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VELOCITY EXPONENT AND CAVITATION NUMBER FOR VENTURI CAVITATION EROSION OF 1100-O ALUMINUM AND 1018 CARBON STEEL

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Summary

The purpose of the present investigation is to evaluate the effect of Venturi throat velocity on the cavitation erosion of specimens for constant cavitation number, which is here based on Venturi discharge conditions. 1018 carbon steel and 1100-O aluminum were tested in the University of Michigan high speed cavitation tunnel with tap water at 27 °C (80 °F). Results of present tests are consistent with previous work done at the University of Michigan, showing that the velocity–damage exponent varies over the range ±1 - 5 for the velocity range 10 - 49 m s^{-1}.

1. Introduction

Cavitation erosion is a major problem in liquid flow systems. Over many years, there have been many investigations of cavitation damage in hydrodynamic machinery both in laboratory and in field tests; investigations have attempted to find damage-predicting criteria for design and industrial applications. The most prominent and well-known cavitation damage "scale effects" are probably those due to variations in the velocity or suppression pressure [1]. Since in the conventional static vibratory facility, which is the most economical and accelerated device for cavitation erosion testing, basic flow parameters such as velocity are lacking, the velocity effect on damage can be investigated only in flow systems such as a Venturi system. However, in such systems more time is needed to attain results and they are therefore more expensive.

The now well-known velocity effect "exponent law" (the damage rate is proportional to V^n) was first proposed by Knapp [2]. He investigated velocity effects on the pitting rates of soft aluminum in a water tunnel at the California Institute of Technology in the 1950s. He found that the

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exponent was about 6. Because of its simplicity, Knapp's exponent law has been widely adopted in the comparison of velocity damage data. However, the model appears to be oversimplified. Values of the velocity exponent reported elsewhere (*e.g.* refs. 1 and 3) vary over a very wide range from about −74 to 17. Most investigators [4], however, have obtained exponents closer to the exponent found by Knapp. Previous data summarized in Table 1 (which is from ref. 4) are included here for convenience. The large scatter of velocity exponent values indicates that it is affected by numerous factors such as suppression pressure, cavitation number σ (σ is defined in eqn. (1)), the geometry of the flow device, the Reynolds number, the size and shape of the cavitation source, test fluid (*e.g.* the air content in water), flow stability, the material and shape of the specimens etc.

It is obvious that velocity and suppression pressure cannot be varied arbitrarily and independently if the cavitation number σ is to be maintained constant. It is considered probable that the erosion exponent n will be very sensitive to variation in downstream suppression pressure. The cavitation number is thus here so defined. Also, "pseudo" and "true" damage scale effects [1] should be distinguished. True damage scale effects are defined [1] as those for which the cavitation number and the flow geometry are fixed.

Venturi damage tests at constant σ for two materials (1018 carbon steel and 1100-O aluminum) were recently conducted in the high speed cavitation tunnel at the University of Michigan in tap water at 27 °C (80 °F). The purpose of these tests was to study and evaluate the effect of flow velocity on cavitation erosion and to compare the results with previous data from the same facility.

2. Venturi tunnel

The cavitation tests were performed in a high speed closed-loop cavitation tunnel. The Venturi Plexiglas test section is shown in Fig. 1. The throat diameter is 12.7 mm (0.510 in). The throat velocities, controlled by the pump speed and the downstream pressure (which is maintained by a surge tank attached to the downstream tank), were 36.3 and 49 m s^{-1}. The water temperature was 27 °C (80 °F). Two erosion specimens (6.35 mm in diameter) were inserted flush with the Venturi diffuser wall in the same axial plane (Fig. 1) together with a pressure probe (for some tests). Termination of the cavitation cloud (observed visually) is in the specimen–probe plane for the lower velocity. It moves somewhat upstream for the higher velocity, if σ is maintained constant.

The cavitation number K (also symbolized by σ) is defined for these tests as follows:

$$\sigma = K = \frac{P_d - P_v}{0.5\rho V^2} \tag{1}$$

TABLE 1

Summary of experimental studies: the velocity exponent for cavitation erosion[a]

Type of test equipment	*Material of the test specimen*	*Cavitation number or cavity length*	*Test duration*	*Velocity* ($m\ s^{-1}$)	*Erosion criterion D*	*Velocity exponent in* $D = Ku^{n_1}$ *or* $D = K(u - u_0)^{n_2}$
Axisymmetric water tunnel; hemispherical nose ogival after body	2S-F Al	l = 25 mm and l = 51 mm	10 - 30 min	18 - 30	Number ($s^{-1}\ in^{-2}$) of pits	$n_1 = 6$
Field test on 30000 kW Francis turbine	2S-O Al test piece on runner	l = 152 - 203 mm	5 - 20 min	18 - 30	Number ($s^{-1}\ in^{-2}$) of pits	$n_1 = 6$ (5.6 - 6.3)
Two-dimensional water tunnel; cylindrical source	Pb	$\lambda = 3$ near peak erosion	—	14 - 23	Rate of volume erosion	n_1 = 4 - 5 near peak erosion
Field hydraulic turbine	Steel runner	—	Up to 100 min	5 - 9	Radioisotope technique	n_1 = 5 - 8
Venturi test rig, cylindrical source	Steel, Al and Plexiglas	Near peak erosion	Varied	15 - 30	Volume loss	n_1 = 1.7 - 5; n_1 increases with test time
Two-dimensional water tunnel; cylindrical source	Pb	$\lambda = 3$	Varied	9 - 14	Weight loss	n_1 = 2 - 5; n_1 increases with test time
Venturi test rig; tapered piece projecting into the Venturi; Hg	302 stainless steel	Varied	30 - 100 h	6 - 20	Volume loss	$n_1 = \pm 1$ - 2
Venturi test rig; tapered piece projecting into the Venturi; Hg	302 stainless steel	Varied	—	6 - 20	Volume loss	n_1 = 0 - 5; depends on σ
Venturi test rig	Brass	Constant	—	37 - 49	Weight loss	$n_1 = 7$
Two-dimensional water tunnel; cylindrical source	Pb	λ = 2.5 - 3	Incubation period	12 - 20	Volume loss	$D \propto L^3 u^{n_1}$; $n_1 = 5$

