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VELOCITY EXPONENT FOR HYDRODYNAMIC CAVITATION EROSION

أس السرعة لتآكل التكهف الهيدروديناميكي

M. A. Hosien and S. M. Selim

KEYWORDS:
Cavitation, erosion, velocity exponent, cavitation number, weight loss

الملخص العربي:- **الغرض الرئيسي من هذا البحث هو دراسة تأثير سرعة الخنق على معدل تآكل التكهف في فترة ثابتة الحالة ودراسة وجود قانون اسى بين معدل التآكل وسرعة التدفق وحساب اس للسرعة. أجريت تجارب معدل فقدان الوزن في نفق مائى للتكهف وفى نطاق سرعة 24 حتي 42.5 م / ث مع ثبوت معامل التكهف لثلاثة أشكال مختلفة من مصدر التكهف وأحجام مختلفة تتراوح مابين 15-27 ملم. تم تحديد التآكل لعينات من الألمنيوم النقي بنسبة 99 في المئة وذلك باستخدام عينة جدار لمصادر ثلاثة واستخدام الاسطوانة نفسها كعينة. لجميع العينات وظروف التشغيل، وجد ان معدل فقدان الوزن يعتمد بشدة على سرعةالتدفق ومعدل فقد الوزن تربطة علاقة اسية مع السرعة (WLRα Ue). وتراوح اس السرعة التى تم الحصول عليها في هذا البحث 3 الى 12.62 اعتمادا على شكل المصدر وحجم ومكان التآكل. وأشارت النتائج التجريبية أن أس السرعة يتناسب مع حجم مصدرالتكهف رفعت إلى اثنين من الاسس المميزة : في نطاق حجم 15-20 ملم الاس 0.47 ولكن لحجم 20-27 مم كان الأس 1.85 لجميع جدار عينات التآكل. و الأسين يعتمدان على هندسة المصدر. ومع ذلك، لتآكل الاسطوانة نفسها الاسين كانا 0.15 لحجم 15-20 ملم و 2.67 لحجم 20-26 ملم.**

Abstract— **The main purpose of this paper is to investigate the effect of throat velocity on cavitation erosion rate in steady –state period and examine the existence of power law between the erosion rate and the flow velocity and evaluates the velocity exponents. Weight loss rate tests were conducted in a cavitation water tunnel in velocity range 24-42.5 m/s at constant cavitation number for three different shapes of cavitation inducer and various inducer sizes ranging from 15 to 27 mm. The erosion of 99 percent pure aluminum was determined using a sidewall specimen for the three inducers and using the cylinder itself as specimen. For all specimens and operating conditions, weight loss rate was found to be strongly dependent on the flow velocity and the weight loss rate varied with some power of the velocity (WLR∝U^e) . The velocity exponents obtained in the present work ranged from 3 to 12.62 depending on the source shape and size and the place of erosion. The experimental results indicated that the velocity exponent was proportional to the size of the inducer raised to two characteristic exponents: in the size range 15-20 mm was of order 0.47 but for size of 20-27 mm the exponent was about 1.85 for all sidewall erosion specimens. The two exponents were independent of the geometry of the inducer. However, for erosion of cylinder itself as a specimen the two exponents were 0.15 for size 15-20 mm and 2.67 for size 20-26 mm.**

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I. INTRODUCTION

At first glance, cavitation appears as a harmful phenomenon that must be avoided. However, in many cases the free cavitation is the most severe condition with which the designer is faced. The search for more compact and lighter machine, besides avoidance of excessive financial charges has forced the designer to operate his machine with some cavitation provided that it does not cause serous materials erosion or appreciable loss of efficiency. Although the amount of literature available on cavitation is immense, yet the hydraulic machinery designer cannot relate cavitation erosion measurements on different machines or even in the same machine at different operating conditions. This is because the major research efforts have been devoted to studies of the resistance of material to cavitation erosion and its relation to various physical and metallurgical properties. So, much in fact the hydraulic machinery designer has a fair idea which is the most resistance materials at his disposal even if he does not fully understand why they are the best. On the hydraulic side, however, he does not have much reliable information on how cavitation erosion may vary with operating speed.

Flow velocity plays an important role in the case of development cavitation and is the source of additional complexity in the scaling laws of cavitating flows. Previous investigators [1-27] claimed that cavitation erosion rate increased to some power of flow velocity which varied enormously from about 3 to 10 with 6 being a popular choice somewhere in between. This is not very useful to the hydraulic machine designer because of the uncertainty of prediction. If he decides to double the operating speed, it is not much help to know that the erosion rate may increase somewhat between 8 and about 1000.

