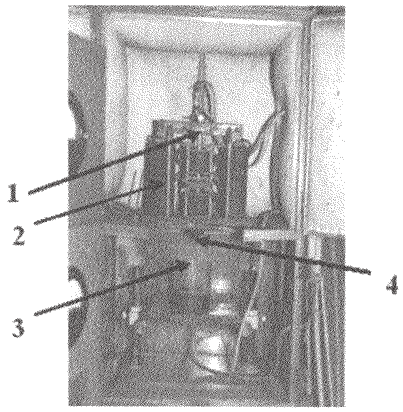

Fig.1 The magnetostrictive vibratory apparatus T1 (TMHL). 1. Nickel tube, 2. Coils for realizing the pulsating magnetic field. 3. Vessel containing the cavittion liquid, 4. specimen

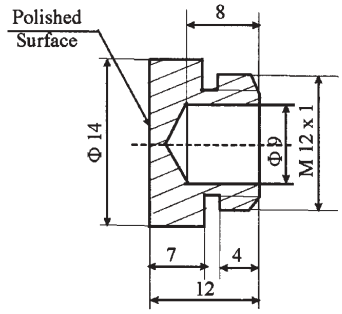

Fig.2. Specimen geometry

Regardless of the laboratory or the used device, the complete duration of the cavitation attack is divided in a number of test periods. Shortly before beginning the tests and after each test period, the specimen is washed successively in: drinking water, distilled water, alcohol and acetone. Immediately after that, the specimen is carefully dried in a warm air jet, weighted and preserved in a closed box in order to be protected against the influence of substances, which can react chemically with the material.

Even for liquids with reduced chemical aggressiveness, the cavitation test determines important erosions. This fact proves the importance of the mechanical component during the cavitation attack. Evidently, when the liquid is chemically aggressive a cumulative effect cavitation-corrosion appears. The importance of the corrosion factor depends upon both the liquid aggressiveness and the tests duration.

Results and discussions

To analyze the effect of corrosion in figures 3-10 are given the results obtained by the autors on various materials and testing liquids, using the THML T1 device (fig.1). For the same purpose in figure 15 are presented the results