(continued)

TABLE 1 *(continued)*

Type of test equipment	*Material of the test specimen*	*Cavitation number or cavity length*	*Test duration*	*Velocity* ($m\ s^{-1}$)	*Erosion criterion D*	*Velocity exponent in $D = Ku^{n_1}$ or $D = K(u - u_0)^{n_2}$*
Rotating disk in water; holes on the disk to induce cavitation	Eight different alloys	$\sigma = 0.084$, $\sigma = 0.125$ and $\sigma = 0.217$	Up to 40 h	39 - 63	Volume loss	$1 < n_1 < 12$; $1 < n_2 < 7$; high exponent at low volume loss
Rotating disk; cylindrical source	Pb–Sb alloy	$\sigma = 0.25$, $\sigma = 0.5$ and $\sigma = 0.75$	90 min	23 - 50	Weight loss	$7 < n_2 < 10$; $0.25 < \sigma < 0.75$; u_0 depends on static pressure
Rotating disk; holes on the disk to induce cavitation	Al	$\sigma = 0.23$	30 min	26 - 34	Weight loss	$n_1 = 9.55$
Venturi test rig; cylindrical source	Pb	$\lambda = 1 - 10$	—	15 - 25	Volume loss	$5 < n_1 < 8$ for noise and erosion
Venturi test rig; cylindrical source; Hg	304 stainless steel	At peak erosion	For constant rate erosion	7, 9	Weight loss rate	$n_1 = 3.7$
Two-dimensional water tunnel; cylindrical source	Pb	Near peak erosion	0 - 14 h	7 - 25	Weight loss	$n_1 = 2 - 5$; n_1 increases with test time
Two-dimensional water tunnel; cylindrical and 30° wedge sources	Pb	Near peak erosion	—	9 - 14	Volume loss rate	$n_1 = 5$ for erosion and noise; n_1 depends on σ
Water tunnel	—	—	Varied up to 5 h	—	Weight loss	$n_1 = 10 - 2.5$; n_1 decreases with test time
Two-dimensional water tunnel; cylindrical source	Al	Varied	Varied up to 100 min	20 - 30	Volume loss	$n_1 = 6$ for initial cavitation; $n_1 = 17$ for peak erosion

Venturi test rig; circular pin	Al and Cu	—	1 h	18 - 27	Weight loss	$n_1 = 7$
Rotating foil facility; hydrofoil (NACA-16-021) source	1100-F Al	At peak erosion	10 - 70 h	49 - 59	Erosion intensity	$n_1 = 6$; erosion depends on source size and σ
Two-dimensional water tunnel; cavitation behind a step	1100-F Al	$\sigma = 0.33$	10 - 190 min	17 - 21	Number (s^{-1} in^{-2}) of pits	$n_1 = 6$
Rotating disk; equilateral prism (apex facing downstream)	1100-O Al	$\sigma = 0.196$	30 min	39 - 46	Weight loss	$n_1 = 5.5$ for peak erosion and optimum source size

[a]Table from ref. 4.

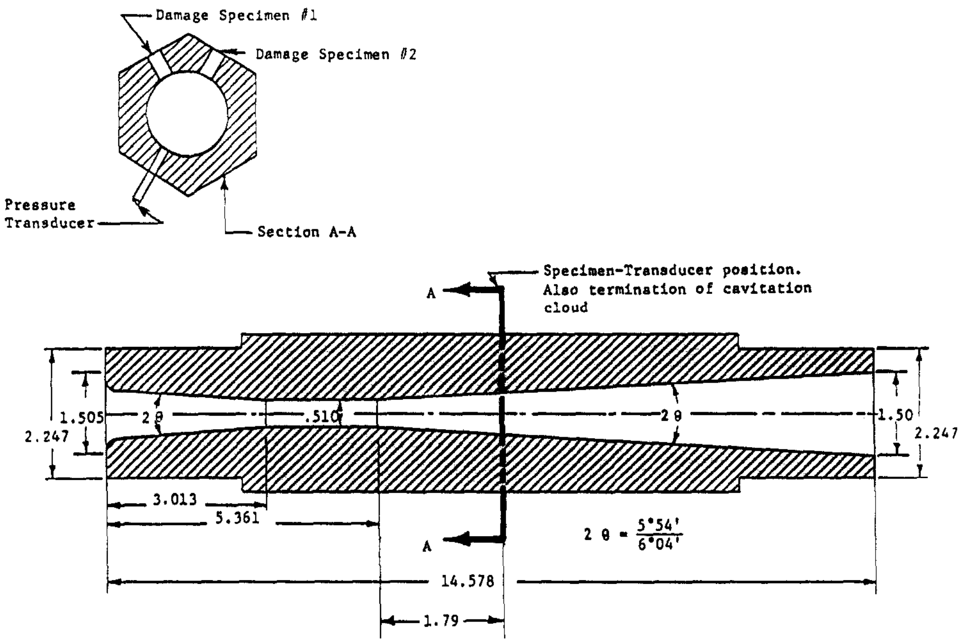

Fig. 1. Damage Venturi flow path (all dimensions in inches).

where P_d is the pressure immediately downstream of the Venturi, P_v the vapor pressure, V the throat velocity and ρ the liquid density. Since the cavitation damage rate has been shown here to be very sensitive to downstream pressure, this value is used to define the cavitation number σ.