In spite of wide spread support for a power law variation of cavitation erosion with velocity, Shalnev [28] and Rasmussen [29] reported that the intensity of cavitation damage varied linearly with velocity. While Kohl [30] and Thiruvengadam [31] erosion results indicated that the rate of erosion increases with velocity to a maximum and then decreases with increasing velocity.

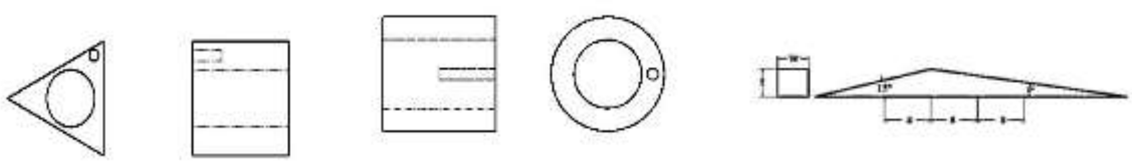
A major discrepancy emerges from this brief review of cavitation erosion variation with velocity, namely that one set of investigators found a power law and the other investigators reported a linear variation with velocity. Indeed, these findings reflect the complexity of the relationship between cavitation erosion and velocity as well as the necessity for more detailed investigation.

Hence, the present paper mainly aims to study experimentally the effect of flow velocity on cavitation erosion rate in the steady state weight loss zone and to assess the velocity exponent at various flow conditions and different cavitating source geometries to simulate the types of cavitation encountered in practice. In this way it is hoped to provide some guidance for the hydraulic designer in choosing safe velocities to operate machines and to predict whether his design is safe or not.

II. EXPERIMENTAL DETAILS

Cavitation erosion measurements have been done in a variable pressure closed circuit water tunnel at Faculty of Engineering, Menoufia University [32, 33]. Water was circulated by a centrifugal pump and by pass control to give velocities ranging from 15-45 m/s in a parallel sided test section of regulator with cross section of 42.5 x 18.5 mm. The pressure varied independently over a range of 0-10 bar. The effects of velocity at constant cavitation number were investigated for three shapes of cavitating source spanning the 18.5 mm direction.

The cavitating source configurations are shown in Figure 1 as follows:



600 Symmetrical wedge sources. Circular cylinder sources. Con. div. Wedge sources.

Fig. 1. Details of cavitating sources.

Source shape	Source size [mm]	Source height [mm]
600 symmetrical wedge	15, 17, 18.5,20,22,24 and 27	18.5
Circular cylinder	15, 17, 18.5,20,22,24 and 26	18.5
Convergent –divergent wedge	15, 17, 18.5,20,22,24 and 26	18.5

Source 1 gives vortex cavitation which occurs in the cores of vortices behind the body. Source 2 represents the travelling cavitation appearing along the surface of the source and growing in wake zone of the body. Source 3 produces cyclic fixed cavity attached to the solid boundary of the source. These types of cavitation are encountered in practical situations on bodies of rotating machinery, lifting hydrofoil, venture nozzles and internal flows devices.

It is difficult to measure, directly, the cavitation number in the region of the cavity. Therefore the cavitation number (σ_o) at the entrance to the tunnel working section is measured and then converted into the local cavitation number (σ) at the throat. This can be done quite simply by assuming ideal flow between the upstream section at entrance of the working section and the vena contract a using Bernoulli's equation.

If the upstream and local cavitation numbers are defined as follows,

$\sigma_o = \frac{P_o - P_v}{\frac{1}{2}\rho U_o^2}$, $\sigma = \frac{P - P_v}{\frac{1}{2}\rho U^2}$ where, P_o and U_o are respectively measured pressure and velocity upstream of the body and P_v is the vapour pressure corresponding to the bulk water temperature, P and U are respectively the static pressure and mean velocity at the throat and ρ is the fluid density.

At advanced cavitation and flow breakdown σ and the value of σ_o is minimum σ_{ob}, can be used to determine the effective contraction of the flow at the vena contracta. Hence, the local σ can be calculated from:

$\sigma = \frac{\sigma_o - \sigma_{ob}}{\sigma_{ob}+1}$ where σ_{ob} is the value of σ_o at flow breakdown. The vapour pressure (P_v) is taken to be that appropriate to the bulk liquid temperature. It has been found that σ_{ob} is very nearly independent of flow velocity but it depends on the shape of the source. Furthermore, the velocity at the vena cotracta can be obtained from the following equation: $U = U_o\sqrt{1 + \sigma_{ob}}$

The objective was to study effects of flow velocity on the cavitation damage on a specimen due to cavitation of various kinds produced by different configurations operating at different flow conditions. To compare these cavitating flows, it was necessary to choose a convenient method to measure the progressive loss in weight of the specimen due to erosion damage.

