THE INTENSITY AND SCALE EFFECT OF CAVITATION DAMAGE

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Introduction

The extensive investigations on cavitation damage conducted by means of different equipment types — mostly by using magnetostriction, rotating disc, and flow test devices — were primarily aimed at the classification of the relative resistance of different materials to cavitation damage. Thus, not many attempts were made in order to correlate the results obtained by this variety of equipment types, and even less to establish a connection between the results obtained and existing hydraulic (flow) conditions.

Obviously, this problem is in close connection with that of cavitation damage intensity although this could not so far be explained in a sufficiently acceptable manner, nor defined appropriately [1]. The greatest difficulty in the determination of cavitation damage intensity is presented by the fact that, in course of the experiments, the weight loss (or volume loss) curves plotted in function of time do not represent a constant weight loss and/or volume loss per unit time but will change in function of time. Furthermore, it must be remembered that the physical state of the material will similarly change as the damage goes on, of course, causing strength property modifications as well.

Taking the problems outlined above into consideration, it seems that their solution may only be approached by energetical hypotheses. Certain attempts, although not a great number, have already been made in this direction. Thus, for example, GOVINDA RAO [2] suggested a nondimensional factor (Cavitation Damage Number) by which the energy required for the removal of the damaged (eroded) material would be related to the energy of the collapsing bubbles. THIRUVENGADAM [3] demonstrated that the former concept which used the yield strength of the material as mechanical strength property proved suitable for aluminium sheets of identical purity but different mechanical strength, did not, however, appear adaptable for various other metals and, therefore, the author suggested its modification. The proposed Cavitation Damage Number included the strain energy of the respective material instead of its yield strength but the objectionable denominator involving maximum bubble radius remained unchanged. Previously, VARGA, CHER-

NYAVSKY, SHALNEV [4] pointed out that the energetical parameter suggested earlier by SHALNEV [5] actually represented the reciprocal of contraction work (specific fracture energy, i.e. the energy absorbed per unit volume of the material up to complete fracture — [6]) and, consequently, the energetical parameter gave a suitable basis for comparison purposes. The specific fracture energy of metals per unit volume does not depend on the force type causing fracture and it is, in practice, independent of the number of stresses required to satisfy the energy demand necessary for fracture, this being of a constant value for each material type. For metals exhibiting no chemical corrosion tendency upon the effect of cavitation, therefore, the energetical parameter makes possible the determination of an interrelationship between cavitation damage effects and specific fracture energies.

Thus, the theory explained above appears suitable to establish an energetical parameter characteristic for cavitation damage intensity which would not depend on the experimental period but, on the other hand, would practically eliminate the changes of material characteristics encountered in the course of the experimental period and is close connected to flow conditions.

The critical material quantity damaged within the incubation period

The previous experiments conducted by authors with cylindrical models employed in test sections built into closed circuit hydrodynamic test devices [7] led to the conclusion that the so-called *critical material quantity value* indicating the completion of the incubation period *does not depend on flow velocity (Fig. 1)* but only on geometrical dimensions such as model diameter, test section dimensions and cavity length (which appears to represent a unique function of the cavitation number — [8], [9]). This was verified by experiments conducted with lead and aluminium test specimens. The same was

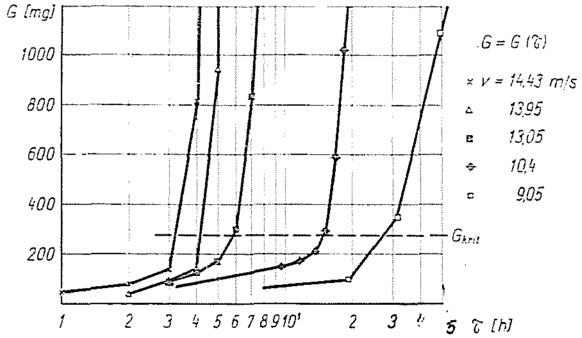

Fig. 1. Erosion weight loss (G) in function of experimental time (τ) for different flow velocities

