Ideal Cavitation Erosion Process and Characteristic Erosion Curves

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The most used methods to estimate cavitation erosion resistance give a special attention to the velocity erosion curve, but the theoretical analytical characteristic curves of cavitation erosion near incubation period, used until now, contradict experimental data. In this paper, depending on the nature and condition of eroded materials, other kinds of the volume loss rate curve of erosion cavitations progress are proposed. The analytical model describing cavitation erosion of materials uses the differential equations. The real parameters which appear (in a natural way), inside the general solutions will be determined, fitting the erosion curves to the experimental data.

Keywords: analytical model, cavitations, erosion

In the design and operation of industrial equipment, the effect of cavitation erosion on metals is extremely important. Usually the cavitation process is divided into two general classes of material behaviour:

a) inertial (or transient) cavitation,

b) noninertial cavitation.

Inertial cavitation was first studied by Lord Rayleigh, when he considered the collapse of a spherical void within a liquid. When a volume of liquid is subjected to a sufficiently low pressure, it may appear a rupture and form a cavity. This phenomenon is termed cavitation inception and may occur behind the blade of a rapidly rotating propeller [1] or on any surface vibrating underwater with sufficient amplitude and acceleration.

Noninertial cavitation is produced in the process in which small bubbles in a liquid are forced to oscillate in the presence of an acoustic field, when the intensity of the acoustic field is insufficient to cause total bubble collapse. By comparison, this form of cavitation causes significantly less erosion than inertial cavitation, and is often used for the cleaning of delicate materials, such as silicon wafers.

Particularly speaking the *cavities* are formed into a liquid when the static pressure of the liquid is reduced below the vapor pressure of the liquid in current temperature. If the cavities are carried to higher-pressure region they implode violently and very high pressures can occur. In this process, air diffuses through cavity wall into the cavity. When pressure in the liquid is further reduced, evaporation pressure of the liquid is achieved. At this point the liquid starts to evaporate and cavities start to be filled with vapors. When this kind of a cavity is subjected to a pressure rise cavity growth is stopped and once the pressure gets higher, the cavities start to diminish. Cavities disappear due to dissolution of air and condensation of vapors. When a cavity is mostly vapors filled and subjected to a very rapid pressure rise it implodes violently and causes very high pressure peaks. Implosion is less violent if the gas quantity of a cavity is big. This requires relatively slow nucleation of a cavity.

An interesting type of cavitation, called hydrodynamic cavitation, describes the process of vaporisation, bubble generation and bubble implosion which occurs in a flowing liquid as a result of a decrease and subsequent increase in pressure. In pipe systems, cavitation typically occurs either as the result of an increase in the kinetic energy (through an area constriction), or an increase in the pipe elevation.

As an uncontrolled process, the cavitation phenomenon is damaging. However, by controlling the flow of the cavitation, the power is harnessed and non-destructive. Controlling the cavitation process can be used to enhance chemical reactions or propagate certain unexpected reactions because free radicals are generated in the process due to disassociation of vapors trapped in the cavitating bubbles [2].

Chemical engineering applications

In the chemical industry, cavitation is often used to homogenize, or mix and break down, suspended particles in a colloidal liquid compound such as paint mixtures or milk. Many industrial mixing machines are based upon this design principle. It is usually achieved through impeller design or by forcing the mixture through an annular opening that has a narrow entrance orifice with a much larger exit orifice. In the latter case, the drastic decrease in pressure as the liquid accelerates into a larger volume induces cavitation. This method can be controlled with hydraulic devices that control inlet orifice size, allowing for dynamic adjustment during the process, or modification for different substances. The surface of this type of mixing valve, against which surface the cavitation bubbles are driven causing their implosion, undergoes tremendous mechanical and thermal localized stress; they are therefore often constructed of super-hard or tough materials such as stainless steel, Stellite, or even polycrystalline diamond (PCD).