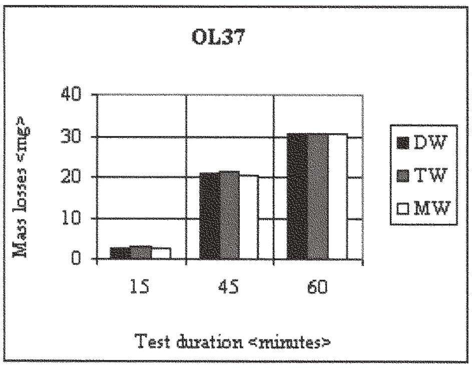

Fig. 3

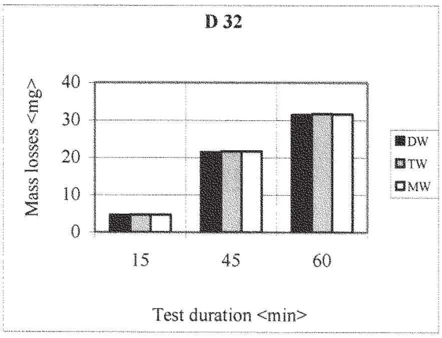

Fig. 4

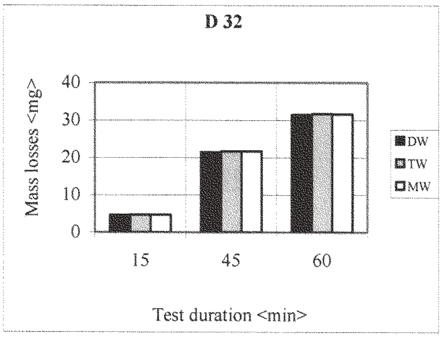

Fig. 5

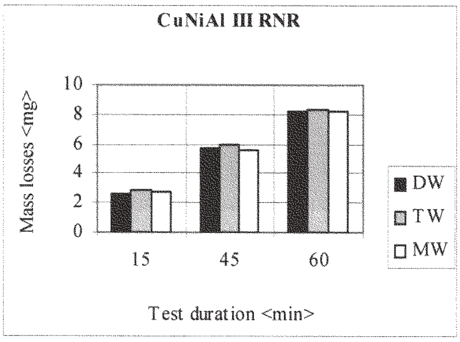

Fig. 6

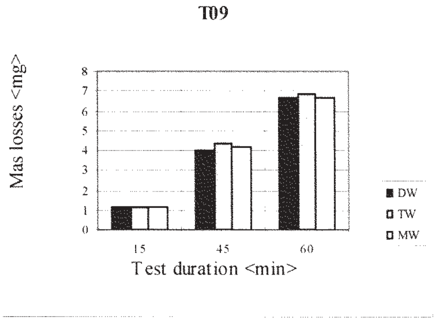

Fig. 7

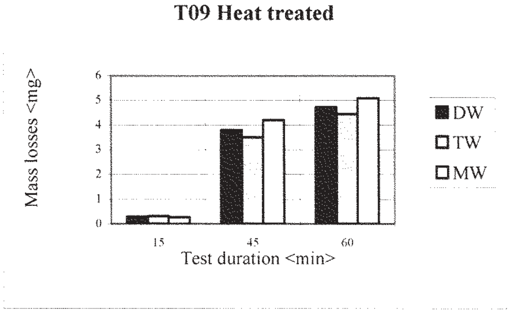

Fig. 8

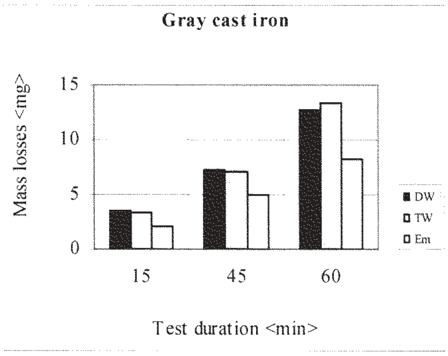

Fig. 9

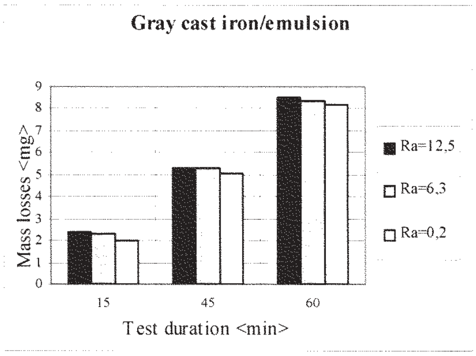

Fig. 10

Note: In the Figs. 3-10, the following notations are made: DW- distilled water, TW- drinking water, MW- standard marine water; Em- emulsion; Ra- roughness of the specimen active face, before the cavitation; for the Figs. 3-9 Ra =0.2μm

obtained by Garcia a. o. [6] and in figures 11-14 those obtained by Sisak a. o. [12]. The selection of working liquids and specimen materials were made in such a manner to put into evidence either the independence of cavitation erosion or the cumulative effect cavitation-chemical corrosion. The 60 min duration for the tests carried out in THML, as maximum reference duration, was accepted because after this period the mass losses remained unchanged (of course, with inherent small, non significant variations).

The results in figures 3-8 show that for the same material (regardless if it is OL 37, 40Cr10, D32, T09 heat treated or not) indifferent of the working liquid used (distilled water, drinking water or standard marine water) the losses are produced only through the cavitation mechanical effect (the impact of the shock waves or the microjets generated by the bubble implosions, upon the specimen active surface) without an important contribution of the surface or intercrystalline corrosion. The losses are approximately the same; the differences are in the limits of the tolerance prescribed by the ASTM standards [14], below ± 15%

(characteristic value for complex phenomena such as cavitation erosion). Numerous researchers [5, 6, 10, 11] explain the absence of chemical corrosion in those three analyzed working liquids by:

a.the result of very short testing periods (maximum 15 minutes/period);

b.between two testing periods the specimens are kept in conditions which exclude the chemical reactions with the environment.