verified by experiments conducted in order to determine the velocity exponent where the equation $\tau v^5 = \text{const}$ was found to apply to either the critical material quantity damaged or the constant material quantity damaged exceeding the critical quantity, and where τ indicated the experimental period of time, and v represented flow velocity [10]. The exponent value was shown to be less than 5 and of a variable value in the period of incubation prior to arriving at the critical material quantity damaged, and to reach the constant value 5 only by the end of the incubation period, that is, when the critical material quantity damaged has been arrived at. Under the aforesaid conditions the completion of the incubation period can be readily determined although this could be more accurately ascertained by plotting the G/τ^2 curves *(Fig. 2)*. The experiments referred to above similarly verified that the *weight loss per unit time was, within the period of incubation, of a constant value* and, consequently, did not depend on time.

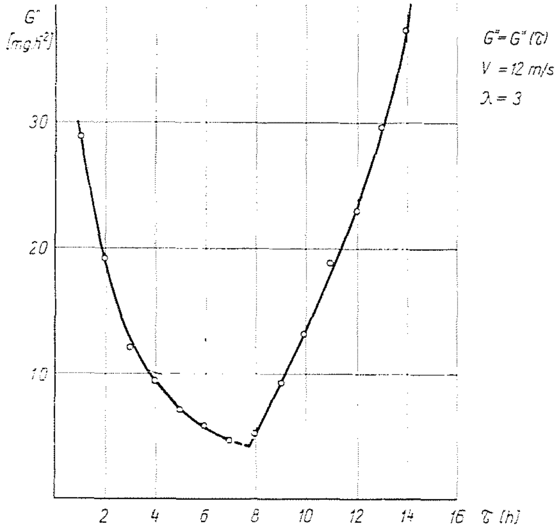

Fig. 2. Variation of the value $G'' = G/\tau^2$ in function of experimental time (τ)

The results introduced support the opinion that, in investigating cavitation damages, the incubation period deserves particular attention. This is all the more true as it may well be assumed that the physical state of the material does not undergo any basic transformation as soon as within the incubation period since only small-size individual pits are created over the surface of the material during that time, with not more than a minimum weight loss. Consequently, the incubation period might be considered as the pure, non-cumulative, true cavitation damage phase (without any secondary phenomena). The second reason why in the incubation period particular attention should be paid is represented by the fact that the weight and/or volume loss produced per unit time is independent of time. When studying the incubation period, the two facts mentioned above refer to the possibility of setting up an energetical parameter suitable for satisfying the requirements discussed in the introduction as well as to arrive at conclusions concerning the geometrical scale effect.

The energetical parameter and the intensity of cavitation damage

Cavitation erosion studies have been conducted in geometrically similar test sections. In the course of the experiments, cavity length equalled the treble of the cylinder diameter, that is, $l_z = 3d$, with the relative (nondimensional) cavity length being of the constant value $\lambda = l_z/d = 3$. As is well known, there is a unequivocal correlation existing between cavity length and cavitation number [8], [9]. Among others, measurement results revealed that, in the course of cavitation damage experiments conducted under identical conditions in geometrically similar test sections of different dimensions, the eroded surfaces are likewise similar. It seemed, therefore, reasonable to determine a geometrical scale number by comparing the eroded surfaces to a characteristic surface area of the specimen tested. As reference area, a quadrangle was selected having one of its dimensions represented by the cylinder diameter and the other by the cavity length. On the basis of the experimental results it could be stated that the eroded surface always appeared proportional to the reference area, and the ratio obtained for geometrically similar test sections represented a constant value. Similar conclusions had been arrived at by GOVINDA RAO [2] in the course of experiments conducted by using a cylindrical model where he found the area of erosion always equals the cavity area. With the reference area indicated by A, and that pertaining to the cylinder of unit diameter by A_0, the energetical parameter may be expressed by the following equation:

$$e = \frac{\Delta V}{Fv}\,\frac{A_0}{A} \quad (\mathrm{mm^3/mkp})$$

where

$\Delta V = G_{kr}/\gamma\tau_{kr}$, the volume loss per unit time in which G_{kr} indicates the weight loss at the end of the incubation period (a constant value independent of flow velocity and characteristic, in case of a given cavity length, to the test section), and τ_{kr} is the experimental period (up to arriving at the critical weight quantity),