Cavitating water purification devices have also been designed, in which the extreme conditions of cavitation can break down pollutants and organic molecules. Spectral analysis of light emitted in sonochemical reactions reveal chemical and plasma-based mechanisms of energy transfer. The light emitted from cavitation bubbles is termed sonoluminesence.

Hydrophobic chemicals are attracted underwater by cavitation as the pressure difference between the bubbles

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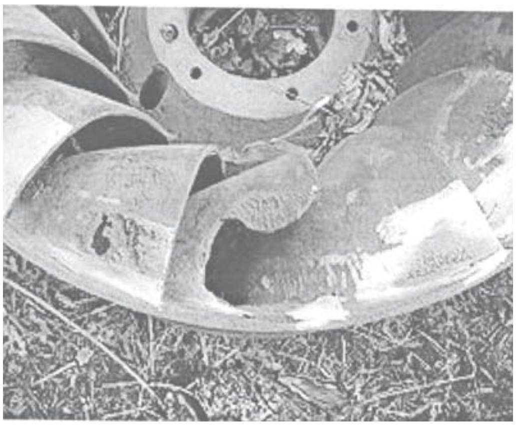

Fig.1. Cavitation damage to a Francis turbine

and the liquid water forces them to join together. This effect may assist in protein folding.

Cavitation in pumps and propellers.
Major places where cavitation occurs are in pumps, on propellers, or at restrictions in a flowing liquid. As an impeller's (in a pump) or propeller's (as in the case of a ship or submarine) blades move through a fluid, low-pressure areas are formed as the fluid accelerates around and moves past the blades. The faster the blades move, the lower the pressure around it can become. As it reaches vapor pressure, the fluid vaporizes and forms small bubbles of gas. This is cavitation. When the bubbles collapse later, they typically cause very strong local shock waves in the fluid, which may be audible and may even damage the blades.

Cavitation in engines
Some bigger diesel engines suffer from cavitation due to high compression and undersized cylinder walls. Vibrations of the cylinder wall induce alternating low and high pressure in the coolant against the cylinder wall. The result is pitting of the cylinder wall, which will eventually let cooling fluid leak into the cylinder and combustion gases to leak into the coolant.

It is possible to prevent this from happening with the use of chemical additives in the cooling fluid that form a protective layer on the cylinder wall. This layer will be exposed to the same cavitation, but rebuilds itself.

Since the early 1980s, the new models of small gasoline engines also show cavitation phenomenon. One answer to the need for smaller and lighter engines was a smaller coolant volume and a correspondingly higher coolant velocity. This gave rise to rapid changes in flow velocity and therefore rapid changes of static pressure in areas of high heat transfer. Where resulting vapor bubbles collapsed against a surface, they had the effect of first disrupting protective oxide layers (of cast aluminum materials) and then repeatedly damaging the newly formed surface, preventing the action of some types of corrosion inhibitor (such as silicate based inhibitors). A final problem was the effect that increased material temperature had on the relative electrochemical reactivity of the base metal and its alloying constituents. The result was deep pits that could form and penetrate the engine head in a matter of hours when the engine was running at high load and high speed. These effects could largely be avoided by the use of organic corrosion inhibitors or (preferably) by designing the engine head in such a way as to avoid certain cavitation inducing conditions.

As a first synthesis of the above, in many cases the cavitation is considered an undesirable occurrence. In devices such as propellers, pumps and even at some screws [3], in special conditions, cavitation produces a loss of efficiency because it causes a great deal of noise, vibration and damage to components.

According to experimental observations, in any cavitation (or droplet impact) erosion test, the damage rate is generally time dependent [4]. The typical erosion curves $V=V(t)$ and $\upsilon=\upsilon(t)$, for unity eroded surface area, are represented qualitatively in figure 2 and 3.