The weight loss rate (WLR) can be obtained from the weight loss versus exposure time defined as:

$$\text{WLR} = \frac{\Delta W}{\tau - \tau_o} \text{ mg/hr}$$

where τ is the time after beginning the tests (total exposure time) and τ_o is so-called incubation time during which there is no measurable weight loss. Soon after, weight loss commences and varies for a short period non-linearly with time. Thereafter, during the early stages of damage, the weight loss varies linearly with time and WLR as defined above is constant (i.e. steady state weight loss region). For systematic analysis and correlation, data from our different tests have been taken from this steady state weight loss zone. All the experimental values of the WLR have been obtained by the method of least squares.

The cavitation erosion was determined using a specimen of the material mounted on the sidewall of the test section downstream of the source. The lengths of these 6 mm thick and 42.5 mm width specimens varied with each shape because the maximum length of cavity at maximum cavitation number was different. The longest was for the con.-div. wedge. Cylindrical specimens of different diameters and 18.5 mm heights were used. The shortest test specimen was for 60^0 symmetrical wedges. Erosion was measured on some of the sources themselves but mostly on the sidewall downstream, where it was usually more severe, because such tests could be shorter. The specimens (sources and sidewalls) were mostly made for 99% pure aluminum (SIC B.S.1470:1969) determined by weighing the specimen by a precision electronic balance (Oertling, model LA264) which allowed the weight to be determined to the nearest 0.1 mg.

The aluminum specimens before tests were polished by hand using grade 600 silicon carbide paper. They were then washed with soap and water, and dried with a hair dryer. They were weighted initially and then exposed to the required cavitation condition for a desired period. Then, they were removed from the test section for washing, drying and reweighting and the weight loss determined by subtraction from the initial weight. The process is repeated with constant time increments until satisfactory points in the steady state weight loss zone had been obtained. The time increment was dependent on the intensity of cavitation attack (i.e., source shape, flow velocity and cavitation number).

Preliminary erosion tests were conducted to determine the suitable length for the specimen for different shapes of source, the cavitation number at which the maximum weight loss occurs for each cavitation source, the exposure time of specimen to cavitation attack to obtain a sufficient weight loss for analysis, the maximum and minimum weight loss rates to estimate a suitable time measurement increment and the repeatability of erosion test results.

The preliminary erosion tests indicated that the side wall erosion was usually more severe than the cavitating body erosion itself. It was also observed that the main erosion area appears with the trailing cavity for both 60^0 symmetrical wedges and the circular cylinder, whilst for the con.-div. wedge, the main erosion area takes place at a distance of about twice the cavity length downstream. In addition, it was observed that the WLR measured on sidewall specimens produced by 60^0 symmetrical wedges is about 20 times the WLR produced by the circular cylinder and about 180 times that produced by the con.-div. wedge at the same flow condition.

The calculation of σ is dependent on the accuracy of measuring the pressure, flow rate and temperature in the test section entrance. The test section pressure readings were measured by precision pressure transducers to within 0.02 bar which converted to uncertainty of ± 0.6% in cavitation number. The flow velocity in the test section was obtained from the measurements of flow rate in the test section. The flow rate was measured by an electromagnetic flow meter. The expected uncertainty in the flow velocity is ± 0.12 m/s which can be converted to an uncertainty of ± 0.2%. The variation in vapour pressure due to the change of water temperature is 2.5x 10^{-3} bar/^{o}C. The change in water temperature during the operation of the tunnel was 2 ^{o}C. Thus, the variation in the vapour pressure will not significantly affect the estimation of σ. Accordingly, the uncertainty in σ is approximately ± 0.9%. The uncertainty in the weight loss in the steady –state zone is about ± 1.5%. Considering the uncertainty in the operation conditions it appears that the uncertainty in the weight loss results is within ± 2.5%.