Using gray cast iron (fig. 10), the results show small differences depending on the manufacturing procedure of the active surface (different Ra). Those differences are significant in the first 15 min when the top of the roughness is destroyed. So the losses are greater for Ra = 12 μm. From the 45-min of the cavitation attack, the relative losses decrease and remain in the limits of ±15%.

The results presented in figure 9 show the influence of the viscosity upon the cavitation dynamic. Because the greater viscosity of the emulsion in comparison with that of drinking or distilled water, the value of the pressure generated by the shock waves or microjets is reduced. This reduced value determines smaller erosions.

The effect of the modified physical properties (viscosity, superficial tension, density) is put into evidence also in figure 9 where the losses are smaller than those obtained in distilled and standard marine water. In figures 11-14 there are presented a workup of the results obtained by Sisak a. o. [12] upon the stainless steel W4 (0.06 % C; 18.03% Cr; 9.75 % Ni; 1.40% Si; 1.37% Mn; 2.16% Mo; 0.024% Nb; 0.009% S; 0.026% S), used for manufacturing pump runners employed in the chemical industry. The tests were carried out at $20 \pm 1\ ^{0}C$**.** The results in figure 15 represent a workup of the results obtained by Garcia [6], on the standard stainless steels 304 SS and 316 SS cavitation attacked in the following working liquids: distilled water at $21^{0}C$ (ρ=1.0 g/cm^3, σ=72.8 . 10^{-5} N/cm, ν=36.23cm^2/h, P_v=2482 Pa); mercury at 21 ^{0}C (ρ=13.55 g/cm^3, σ=465 . 10^{-5} N/cm, ν=4.088cm^2/h, P_v=0 Pa); mercury at $260^{0}C$ (ρ=12.98 g/cm^3, σ=419 . 10^{-5} N/cm, ν=2.79cm^2/hr, P_v=13307 Pa); Pb-Bi at 260 ^{0}C (ρ=10.38 g/cm^3, σ=397 . 10^{-5} N/cm, ν=5.95cm^2/h P_v=0 Pa).

From these figures (11-15) results the cumulative effect of chemical corrosion and cavitation erosion upon the tested materials.

The data in figure 11 present the effect of various liquids and the value of concentration. The data in figures 12-14 evidences the effect of various concentration of chemical aggressive liquid upon the cavitation erosion. Some important aspects can be observed:

- for NaCl dissolved in water, the greatest mass losses appear for the concentration of 10 %. When the

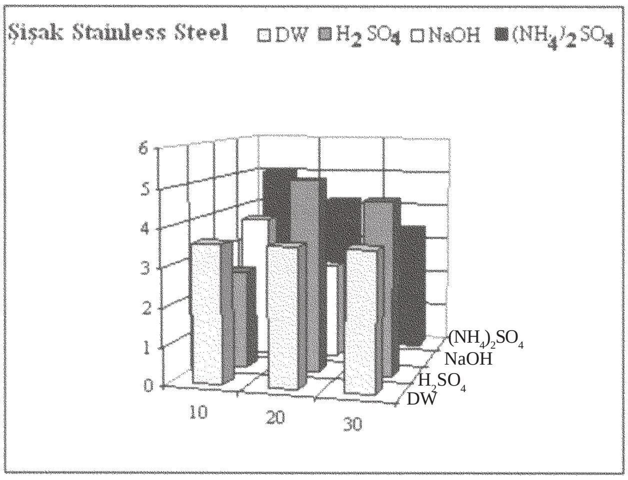

Fig. 11. Data processing of the results obtained by Sisak a. o. [12]

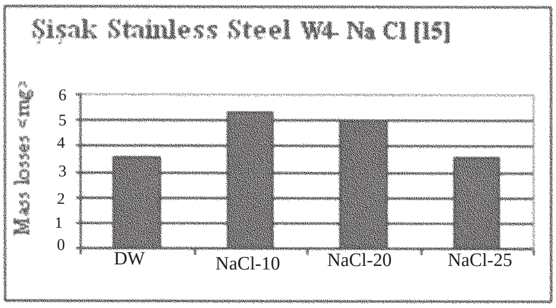

Fig. 12. Data processing of the results obtained by Sisak a. o. [12]