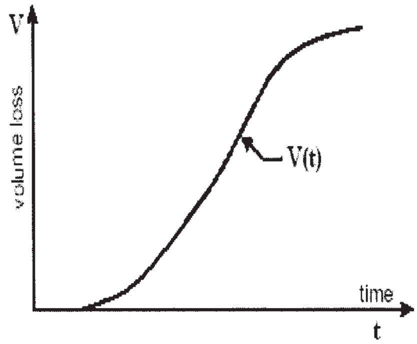

Fig.2. Volume loss curve

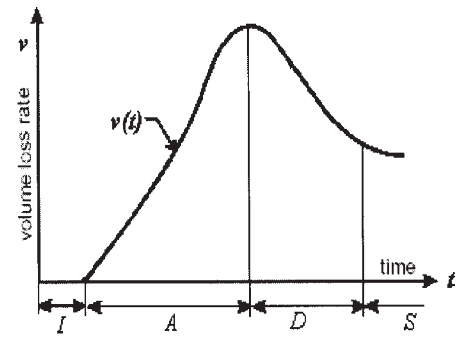

Fig. 3.Volume loss rate curves

The volume loss rate curve, figure 3, can be divided into four typical periods, namely:

1. I - Incubation period;
2. A - Acceleration period;
3. D - Deceleration period;
4. S - Steady state erosion period.

Experimental part

Cavitation Erosion Model

In our case, the eroded material tested is subject to a vibration force and a damping force using a vibratory device with nickel tube.

As it is known, the best information about the material behaviour at microscopic level is obtained by Scanning Electron Microscopy (SEM) of the cavitated surface. In figures 2 and 3, two SEM photographs of sample surface in the zone of cavitated area, for different magnifications, are presented.

Taking into account this particular situation the phenomenological "damped" model is proposed.

A certain simplified mathematical formulation of damping process and energy dissipation can be associated with a class of physical phenomena. The damping force F_d is assumed to be proportional to the instantaneous velocity, that is $F_d = -\alpha(dx/dt)$ and the coefficient of proportionality, α, is known as the dashpot-constant or viscous damping constant. Now suppose that an ideal mass-spring-damper system with mass m, spring constant k and viscous damper of damping coefficient α is subject to an oscillatory force $F_\upsilon=-kx$ and a damping force F_d, as above. Considering

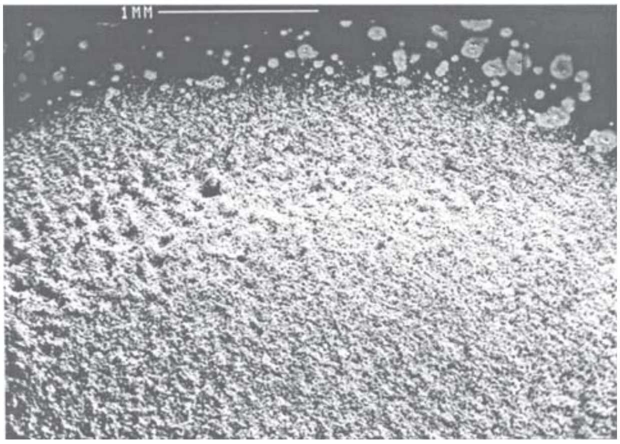

Fig. 4.General view of the cavitated area

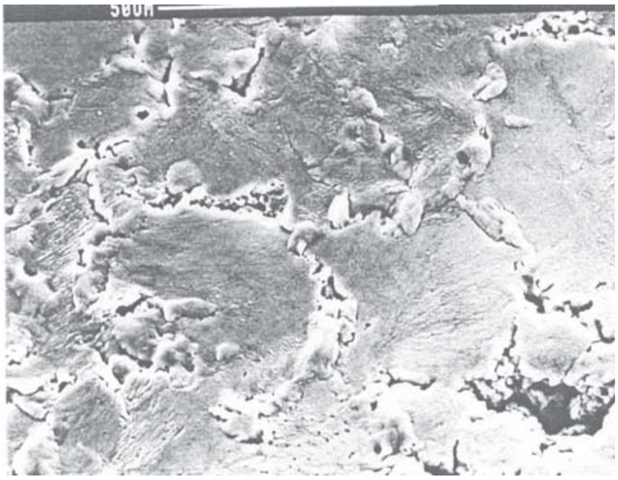

Fig.5. Initial cavitation damage as seen at the edge of the cavitated area

the mass *m* as a free body, the Newton's second law and the principle of superposition lead to