In the Venturi tunnel at the University of Michigan, the cavitation condition and throat velocity are controlled by the pump speed and the visual observation of the termination of the cavitation cloud. It is desirable to terminate this cloud approximately in the axial plane where the specimens are located. This setting can be achieved by regulating both upstream and downstream pressures to hold the pressure difference across the Venturi section as needed to obtain the desired throat velocity for the proper termination point. For given Venturi and cavitation cloud termination, there should ideally be only one cavitation number for a given throat velocity. However, bubbles in the cavitation cloud cover an extended axial region in the Venturi (Fig. 2) and do not collapse in a simple steady state plane, as earlier confirmed by high speed motion pictures [1]. For this reason, and also because of other undefined cavitation scale effects, different values for σ were obtained when the throat velocity was varied and the visual cavitation termination point was held constant. Thus the cavitation number was maintained constant for the present tests although the visual termination point then varied, moving slightly upstream as the velocity was increased.

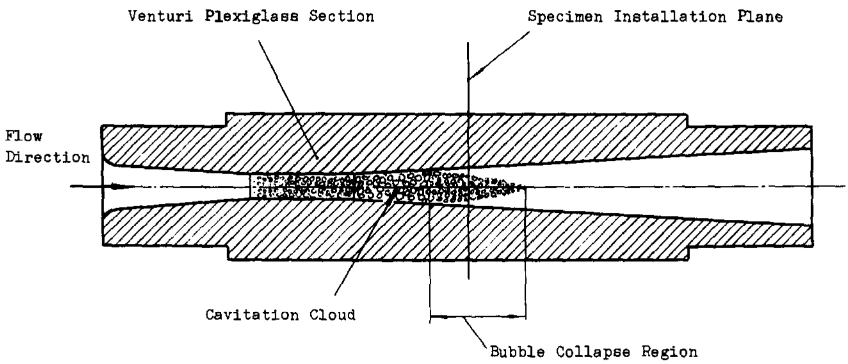

Fig. 2. Cavitation cloud in Venturi test section.

3. Test results

Figure 3 shows the cumulative erosion of 1018 carbon steel specimens as a function of cumulative time. The results are summarized in Table 2. Curves 1 and 2 of Fig. 3 allow a constant σ (0.76) comparison. Values of the mean depth of penetration rate MDPR are the best straight line approximations for the steady portion of the cumulative curves. They are thus not maximum values $MDPR_{max}$. In these and other curves the small oscillations in the erosion rate should be noted. These variations are valid, since they generally involve several successive data points. A comparison of curves 1 and 2 of Fig. 3 shows that the velocity exponent n in the relation MDPR $\propto V^n$ is 1.06 at $\sigma = 0.76$ (see Fig. 8). Thus velocity in this test did not have as much effect on the erosion rate as usual. Figure 3, curves 1 and 3, are for the same velocity, but differing values of σ. The erosion rate from Fig. 3, curve 1 (higher σ), is four times higher than that from Fig. 3, curve 3, which is for a lower (0.62) value of σ.

TABLE 2

Summary of results for 1018 carbon steel

Specimen number	*Throat velocity* (m s^{-1})	*Cavitation number K*	MDPR (μm h^{-1}	($\times 10^{-3}$ in h^{-1}))	n[a]
16, Cr-5, Cr-4	49	0.76	1.12	(0.044)	1.06
11, 12[b]	36.3	0.76	0.81	(0.032)	
7, 8[b]	49	0.62	0.31	(0.012)	

[a] n is the exponent in the relation MDPR $\propto V^n$; $K = 0.76$.
[b] Reference 5.

