OBSERVATIONS ON CAVITATION VELOCITY-DAMAGE EXPONENT IN A FLOWING SYSTEM

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Several research workers have come to the conclusion that velocity has an extremely strong influence on cavitation erosion, and the eroded volume will change according to some exponent of velocity. Shalnev [1] found this exponent to be $n = 5$. Knapp's [2] tests showed $n = 4 \ldots 6$. Kerr and Rosenberg [3] claim that $n = 5$. Rata [4] and Rao [5] found the exponents between $n = 4 \ldots 8$. Recently, Hammitt [6] submitted data of this kind in connection with his tests carried out on stainless steel specimens in Venturi tube and found that the value of the exponent above a certain time approaches the value of 5.

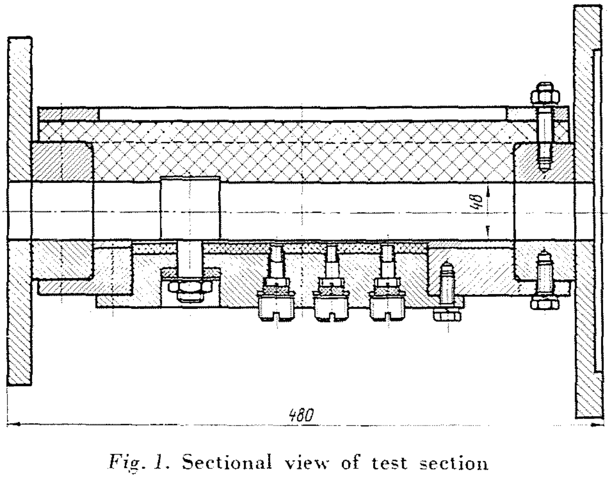

Fig. 1. Sectional view of test section

The results of cavitation erosion tests carried out in the two dimensional closed circuit water tunnel of the Institute of Hydraulic Machines of Polytechnical University, Budapest [7] have proved suitable to investigate the above problem more closely; therefore, in the following considerations, we present such test results as can be referred to the problem.

Test equipment. The experiments were carried out in a test section of 48×200 mm built in to the water tunnel (Fig. 1), in which a bronze cylinder

Table 1

Quotients of the erosion periods
Thickness of the lead plate: $a = 3$ mm
Test section dimensions: 48×200 mm^2
(k)

	$G = 500$	$G = 1000$	$G = 1500$	$G = 2000$ mgr	$G = 3000$	$G = 4000$	$G = 5000$	$G = 6000$
$\frac{\tau_2}{\tau_1}$	1.25	1.22	1.19	1.17	1.18	1.18	1.20	1.22
$\frac{\tau_3}{\tau_1}$	1.45	1.46	1.45	1.43	1.42	1.42	1.45	1.44
$\frac{\tau_4}{\tau_1}$	1.79	1.73	1.70	1.67	1.67	1.68	1.69	1.69
$\frac{\tau_5}{\tau_1}$	4.51	4.35	4.39	4.37	4.46	4.50	4.55	4.57
$\frac{\tau_6}{\tau_1}$	9.52	10.41	11.01	10.76	10.69	10.72	10.85	10.80
$\frac{\tau_3}{\tau_2}$	1.16	1.20	1.21	1.22	1.20	1.20	1.20	1.19
$\frac{\tau_4}{\tau_2}$	1.42	1.42	1.42	1.43	1.41	1.42	1.41	1.39
$\frac{\tau_5}{\tau_2}$	3.60	3.57	3.67	3.72	3.78	3.81	3.79	3.76
$\frac{\tau_6}{\tau_2}$	7.60	8.54	9.21	9.17	9.04	9.08	9.05	8.87
$\frac{\tau_4}{\tau_3}$	1.23	1.18	1.17	1.17	1.17	1.18	1.17	1.17
$\frac{\tau_5}{\tau_3}$	3.11	2.97	3.03	3.04	3.13	3.17	3.14	3.17
$\frac{\tau_6}{\tau_3}$	6.56	7.12	7.60	7.50	7.50	7.56	7.51	7.48
$\frac{\tau_5}{\tau_4}$	2.52	2.51	2.58	2.61	2.68	2.68	2.69	2.71
$\frac{\tau_6}{\tau_4}$	5.32	6.01	6.47	6.43	6.41	6.40	6.42	6.40
$\frac{\tau_6}{\tau_5}$	2.11	2.39	2.51	2.46	2.39	2.38	2.39	2.36