$$m\frac{d^2x}{dt^2} = -\alpha\frac{dx}{dt} - kx \quad . \tag{1}$$

Using the notations $2\gamma = \frac{\alpha}{m}$ and $\beta^2 = \frac{k}{m}$, we obtain the equation

$$\frac{d^2x}{dt^2} + 2\gamma\frac{dx}{dt} + \beta^2 x = 0 \quad . \tag{2}$$

The volume loss curve is given by

$$V(t) = A[v_s t - f(t)] , \tag{3}$$

where v_s is the ultimate value of the volume loss rate and *f (t)* is one of the solutions of homogenous linear differential equations (2), only if $\gamma = \beta$, respectively

$$\frac{d^2x}{dt^2} + 2\beta\frac{dx}{dt} + \beta^2 x = 0 \quad . \tag{4}$$

Well known differential equation of the second order with constant coefficients (4) describes the "damped" oscillations with "infinite period" and the system is said to be critically damped. Taking into account that *f (t),* the solutions of homogenous linear differential equations (4), strictly respect the conditions f(0) = 0, $\lim_{t\to\infty} f(t) = 0$ and $\lim_{t\to\infty}\frac{df}{dt}(t) = 0$, the volume loss is given by formula

$$V(t) = A[v_s t - \lambda t e^{-\beta t}] \tag{5}$$

and the volume loss rate curve becomes

$$v(t) = A[v_s - \lambda e^{-\beta t} + \lambda\beta t e^{-\beta t}] . \tag{6}$$

In equation (6), the real parameters υ_s λ and β will be determined by fitting the erosion curve to the experimental data (by applying the least squares method or another numerical method).

Results and discussion

Instead of the volume loss curve (5), the mass loss curve may be used

$$m(t) = \rho V(t) = A[\rho v_s t - \rho\lambda t e^{-\beta t}] \tag{7}$$

where ρ is the density of material and *A* stands for the eroded surface area. For $a = \rho\, v_s$ and $b = \rho\lambda$, equation (7) has the form

$$m(t) = A[at - bte^{-\beta t}] . \tag{8}$$

Considering the volume loss rate curve (6), the mass loss rate curve is

$$q(t) = \frac{dm(t)}{dt} = \rho\frac{dV(t)}{dt} = \rho v(t) = A[a - be^{-\beta t} + b\beta t e^{-\beta t}] . \tag{9}$$

On this occasion, we mention that errors occurred in the paper [5] have been corrected. The real parameters *a b* and β will be determined by the formula (8) or fitting [6] the erosion curve to the experimental data.

Analogous results, but less substantiated, were obtained [7].

In the table 1, the exposure durations (**T**$_i$), and the massic loss (**M**) of OL370 steel, in cavitational attack tests with vibrating device, are shown. The experimental results

Table 1
THE EXPOSURE DURATIONS AND THE LOSS MASS

i	T_i (min)	**M** (grams)
1	0	0
2	5	0.00082
3	15	0.00245
4	30	0.01004
5	45	0.02070
6	60	0.03065
7	75	0.04200
8	90	0.05350
9	105	0.06390
10	120	0.07290
11	135	0.08502
12	150	0.09760

from above were obtained in the Laboratories of "Politehnica" University of Timisoara.

The real parameters *a b* and β, determined by fitting the erosion curve to the experimental data for unity surface area (*A=1u)*, are

$$a = 6{,}571 \cdot 10^{-4},\ \ b = 6{,}709 \cdot 10^{-4}, \beta = 2{,}551 \cdot 10^{-2}. \qquad (10)$$

In figure 6, the mass loss curve for unity surface area (continuous line), given by function

$$m(t) = 6{,}571 \cdot 10^{-4} t - 6{,}709 \cdot 10^{-4} t e^{-2{,}551 \cdot 10^{-2} t} \qquad (11)$$

and the experimental data (box), are simultaneously plotted.