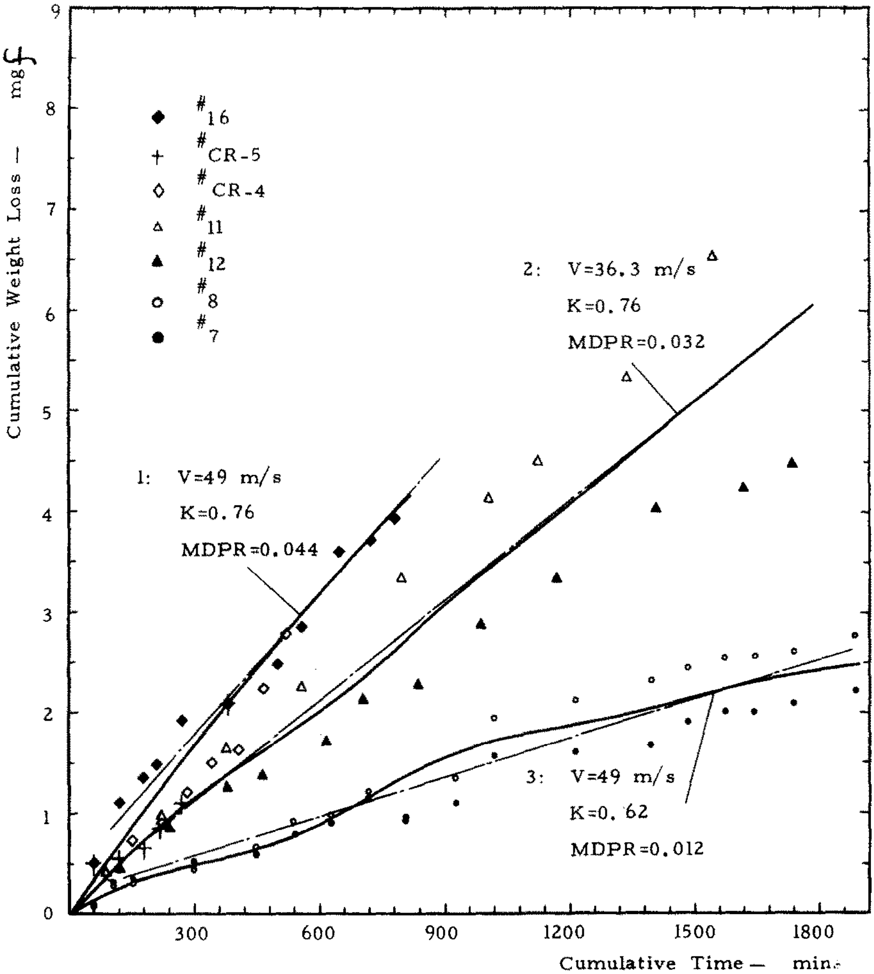

Fig. 3. Effect of σ and velocity in 1018 carbon steel Venturi test in tap water at 80 °F.

Figure 4 shows the probable overall variation in MDPR with σ for these tests for both aluminum and carbon steel. The MDPR variation for changing σ is presumably caused by the conflicting effects at increasing suppression pressure $P_{sv} = P_d - P_v$ of increased stresses from bubble collapse and the reduced number of bubbles. Damage of course vanishes at either very high values of σ (no cavitation) or very low values of σ ($P_{sv} = 0$). Since the erosion rate increases strongly with σ, at least for carbon steel, over the velocity range tested, it is certain that a simple velocity exponent model is not in general tenable.

Figures 5 - 7 show the results of various tests of weight loss *versus* cumulative time for 1100-O aluminum. These are summarized in Table 3. Figure 5, which shows our latest results, agrees fairly well with our previous

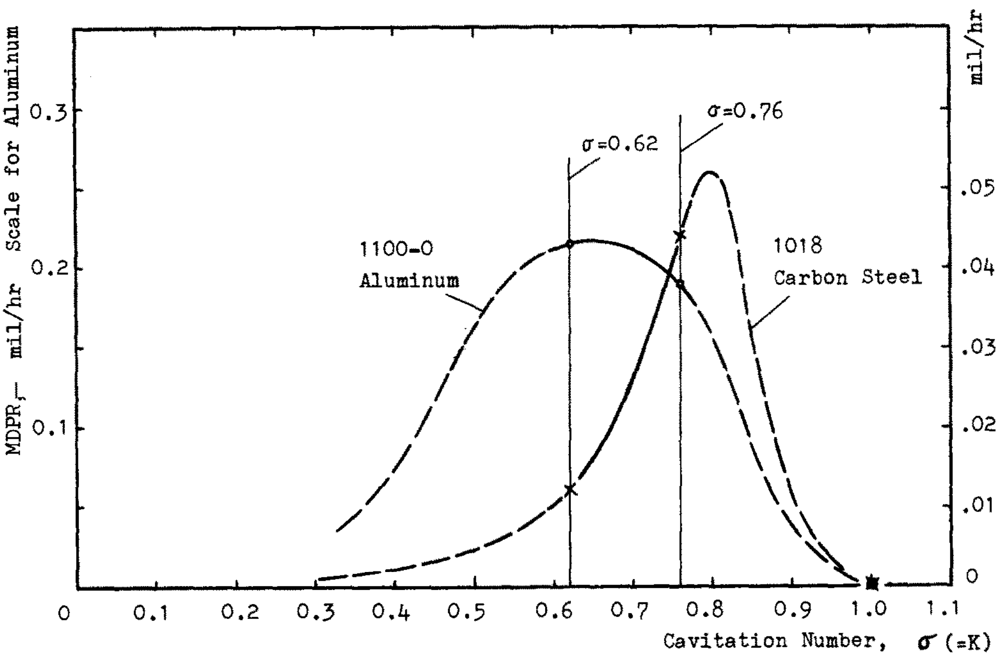

Fig. 4. Effect of the downstream cavitation number on the erosion rate in the University of Michigan Venturi at a velocity of 49 m s^{-1}.

TABLE 3

Summary of results for 1100-O aluminum

Specimen number	*Throat velocity* (m s^{-1})	*Cavitation number K*	MDPR (μm h^{-1}	($\times 10^{-3}$ in h^{-1}))	n[a]
3, 4[b]	49	0.76	6.35	(0.25)	
1, 2[c]	49	0.76	3.30	(0.13)	
4	49	0.62	6.35	(0.25)	
3[d]	49	0.62	4.47	(0.18)	
Plain 1[e]	49	0.61	7.07	(0.28)	
Plain 2[e]	49	0.61	7.19	(0.28)	
Curve 1[e]	49	0.61	4.72	(0.19)	$4.0^{+16\%}_{-31\%}$
Curve 2[e]	49	0.61	6.93	(0.27)	
Plain 1[e]	36.3	0.56	1.83	(0.072)	
Plain 2[e]	36.3	0.56	1.96	(0.077)	
Curve 1[e]	36.3	0.56	1.77	(0.070)	
Curve 2[e]	36.3	0.56	1.78	(0.071)	

[a] n is the exponent in the relation MDPR $\propto V^n$; $K = 0.60$.
[b] Reference 6.
[c] Reference 7.
[d] Reference 8.
[e] Reference 9.