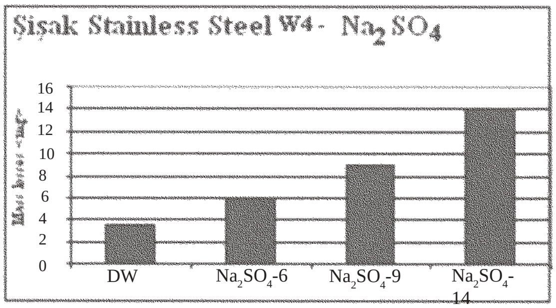

Fig. 13. Data processing of the results obtained by Sisak a. o. [12]

(Significance of the notations: DW- distilled water, NaCl – 10:10% NaCl concentration in water; NaCl – 20:20% NaCl concentration in water; NaCl – 25:25% NaCl concentration in water; Na_2SO_4-6: 6% Na_2SO_4 concentration in water; Na_2SO_4-9: 9% Na_2SO_4 concentration in water; Na_2SO_4-14: 14% Na_2SO_4 concentration in water)

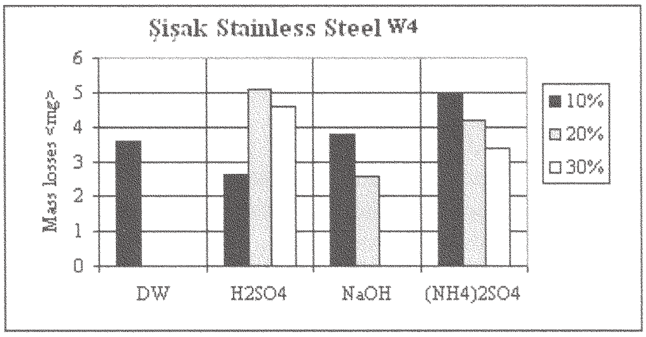

Fig. 14 Data processing of the results obtained Sisak a. o. [12] (Notations: DW- distilled water, H_2SO_4 – H_2SO_4; $(NH_4)_2SO_4$-$(NH_4)_2SO_4$; 10%, 20% 30% -solution concentrations in water)

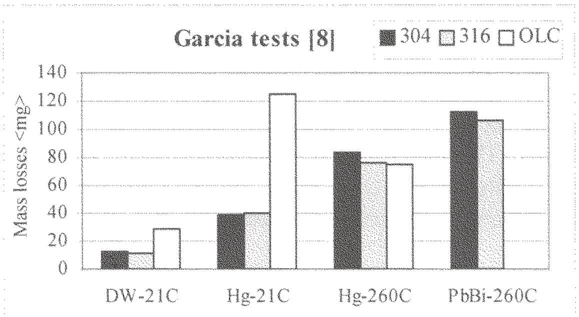

Fig.15 Data processing of the results obtained by Garcia a. o..[6] (Notations: DW- distilled water at $21^{0}C$, Hg – mercury at $21^{0}C$; lead-bismuth at $260^{0}C$)

concentration increases to 25 %, the mass losses decreases up to the value obtained in distilled water. We believe that this decrease is a result of the increased viscosity of the working liquid that reduces significantly the impact pressure of the shock waves or microjets; so for an increased concentration the mass losses decreases, even if the corrosion is higher;

- for Na_2SO_4 dissolved in water the greatest mass losses is obtained for a concentration of 14%. In this case, a very important chemical corrosion effect appears and compensates the reduction of the mechanical component, determined by the increased viscosity;

- the data in figure 14 shows that the influence of the chemical corrosion in the cavitation process is very important for a concentration of 20% H_2SO_4, 10 % NaOH and $(NH_4)SO_4$. If the concentration exceeds the mentioned limits, the cavitation losses are reduced as a result of the modifications in the physical characteristics (especially the superficial tension and viscosity) and their effect upon the cavitation dynamics.

The figure 15 shows the manner in which is influenced the cavitation erosion by the nature of the working liquid (expressed by density, viscosity, superficial tension and temperature) and the nature of the used material. It must be remarked that regardless of used material the lowest values are obtained in distilled water. For the stainless steels 304SS and 316SS tested in mercury the greatest losses occur at 260^0C. This represents the effect of the intercrystalline corrosion, which is greater for high temperatures [7- 9]. Surprisingly, the greatest chemical corrosion effect was obtained for the carbon steel (OLC) tested in mercury at 21^oC. Momentary we cannot explain this results because we have not enough information upon the material characteristics.