τ_1 Period of the erosion test carried out with a velocity $v_1 = 14.43$ m/s
τ_2 Period of the erosion test carried out with a velocity $v_2 = 13.95$ m/s
τ_3 Period of the erosion test carried out with a velocity $v_3 = 13.6$ m/s
τ_4 Period of the erosion test carried out with a velocity $v_4 = 13.05$ m/s
τ_5 Period of the erosion test carried out with a velocity $v_5 = 10.4$ m/s
τ_6 Period of the erosion test carried out with a velocity $v_6 = 9.05$ m/s

Table 2

Quotients of the erosion periods
Thickness of the lead plate: $a = 8$ mm
Test section dimensions: 48×200 mm^2
(k)

	$G = 500$	$G = 1000$	$G = 1500$	$G = 2000$ mgr	$G = 3000$	$G = 4000$	$G = 5000$	$G = 6000$
$\frac{\tau_2}{\tau_1}$	1.23	1.26	1.28	1.30	1.33	1.36	1.34	1.34
$\frac{\tau_3}{\tau_1}$	2.15	2.06	2.07	2.11	2.04	2.04	1.98	1.97
$\frac{\tau_3}{\tau_2}$	1.75	1.64	1.62	1.62	1.54	1.50	1.48	1.47

τ_1 Period of the erosion test carried out with a velocity $v_1 = 14.35$ m/s
τ_2 Period of the erosion test carried out with a velocity $v_2 = 13.6$ m/s
τ_3 Period of the erosion test carried out with a velocity $v_3 = 12.74$ m/s

Fig. 2. Photograph of lead specimen submitted to cavitation erosion. Size of specimen is 96×240 mm

Table 3

Velocity-scale factor of cavitation erosion
Thickness of the lead plate: $a = 3$ mm
Test section dimensions: 48×200 mm²

	$\sqrt[5]{k}$							
	$G = 500$	$G = 1000$	$G = 1500$	$G = 2000$ mgr	$G = 3000$	$G = 4000$	$G = 5000$	$G = 6000$
$\frac{v_1}{v_2} = 1.034$	1.046	1.040	1.036	1.032	1.034	1.034	1.037	1.040
$\frac{v_1}{v_3} = 1.061$	1.077	1.079	1.077	1.075	1.073	1.073	1.077	1.076
$\frac{v_1}{v_4} = 1.106$	1.123	1.116	1.112	1.108	1.108	1.109	1.111	1.111
$\frac{v_1}{v_5} = 1.388$	1.351	1.342	1.344	1.345	1.348	1.351	1.354	1.355
$\frac{v_1}{v_6} = 1.594$	1.569	1.598	1.616	1.608	1.606	1.607	1.611	1.609
$\frac{v_2}{v_3} = 1.026$	1.030	1.037	1.039	1.041	1.037	1.037	1.037	1.035
$\frac{v_2}{v_4} = 1.069$	1.073	1.073	1.073	1.074	1.071	1.073	1.071	1.068
$\frac{v_2}{v_5} = 1.341$	1.292	1.290	1.297	1.301	1.305	1.307	1.306	1.303
$\frac{v_2}{v_6} = 1.541$	1.500	1.536	1.559	1.558	1.553	1.555	1.554	1.547
$\frac{v_3}{v_4} = 1.042$	1.043	1.034	1.032	1.032	1.032	1.034	1.032	1.032
$\frac{v_3}{v_5} = 1.308$	1.254	1.235	1.248	1.246	1.256	1.260	1.257	1.260
$\frac{v_3}{v_6} = 1.503$	1.457	1.481	1.500	1.497	1.497	1.499	1.497	1.496
$\frac{v_4}{v_5} = 1.255$	1.203	1.202	1.209	1.212	1.218	1.218	1.219	1.221
$\frac{v_4}{v_6} = 1.442$	1.397	1.432	1.453	1.451	1.450	1.450	1.451	1.450
$\frac{v_5}{v_6} = 1.149$	1.161	1.190	1.202	1.197	1.190	1.189	1.190	1.187

$v_1 = 14.43$ m/s
$v_2 = 13.95$ m/s
$v_3 = 13.6$ m/s
$v_4 = 13.05$ m/s
$v_5 = 10.4$ m/s
$v_6 = 9.05$ m/s