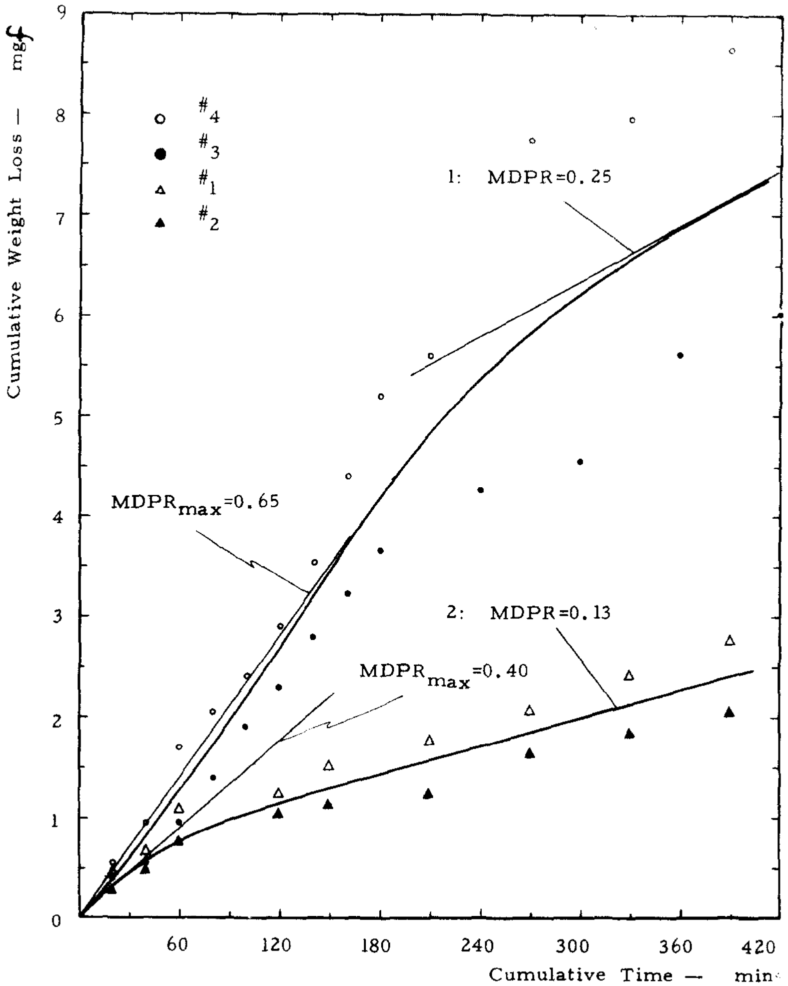

Fig. 5. Weight loss *vs.* cumulative time for 1100-O aluminum Venturi tests (tap water at 80 °F; velocity, 49 m s^{-1}; K = 0.76).

data [5, 10, 11]. These had shown a velocity exponent $n \approx 4$ (Fig. 7) in the relation MDPR $\propto V^n$. In these tests with a fixed cavitation termination point, σ varied substantially, being equal to 0.56 for a velocity of 36.3 m s^{-1} and 0.61 for a velocity of 49 m s^{-1}. Thus the velocity exponents are not valid for comparisons with constant σ. The same specimens (Fig. 7) were continued through the entire test for both velocities. It was thought [5] that the "preconditioning" from the low velocity portion of the tests might have affected the high velocity results. Hence, the high velocity test was repeated [8] and n = 3.5 is obtained by a comparison between Figs. 6 and 7. For the later tests (Fig. 6), the cavitation number was about 0.62. The tests of Figs. 6 and 7 show that the preconditioning was in fact not very important.