II. RESULTS AND DISCUSSION

An extensive series of weight loss measurements was conducted to evaluate WLR at wide range of velocities with constant cavitation number for each source. A total of 178 sidewall and 41 cylindrical aluminum specimens were used in tests using water velocities ranging from 24 to 42.5 m/s at constant cavitation numbers of 0.113, 0.035 and 0.035 for 60^0 symmetrical wedge, circular cylinder, and con.-div. wedge, respectively. The source sizes were ranged from 15 mm to 27 mm. The tests conducted at water temperature 0f 32 ± 2 ^{o}C.

Graphs summarizing the extensive WLR results are shown in Figures 2 to 5. The WLR results versus velocity plotted on a double logarithmic scale. The best fit straight lines to the results were obtained using least squares. The slopes of the lines are taken to be the velocity exponent. These Figures show clearly that the WLR is strongly dependent on the flow velocity and the cavitation source shape and size and erosion place.

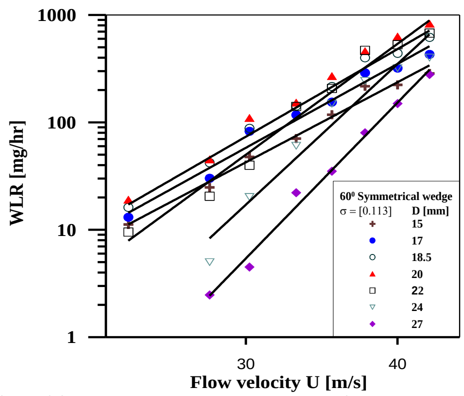


Fig. 2. Effect of flow velocity on weight loss rate for 600 symmetrical and various source size.

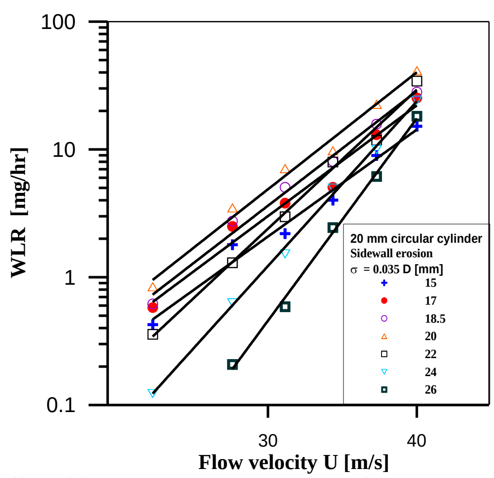


Fig. 3. Effect of flow velocity on weight loss rate for circular cylinder side wall erosion and various source size.

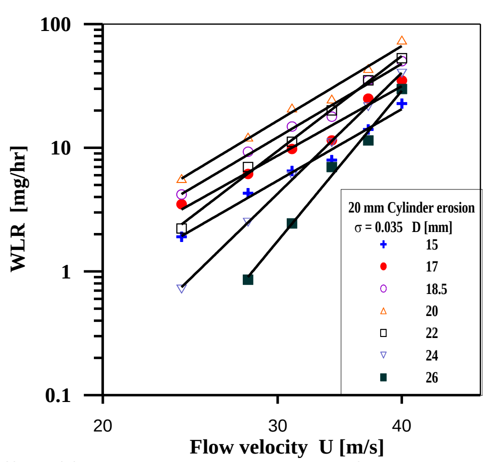


Fig. 4. Effect of flow velocity on weight loss rate for circular cylinder and various source size.

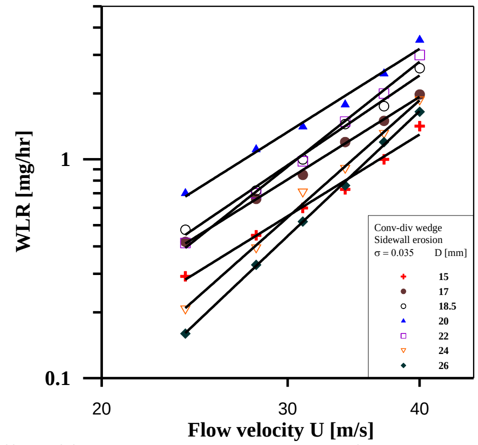


Fig. 5. Effect of flow velocity on weight loss rate for con.-div. wedge side wall erosion and various source size.

Photographs of some damaged specimens are shown in Figures 6-7. These photographs show the erosion patterns produced by different shapes and sizes of cavitation sources for the range of flow conditions considered in this investigation. General observation of cavitation erosion patterns produced by various sources can provide insight into the processes involved in cavitation erosion. These Figures show that the length of the erosion area remains the same at various velocities and constant cavitation number. But noticeable increases in the width of the area affected by increasing flow velocity are observed.