Table 4

Velocity-scale factor of cavitation erosion
Thickness of the lead plate: $a = 8$ mm
Test section dimensions: 48×200 mm^2

	$\sqrt[5]{k}$							
	$G = 500$	$G = 1000$	$G = 1500$	$G = 2000$ mgr	$G = 3000$	$G = 4000$	$G = 5000$	$G = 6000$
$\frac{v_1}{v_2} = 1.055$	1.042	1.047	1.050	1.054	1.058	1.063	1.060	1.060
$\frac{v_1}{v_3} = 1.126$	1.166	1.156	1.157	1.161	1.153	1.153	1.147	1.146
$\frac{v_2}{v_3} = 1.068$	1.119	1.104	1.102	1.102	1.090	1.085	1.082	1.081

$v_1 = 14.35$ m/s
$v_2 = 13.6$ m/s
$v_3 = 12.74$ m/s

of $d = 48$ mm diameter was placed with its horizontal centre line perpendicular to the direction of flow. Lead plates of 3 and 8 mm thickness attached to fredal by adhesive (Elastyrol D) served as specimens exposed to cavitation effect; they were built in to one of the walls of the test section in the manner shown in Fig. 1. A photograph taken from such a specimen which was exposed to cavitation erosion is shown in Fig. 2. Water for the tests was taken from the municipal water system and was kept at nearly constant temperature. Pressure and flow velocity could be altered independently of one another. Length of the cavitation zone behind the cylinder was decided to be $l = 3\,d$ as measured from the centre line of the cylinder, as experience from earlier measurements indicated that erosion is the most intense with this zone length.

Results and their evaluation. Investigation of cavitation erosion was carried out with velocity limits $v = 9.05\ldots14.43$ m/s, i.e. between Reynolds number limits of $Re = 3.58\times10^5\ldots7.2\times10^5$. The eroded volumes in the function of time were determined by weighing, with different $v =$ const velocities. Curves indicating loss of weight with different velocities are shown in Figs. 3 and 4. In figures G is the eroded volume is given in milligrams and τ is the duration of the erosion test in hours. In Tables 1 and 2 are shown the quotients (marked k) of the test times belonging to identical eroded volumes for lead plate specimens of 3 and 8 mm thickness, with reference to 500...6000 mgr of eroded volumes and to all velocities used in the course of testing. Similarly, in Tables 3 and 4, the $\sqrt[5]{k}$ values, as well as the different velocity ratios, for various eroded volumes of constant value are presented, also with lead plates of 3 and 8 mm thickness. A comparison of the data of these last

Tables proves that the eroded volume changes according to the 5th exponent of the velocity. It must be noted that the value of the exponent is the same even with smaller eroded volumes of constant value (approximately up to the value of $G = 500$ mgr). Until the weight reduction of 1000 mgr is reached,

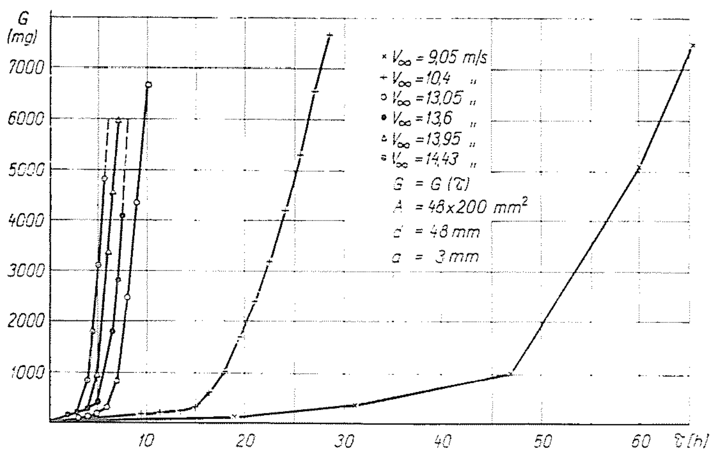

Fig. 3. Eroded volume (G) in the function of time (τ) of the erosion test, with different flow velocities (v_∞). Thickness of lead plate: $a = 3$ mm