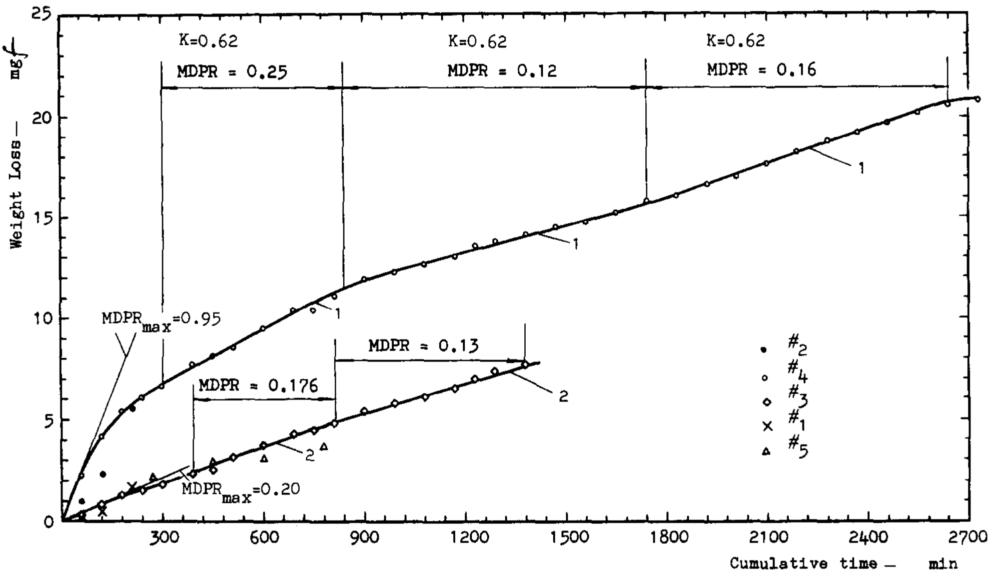

Fig. 6. Weight loss *vs.* cumulative time for 1100-O aluminum Venturi cavitation erosion test (throat velocity, 49 m s^{-1}).

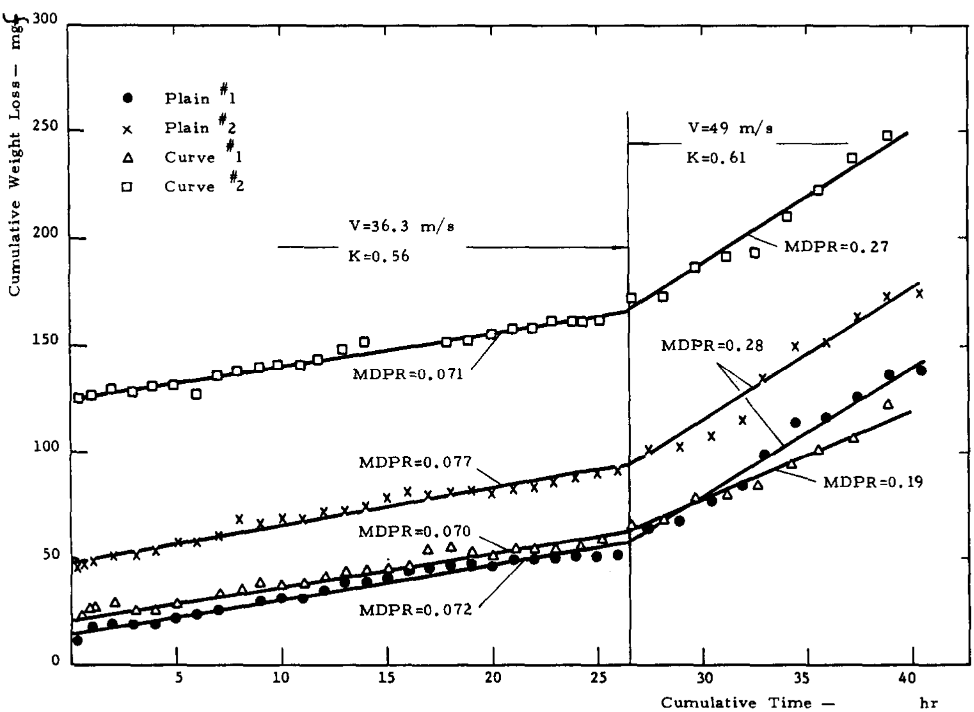

Fig. 7. Results of 1100-O aluminum Venturi cavitation damage tests in tap water at 80 °F.

If all 1100-O aluminum data are combined on a log–log plot, a velocity exponent of about 4 is still obtained (Fig. 8) for 1100-O aluminum. However, for 1018 carbon steel, $n \approx 1.1$. The variation in σ renders the exponent values inapplicable for constant σ but pertinent to a constant extent of cavitation. For 1100-O aluminum the erosion rate (Table 3 and Fig. 4) does not vary appreciably with σ for the two points tested. This result is consistent with our general σ–damage rate curves (Fig. 4).

All the velocity exponent data for cavitation erosion tests in the University of Michigan Venturi facility with water and also mercury as test liquids are summarized in Table 4. In all cases, the exponents were less than