A comparison of the photographs shown in Figures 6 (a, b and c) reveals a significant difference in the damage location and patterns of the main sidewall erosion area for various cavitation source shapes. Visual observations of cavity during tunnel operation indicate that the main erosion area appears within the trailing cavity for both the 60^0 symmetrical wedge and circular cylinder source. Whilst for the con.-div. wedge source the main erosion area takes place at a distance of about twice the cavity length downstream (see Figs. 6 (a, b and c)). It is possible that this is due to the difference in the magnitude of the impact pressure caused by the re-entrant jet after break-off the main cavity. According to the main erosion area, it would be possible to state whether the impact pressure or the pressure of the main flow is responsible for the collapse of the break-away cavities. In the case of the con.-div. wedge the pressure of the flow is the cause of collapse because the break-away cavities have to travel some distance downstream before the pressure of the flow exceeds the vapour pressure inside the cavities, and therefore the main damage area would occur at some distance beyond the downstream end of the main cavity. In the case of both the 60^0 symmetrical wedge and circular cylinder, the impact pressure itself is responsible for collapsing the break-away cavities without further movement after the break-off, and therefore the main damage area would take place inside the main cavity.

Flow direction

τ = 50 min
U= 40 m/s

τ = 7 hrs
U = 24 m/s

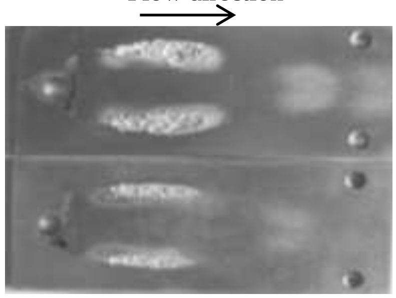


Fig. 6 (a). 600 Symmetrical wedge. σ = 0.113

Flow direction

τ = 2 hrs
U = 40 m/s

τ = 9 hrs
U = 24 m/s

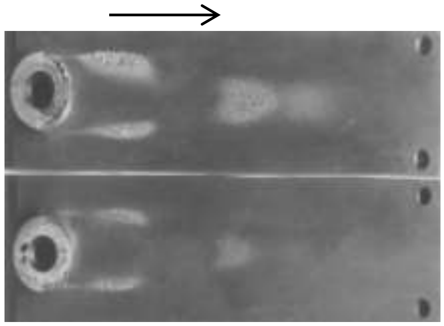
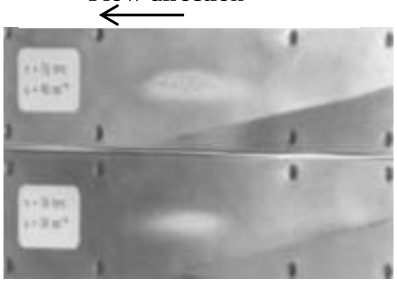


Fig. 6 (b). Circular cylinder. σ = 0.035

Flow direction



τ = 7.5 hrs
U = 40 m/s

τ = 16 hrs
U =24

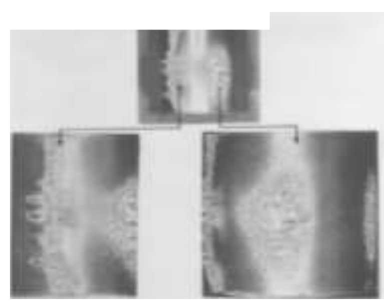
Fig. 6 (c). Con. - div. wedge. σ = 0.035

Figs. 6 Photographs of the erosion patterns for sidewall aluminum specimens at constant cavitation numbers with different flow velocities produced by various cavitating sources.

A comparison of the WLR produced by different cavitation sources (Figures 2 to 5) reveals that the WLR produced by the 60^0 symmetrical wedge is the most dangerous for sidewall erosion and larger of the WLR produced by the circular cylinder and that produced by con.-div. wedge. These differences should be attributed to the variation of many factors such as the total number of collapsing bubbles, the size of collapsing bubbles and the magnitude of the impact pressures created by the re-entrant jet. Generally, for the 60^0 symmetrical wedges and the circular cylinder, the re-entrant jet flow through the cavity will be thick, producing a high impact pressure resulting in high damage potentials. However, in the case of con.-div. wedge the re-entrant jet has a weak momentum because it is thin, and it has the capability of break- off from the cavity at the throat without producing an impact pressure high enough to collapse the bubbles. Therefore, the majority of the old cavities will travel with the flow and collapse when the surroundings pressure exceeds the inside pressure of the bubble. These conclusions were drawn after the observations of the photographs for the cavitation structures in the wake of a two-dimensional wedge by Belahadji et al. [34], Lasheras and Choi [35], Grekula and Bark [36], Bark et al. [37,38 and 39] and Dular [40]. Accordingly the magnitude of the erosion damage produced by the cavity in the wake of cavitation source will be higher than that produced when it terminates on a solid body.