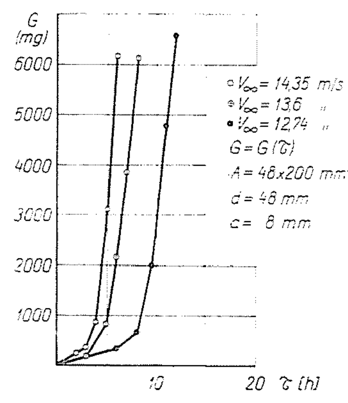

Fig. 4. Eroded volume (G) in the function of time of the erosion test (τ), with different flow velocities (v_∞). Thickness of lead plate: $a = 8$ mm

the specimens show only small individual craters; however, when for instance the reduction amounts to 6000 mgr, rough eroded surfaces appear. In spite of that, the regularity remains valid even between these extreme limits. This fact also proves that successful tests on cavitation erosion can be carried out with lead specimens, in contradiction to EISENBERG's [8] conclusions.

The perfectly identical results of the tests carried out with two lead plates of different thickness, but of identical quality, indicate that no scale effect appears with the specimens.

The fact that the exponent found in the tests carried out by HAMMITT in a Venturi tube with stainless steel specimens offering the strongest resistance to cavitation erosion is identical with the results of the tests carried out on

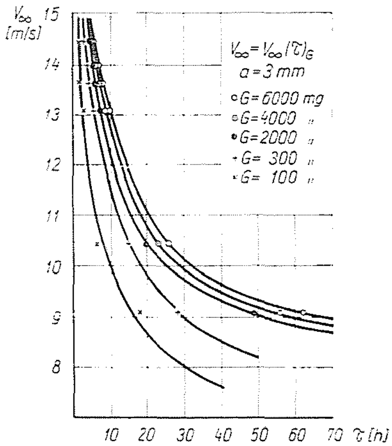

Fig. 5. Relationship between flow velocity and time of erosion test (τ), with constant eroded volumes (G): $v_\infty = v_\infty(\tau)_G$

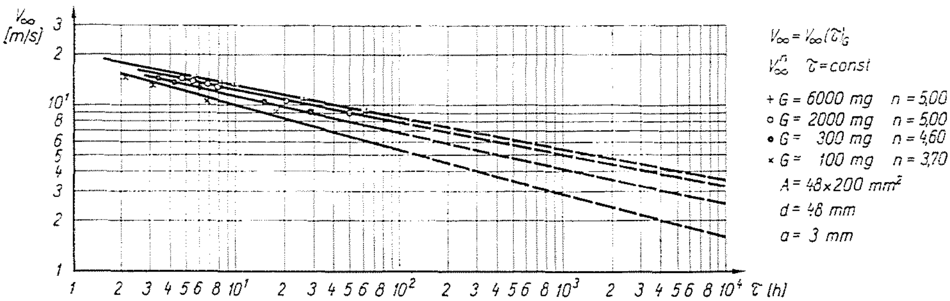

Fig. 6. Relationship between flow velocity (v_∞) and the time of erosion test (τ), with constant eroded volume (G), $\lg v_\infty = \lg v_\infty(\lg \tau)_G$

lead specimens leads us to the conclusion that the value of the exponent is independent of the material, even flow conditions have only little influence on it.

If the velocities belonging to constant eroded volumens are drawn in the function of time, the curves shown in Fig. 5 will appear yielding curves corresponding to equation $\tau\, v^5 =$ const., having the values $G = 6000\ldots500$ mgr. The same drawn in logarithmic scale (Fig. 6), parallel straight lines will appear for the various larger volumes of constant value. For smaller volumes which naturally involve considerably smaller times, the direction tangents of the straight lines drawn in logarithmic scale will show some change, indication of a smaller value of the exponent. This was the basis for drawing the relation shown in Fig. 7., giving the changes in the exponent of velocity for various eroded volumes. HAMMITT [6] submits a similar relation in the function of time, based on tests with three kinds of material (aluminium, stainless steel and carbon steel).