$F = \Delta C_x v^2 \varrho d/2$, unit length fraction of the drag of the cylinder model in which ΔC_x indicates the difference of drag coefficients without and with cavitation, respectively.

It follows that erosion intensity is characterized by the

$$i = \frac{\Delta V}{A} \text{ (mm/s)}$$

the average increase of erosion depth per unit time. With this correlated to the reference area A_0 pertaining to the unit cylinder, the relative erosion volume per unit time $\overline{\Delta V} = \Delta V A_0 / A$ is obtained, and dividing this by the power absorbed by drag (Fv) again results in the energetical parameter.

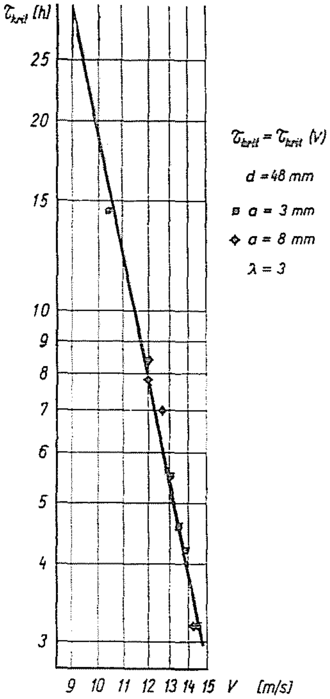

Fig. 3. The critical period of the erosion damage (τ_{krit}) in function of flow velocity (v) — (expressed in logarithmic scale) where a represents specimen thickness

The denominator of the energetical parameter suggested involves the power absorbed by the drag related to the unit length of the model submerged in the flow. This must be proportional to the power absorbed by the damage to the material, that is,

$$P_a = \Delta V \, E_c$$

where $\Delta V = \frac{G_{kr}}{\tau \gamma}$, the volume loss per unit time within the incubation period $(G_{kr} = \text{const})$, and E_c indicates the contraction work. Calculations involving this power seem most reasonable for magnetostriction and rotating-disc test devices but, in case of experiments conducted by using flow devices, the power absorbed by the drag would establish a direct connection with the hydromechanical aspects of the flow. Since in appropriately conducted experiments ϱ, γ, and d represent constant values and ΔC_x may be considered, above the critical Reynolds number, also as constant, the energetical parameter might be expressed in the form

$$e = C_1 \frac{\Delta V}{v^3}$$

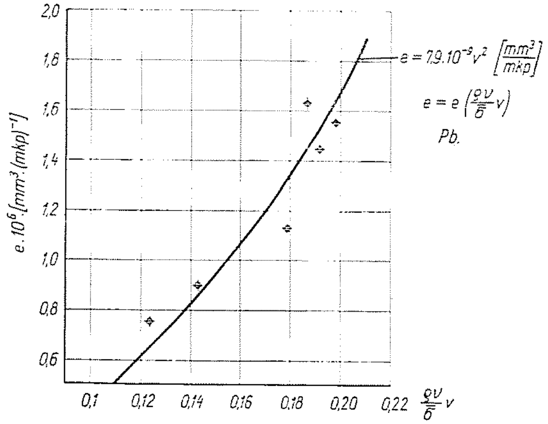

Fig. 4. Energetical parameter (e) in function of the quotient of Weber and Reynolds numbers $\left(\frac{\varrho v}{\bar\sigma} v.\right)$