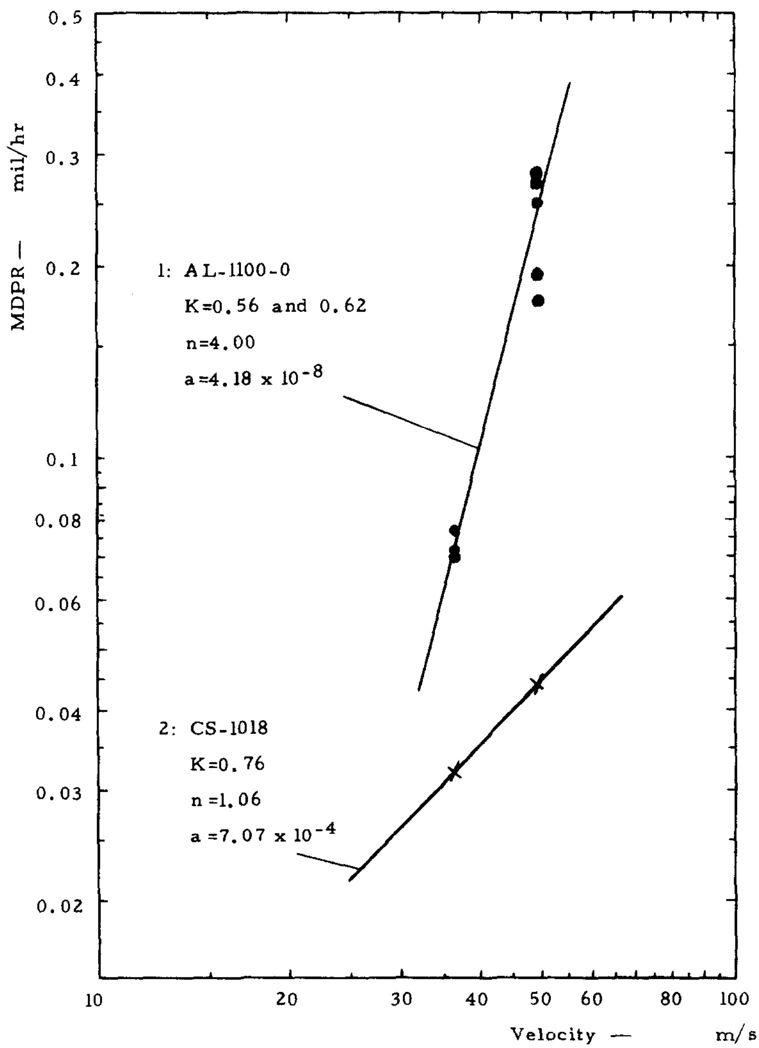

Fig. 8. Velocity exponent for Venturi cavitation erosion tests in tap water at 80 °F: values of a and n are for the relation MDPR = aV^n.

TABLE 4

Summary of velocity–damage exponent values for cavitation erosion tests at the University of Michigan

Type of test equipment and reference	*Test fluids*	*Materials (test specimen)*	*Cavitation number K*	*Test duration* (h)[a]	*Velocity* (m s^{-1})	*Velocity exponent n*
Venturi; cylindrical throat; foil specimen [12]	Water	Stainless steel	Near peak erosion	12	10.4 - 20	4.9
				3.5		3.9
		Carbon steel		1		2.4
		Al		5 min		1.7
Venturi; cylindrical throat; foil specimen [13]	Hg	302 stainless steel	Varied	30 - 100	6 - 20	±1 - 2
Venturi; cylindrical throat; foil specimen [14]	Hg	302 stainless steel	Varied	30 - 100	6 - 20	0 - 5
Venturi; cylindrical throat; foil specimen [15]	Hg	304 stainless steel	At peak erosion	For constant rate erosion	7, 9	3.7
Venturi shown in Fig. 1 [8]	Water	1100-O Al	0.56 - 0.62	20 - 45	36.3 - 49	3.46 ± 20%
Venturi shown in Fig. 1 [6]	Water	1100-O Al	0.56 - 0.61	40	36.3 - 49	4.16 ± 20%
Venturi shown in Fig. 1 (present work)	Water	1100-O Al	0.56 - 0.62	7 - 45	36.3 - 49	$4.0^{+16\%}_{-31\%}$
		1018 carbon steel	0.76	13 - 19		1.06

[a] Unless otherwise indicated.

had been expected from the earlier water tunnel tests of Knapp [2]. The University of Michigan exponents ranged from 1.7 to 4.9 for water and from ±1 to 5 for mercury. Knapp's results are included here for comparison (Fig. 9), showing an average velocity exponent value of 6.4. However, Knapp's results are based on pit counts (not on measured weight loss) and on soft aluminum specimens of ogival shape immersed parallel to the flow axis of the large water tunnel at the California Institute of Technology. Test conditions thus differed widely from those of the University of Michigan Venturi. The University of Michigan velocity exponents were calculated from data measured after a stable weight loss rate was obtained and are thus very different from Knapp's pit rate incubation period tests. If our velocity exponent is calculated from data obtained in the early portion of the tests, which was the procedure carried out by Knapp, n is higher. For 1100-O aluminum $n \approx 5$ so that the disagreement with Knapp's results is then much reduced.

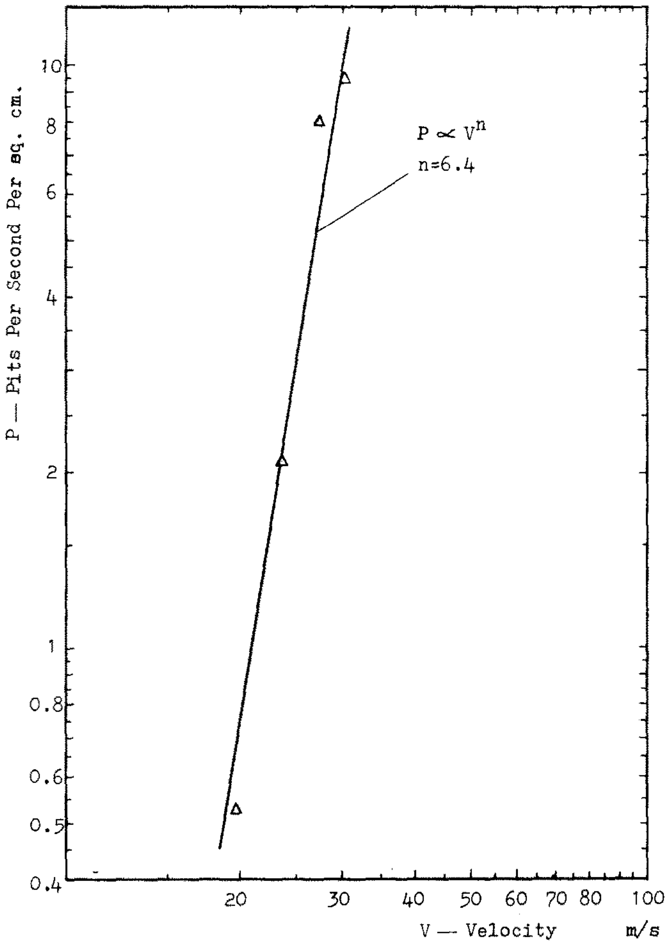

Fig. 9. Effect of velocity on the pit number (material, soft aluminum). (Data from Knapp [2].)