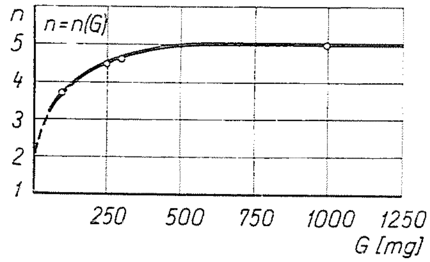

Fig. 7. Velocity-damage exponent (n) in the function of eroded volume (G)

On the basis of experimental results considered previously the following relation between times and velocities can be written for identical eroded volumes

$$\frac{\tau_2}{\tau_1} = \left(\frac{v_1}{v_2}\right)^5$$

or, with $v_1/v_2 = W$

$$\tau_2 = \tau_1 W^5$$

Cavitation erosion is connected with the frequency and the pressure around the bubbles. The frequency determines the number of blows on the surface; the pressure determines the energy of the bubbles.

In our earlier investigations we determined the frequencies of the eddies shedding periodically from the cylinder [9] in the range above the critical Reynolds number, i.e. the range of Reynolds number suitable for the present tests. These tests disclosed a univocal relationship between the Strouhal number (S) and the cavitation number (σ). For the test section in question we found the relation

$$S = 0.197 \sqrt{\sigma}$$

(Fig. 8). From the former relation if follows that if $\sigma = \text{const}$, $S = \text{const}$, $d = \text{const}$ is valid, that is $S = f_1 d/v_1 = f_2 d/v_2$, or

$$\frac{f_2}{f_1} = \frac{v_2}{v_1}$$

According to this, in the case of cavitation erosion damage tests made with constant cavity length (σ = const), the frequency of pulsation of the zone of cavitation will change proportionally to the stream velocity.

If this is compared to the experimental result giving the relation between cavitation erosion and the fifth exponent of velocity, it appears that the role

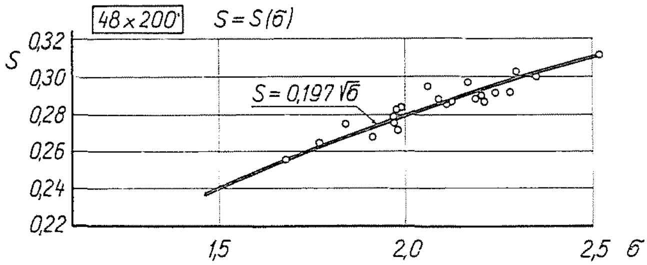

Fig. 8. Strouhal number (S) in the function of cavitation number (σ)

of the pressure is very significant and that cavitation damage is proportional to the square of pressure. The square-relation between the pressure and velocity explains thus the connection to the fourth exponent of the velocity, which leads, together with the relation of the frequency to the velocity, to the fifth exponent. This assumption seems to be justified by the literature dealing with the dynamics of bubbles.

Figs. 5 and 6 also open the way of looking into the problem of threshold velocity [5], [10], [11], [12], which seems to turn up in literature very often. In view of the test results, we cannot speak of threshold velocity in the sense that a given eroded volume could be attained under a certain velocity limit only during an infinite long time. At the same time, practical threshold velocity can be marked down in such a way that a predetermined slight eroded volume should appear after a long time [1] (say, e.g. 500 or 1000 hours, or even longer).

Conclusions

The velocity-damage exponent of the cavitation erosion will be determined fundamentally by flow velocity and its value is independent of the material.

Cavitation erosion will be determined by the frequency and the static and dynamic pressures in the flow.

The velocity exponent of the cavitation erosion is, in the first stage of damage, dependent on time; after a certain time of damage, i.e. after a certain volume of material has been detached, it becomes constant.

Threshold velocity cannot be marked on a theoretical basis, it can be determined at best on the basis of a presumed erosion time based on a practical value.

Summary

The paper presents some results of cavitation erosion tests carried out on lead specimens in a closed water tunnel, using a cylindrical model placed in waterflow. The tests yielded the relationship $\tau_2/\tau_1 = (v_1/v_2)^5$ between test times and flow velocities belonging to identical eroded volumes; this relationship is in deep-going connection with the mechanics of cavitation damage, since cavitation erosion is to be determined by the frequency and the static and dynamic pressures in the flow. The authors claim that the velocity exponent of cavitation erosion is to be determined fundamentally by flow velocities and its value is independent of the material. The velocity damage exponent of the cavitation erosion is, at the beginning stage of damage, dependent on time; after a certain time of damage, i. e. after a certain volume of material has been eroded, it will be of constant value. The authors state that a threshold velocity for the cavitation erosion cannot be marked down on a theoretical basis, it can only be determined on the basis of damage time based on a practical value.

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