where C_1 is constant. Since, again, the formula $\tau v^5 = \text{const}$ applies to the critical material quantity *(Fig. 3)*, the energetical parameter may be expressed by the equation below:

$$e = Cv^2$$

which is well supported also by experimental results. At the same time, the latter relation renders adequate opportunity to take also flow velocity effects into consideration. The energetical parameter may be expressed in function of the Reynolds number it seems, however, more reasonable to express it as a function of the $\frac{\varrho v}{\bar\sigma} v$ quotient of the Weber and Reynolds numbers (where $\bar\sigma$ represents surface tension) for this number includes all values concerning the physical properties of the liquid *(Fig. 4)*.

Geometrical scale number

Scale effect may be concluded at by the following theory: if, in case of two geometrically similar (1 and 2) test sections (where the characteristic model dimensions are indicated by d_1 and d_2, respectively), the energetical parameters are equal, then on grounds of the foregoing statements, the following relationship will apply:

$$e = C \frac{\Delta V_1 A_0}{\Delta C_{x1} d_1 v_1^3 A_1} = C \frac{\Delta V_2 A_0}{\Delta C_{x2} d_2 v_2^3 A_2} .$$

However, in case of a constant cavity length such as, for example, $\lambda = 3$

$$A_1 = 3d_1^2; \quad A_2 = 3d_2^2 .$$

With identical flow velocities, that is, if $v_1 = v_2$ and since, as verified by the drag measurements performed in cavitation type flow by means of a cylinder, $\Delta C_{x1} = \Delta C_{x2}$, as a final result it may be written that

$$\frac{\Delta V_1}{d_1^3} = \frac{\Delta V_2}{d_2^3}$$

or

$$\Delta V_1 = \Delta V_2 \left(\frac{d_1}{d_2}\right)^3 = \Delta V_2 L^3,$$

where L represents the geometrical scale number. This scale effect was confirmed by the experiments completed. For example, in experiments conducted by using lead sheets, the value of the critical eroded material quantity for a $d = 48$ mm diameter cylinder in a 48 × 200 mm profile test section amounted to $G_{kr} = 420$ mg. For a $d = 24$ mm diameter cylinder in a 24 × 100 mm profile test section, according to the measurements by SHALNEV, $G_{kr} = 50$ mg was observed.

Thus the scale number is

$$L^3 = \frac{G_{kr\,48\times200}}{G_{kr\,24\times100}} = 8.4$$

This means that $L = 2.03$ which is in good agreement with the theoretical considerations. It will be noted here that this scale effect has been verified in a number of ways but this will be reported in a subsequent paper.

By taking flow velocity effects into account as described above, actually the strength property affecting the material tested has also been taken into consideration. In order to determine the strength property of the material, there are two parameters required: frequency and amplitude of load application. In a previous paper [11], the frequency of vortices shedding periodically from the cylinder have been shown proportional to flow velocity which means that this velocity includes the frequency of the stress affecting the material, as well. Stress amplitude depends, on the other hand, on pressure which is given within the cavitation number.

Summary

Reviewing the well-known energetical theories concerning the intensity of cavitation damage, authors present the results of experiments conducted by means of closed circuit hydrodynamic test devices. Results are summarized, on the basis of weight loss measured at the end of the incubation period, within an energetical parameter characterizing the intensity of cavitation damage. The so-called critical material quantity indicating the completion of the incubation period was found to have a value independent of flow velocity. The parameter is represented by the relationship between the critical eroded material quantity per unit time and the power absorbed by the flow drag of the specimen causing cavitation. The formula τv^5 = const verified earlier was found to apply also to the critical material quantity, just as to the subsequent erosion phase. Due to the aspects concerning material strength properties, as a basis the critical material quantity should be taken into consideration.

Authors demonstrate that the energetical parameter is suitable, in geometrically similar test sections, to determine geometrical scale effects as well.

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