Conclusions

Examining the data disposable in the literature, for the implosion of cavitation bubbles, we reach to the conclusion that the cavitation erosion is predominantly a mechanical phenomenon, the results of the implosions being either shock waves or high-speed jets.

For specialists concerned with the reliability of machine elements in systems working with fluids, to attribute the global term “corrosion” does not seem efficacious. It is preferably to identify if the wear was produced by one of the following phenomena: cavitation, abrasion, or corrosion (considered as an action produced predominantly by chemical effect).

Both the cavitation erosion obtained in our laboratory and those presented in the literature (especially those obtained at Michigan University) show that important erosions occur in conditions when the chemical reaction between the tested material and the working liquid is unimportant.

Examining the tests results obtained by cavitation in aggressive chemical liquids, it was explained the cumulative action chemical corrosion-cavitation erosion. There have been presented test results, for which increasing the concentration of the aggressive liquid, the total mass losses decreases. These apparently strange results were explained both by the reduction of the mechanical action when the liquid physical properties (viscosity, density, surface tension) were changed as well as by the short tests duration.

Bibliography

1.ACKERET, J.,Experimentelle und theoretische Untersuchungen ueber Hohlraumbildung (Kavitation) in Wasser, Tech. Mech. und Termodznamic, **I**, 1930

2.BORDEAªU,, I., Eroziunea cavitaþionalã asupra materialelor utilizate în construcþia maºinilor hidraulice ºi elicelor navale. Efecte de scarã, Tezã de doctorat, Timiºoara, 1997, p.172

3.CONSTANTINESCU, AL., Detectarea ºi mãsurarea coroziunii. Ed. Tehnicã, Bucureºti, 1976

4.FOLTYN V.- Kathodica Ochrana Protiv Kavitacni Korosi, Strojirenstvi, **2**, no. 9, Czechoslovakia, Sept. 1952, p.402

5.FRANC, J., P., MICHEL, J., M.,Fundamentals of cavitation, Kluwer Academic Publishers-Dordrecht/Boston/London, 2004, p.265

6.GARCIA, R., HAMMITT, F.G., NZSTROM R.E., Correlation of Cavitation Damage, with Other Material and Fluid Properties, Erosion by Cavitation or Impingement, ASTM STP 408, American Society Testing Materials, 1967, p..239

7.MITELEA, I., BORDEASU, I., HADÃR, A.,T, Rev. Chim. (Bucureºti), **56,** nr.11, 2005, p.1169

8.MITELEA, I., BORDEAªU, I., POPOVICIU, M.O., HADAR, Rev. Chim. (Bucureºti), **57** nr.2, 2006, p.215

9.MITELEA, I., BORDEASU, I., HADAR, A., Rev. Chim. (Bucureºti), **58, n**r.2/2007, p.254, ISSN:0034-7752

10.NECHLEBA, M.,Das Problem der Kavitation, Wissenschafliche Zeitschrift der Tech. Hochschule Dresden, H4, 1953, p.543

11.PLESSET, M.S., Cavitation Erosion in Non-Aqueons Liquids, Division of Engineering and Aplied Science. California Institute of Tehnology, Pasadena, California, Februarie 1970

12.SIªAK, A, KUZMAN, F.F., KUZMAN-ANTON, R., POTENCZ, I.,Eroziunea cavitaþionalã în soluþii apoase de diferite concentraþii ale unor substanþe chimice, Memoriile secþiilor ªtiinþifice ale Academiei RSR, Seria IV, Tomul III, nr.2, Iaºi, 1980, p.197

13.WHEELER, W. H., Mechanism of Cavitation Erosion, Cavitation in Hydrodynamics, National Phisical Laboratory, Teddington, Middlesex, October 1955, Art. 21, p.1-31

14.******* Standard method of vibratory cavitation erosion test, ASTM, Standard G32-85

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