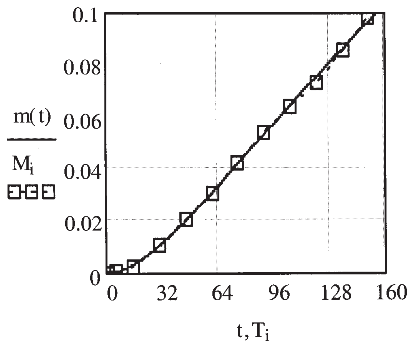

Fig. 6.Mass loss curve (*m=m(t)*) and the experimental data (*M_i*), for OL370

Similarly, the mass loss rate for unity surface area, is the function

$$q(t) = 6{,}571 \cdot 10^{-4} - 6{,}709 \cdot 10^{-4} e^{-2{,}551 \cdot 10^{-2} t} + 0{,}171 \cdot 10^{-4} t e^{-2{,}551 \cdot 10^{-2} t}. \qquad (12)$$

The theoretic mass loss rate curve *q=q(t)*, for OL370 is presented in figure 7.

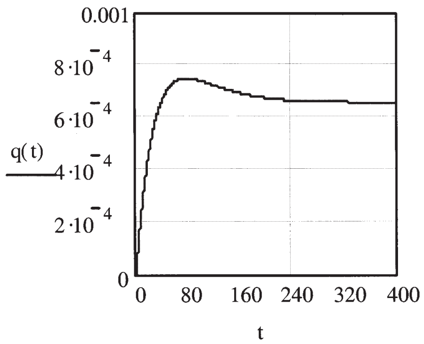

Fig. 7.Mass loss rate (*q=q(t)*) for OL370

Taking into account that the density of material is ρ =7.713, the volume loss and the volume loss rate are

$$V(t) = \frac{m(t)}{7.713} \text{ and } v(t) = \frac{q(t)}{7.713}. \qquad (13)$$

Then, the volume loss curve and the volume loss rate curve are plotted in figure 8 and, respectively, figure 9.

Fundamentally speaking, the model has objective restraints, because it manipulates strictly macroscopic experimental results. To overcome these limitations, we propose to analyze in the future the microscopic-macroscopic complex behaviour of the material, by addressing new problems in the manner specified in previous articles [8-12].

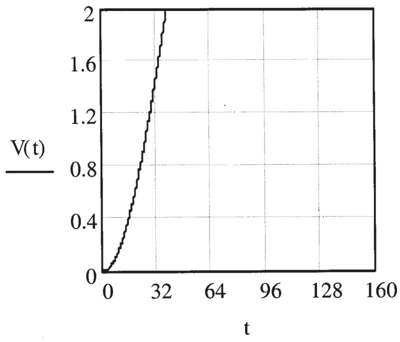

Fig.8. The volume loss curve for OL370

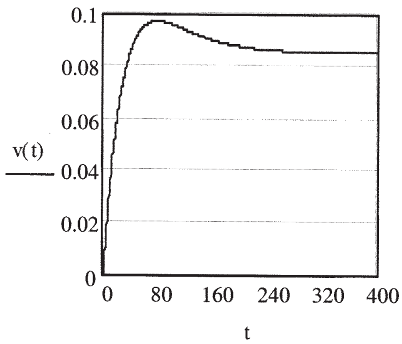

Fig. 9. Volume loss rate curve for OL370

Conclusions

For the erosion behaviour prediction of the tested ductile material, the "damped" model is proposed. The volume loss and the volume loss rate curves, in the cavitation erosion process, are correctly represented.

By fitting procedure of erosion curves to the OL370 carbon steel experimental data, the real parameters *a*, *b* and β have been determined.

Although the present model makes a good prediction, we must be aware that several assumptions or shortcuts were necessary to complete the modeling. In addition, the material was simply characterized by classical engineering tests whereas the natural solicitations in cavitation erosion have a complex character which cannot be surprised in a single type test.

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Manuscript received: 7.12.2009