4. Conclusions

The following important conclusions can be drawn.

(1) From all the University of Michigan data, the cavitation erosion rate increases with velocity when the cavitation number σ is maintained constant. However, the cavitation cloud termination point moves slightly upstream for such conditions.

(2) The velocity exponent n in the relation MDPR $\propto V^n$ was about 4 for 1100-O aluminum and about 1.1 for 1018 carbon steel in the University of Michigan tests, for well-developed steady state damage conditions. It is higher (about 5) for the incubation period for soft aluminum and is thus reasonably close to Knapp's value of 6 for a similar portion of the test and the same material.

(3) The probable overall effects of σ (based on downstream pressure) on erosion rate at constant velocity for these Venturi tests was deduced (see Fig. 4). In general, MDPR must maximize at intermediate values of σ and vanish at either very low or high values of σ. A simple velocity exponent erosion model is thus not in general tenable.

(4) The erosion rate of 1018 carbon steel was very sensitive to σ for the two points tested for fixed velocity; it increased rapidly with σ over the range tested (see Fig. 4). For the same values of σ there was little erosion change for aluminum.

(5) For all the University of Michigan Venturi investigations to date, with both water and mercury as test liquids, the velocity–damage exponent lies in the range ± 1 - 5. The velocity ranged from 10 to 49 m s^{-1} for water and from 6 to 20 m s^{-1} for mercury. The negative exponent indicates that some results for mercury [13] show a decrease in damage rate for increased velocity. Similar results for water have been obtained elsewhere (see, for example, ref. 3).

Acknowledgments

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References

1 F. G. Hammitt, *Cavitation and Multiphase Flow Phenomena*, McGraw-Hill, New York, 1980.
2 R. T. Knapp, Recent investigations of cavitation and cavitation damage, *Trans. ASME*, *77* (1955) 1045 - 1054.
3 B. C. Rao and D. V. Chandrasekhara, Size and velocity scale effects on damage in a Venturi, *Internal Rep.*, 1973 (Civil Engineering Department, Bangalore Institute of Technology).
4 A. S. Ramamurthy and P. Bhaskaran, Velocity exponent for erosion and noise due to cavitation, *J. Fluids Eng.*, *101* (March 1979) 69 - 75.
5 J.-g. He, V. Manoukian and G. Heinrich, Erosion of 1018 carbon steel and other materials in a cavitation Venturi, *DRDA Rep. UMICH 014456-67-I*, August 1980, (Division of Research Development and Administration, University of Michigan, Ann Arbor, MI).
6 W. W. Williams, Vibratory and Venturi cavitation damage, *DRDA Rep. UMICH 014456-81-I*, June 1981 (Division of Research Development and Administration, University of Michigan, Ann Arbor, MI).
7 W. Reecher and D. Olney, Venturi cavitation research, *DRDA Rep. UMICH 014456-82-I*, June 1981 (Division of Research Development and Administration, University of Michigan, Ann Arbor, MI).
8 J.-g. He and C.-D. Hsu, Verifications test of velocity effect upon Venturi cavitation erosion of soft aluminum, *DRDA Rep. UMICH 014456-70-I*, January 1981 (Division of Research Development and Administration, University of Michigan, Ann Arbor, MI).

9 T. D. Helmholdt, Venturi cavitation damage run results on 1100-O aluminum, *DRDA Rep. UMICH 014456-37-I*, December 1978 (Division of Research Development and Administration, University of Michigan, Ann Arbor, MI).
10 F. G. Hammitt, J.-g. He, G. Heinrich, C.-D. Hsu, V. Manoukian and B.-H. Sun, Cavitation erosion of ferrous and aluminum alloys in vibratory and Venturi facilities. In R. L. Waid (ed.), *Proc. ASME Cavitation and Polyphase Flow Forum, 1981*, American Society of Mechanical Engineers, New York, 1981, pp. 24 - 27.
11 F. G. Hammitt, T. D. Helmholdt and M. K. De, Erosion of soft aluminum in cavitation Venturi. In R. L. Waid (ed.), *Proc. ASME Cavitation and Polyphase Flow Forum, 1979*, American Society of Mechanical Engineers, New York, 1979, pp. 9 - 12.
12 F. G. Hammitt, Observation on cavitation damage in a flowing system, *J. Basic. Eng., 85* (September 1963) 347 - 359.
13 F. G. Hammitt, L. L. Barinka, M. J. Robinson, R. D. Pehlke and C. A. Siebert, Initial phases of damage to test specimens in a cavitating Venturi, *J. Basic Eng., 87* (1965) 453 - 464.
14 F. G. Hammitt, Damage to solids caused by cavitation, *Philos. Trans. R. Soc. London, Ser. A, 260* (1966) 245 - 255.
15 F. G. Hammitt and D. J. Kempainnen, Cavitation flow past transverse cylinder in Venturi diffuser with water and mercury, *Proc. 3rd Conf. on Fluid Mechanics and Fluid Machinery, Budapest, September 1969*, Hungarian Academy of Sciences, Budapest, 1969, pp. 255 - 265.