Tests in which the WLR of the cavitation source bodies themselves were measured and showed that the WLR produced on the circular cylinder itself is about 3 times greater than on side wall specimen (Fig. 7). This finding implies that the mechanism of the sidewall erosion was quite different from that on the surface of cavitation source itself. In Fig. 7, the erosion of the cylinder itself takes on two basic zones over the face of the cylinder. One, in the form of comb-teeth, takes place on two opposite lines parallel to the axis at about 90^o from the frontal stagnation point (see Fig.7.a). This is the result of collapsing of numerous small bubbles at the formation point. The other was a deeply eroded area appearing as heavy pitting concentrated in the middle of the back face of the cylinder at approximately 140^o from the frontal stagnation point (see Fig.7.b) This case is the result of collapsing bubbles carried upstream the cavity by the re-entrant jet of the back face of the cylinder creating high impact pressure and collapsing the bubbles there.

Flow direction



(a) "Comb- teeth" erosion band at 900 from the frontal stagnation point.

(b) Heavy erosion area in the middle of the back face of the cylinder.

Fig. 7. Erosion patterns produced by circular cylinder inducer for erosion on cylinder itself as a test specimen. Circular cylinder σ = 0.035, U = 37 m/s.

The results shown in Figs. 2 to 5 indicate that the WLR varies with some power of the throat velocity($WLR \propto U^e$). It is clear from the results that there is no unique exponent of flow velocity. The value of the exponent varies quite widely from 3 to 12.62 in the velocity ranged tested. Table 1 presents the values of velocity exponent obtained from present erosion tests conducted at various parameters. In comparing the experimental values of the velocity exponent (e) it can be seen that the values of the velocity exponent depend on the cavitation source shape, size and erosion place. Thus, this difference in exponent value with source shape can be interpreted as a change in the type of cavitation as each source shape produced different flow regimes. Therefore, the assumption that a single power law of cavitation erosion is applicable over wide range configurations is very weak. It can be seen that for the three sources shapes the flow velocity exponent increases with increasing the source size.

TABLE1. SUMMARY OF THE VELOCITY EXPONENT (E) RESULTS.

Cavitation source shape and operation condition	Erosion place	Source size (D) in mm, velocity exponent (e) and correlation coefficient (r)							
600 Symmetrical wedge σ = 0.113 U[m/s]:42.5,40,37.6,35.31,33,30.228 and 24	Sidewall specimen	D	15	17	18.5	20	22	24	27
		e	5.97	6.25	6.53	6.83	8.26	10.48	11.61
		r	0.9848	0.9761	0.99	0.9911	0.9728	0.9444	0.9904
Circular cylinder σ = 0.035 U[m/s]: 40,37,34,31,28 and 24	Sidewall Specimen	D	15	17	18.5	20	22	24	26
		e	6.37	6.93	7.2	7.76	8.71	10.81	12.67
		r	0.9783	0.973	0.9896	0.9883	0.9927	0.99818	0.9963
	Cylinder Specimen	e	4.63	4.5	4.75	4.83	6.14	7.82	9.73
		r	0.985	0.9691	0.9861	0.9852	0.9964	0.9991	0.9925
Con.-div. wedge σ = 0.035 U[m/s]: 40,37,34,31,28 and 24.	Sidewall specimen	D	15	17	18.5	20	22	24	26
		e	3.0	3.02	3.28	3.04	3.83	4.28	4.57
		r	0.9885	0.9975	0.9908	0.9871	0.9945	0.9949	0.9992

The reason for this high sensitivity of WLR to changes in velocity and shape and size of cavitation sources is not obvious and it is difficult to understand why WLR should vary with some power of the velocity as shown by the results of the exponent. During the tests every effort was made to keep velocity as the only variable. The cavity length was kept constant. Furthermore, the temperature and air content for all of the runs were kept constant as much as possible. Yet, the detailed physics of the cavitation erosion are not well characterized. According to the dynamics of bubble theory and the relevant parameters the velocity has many functions: a) the rate of cavities swept into the collapse zone increases with flow velocity so that the frequency of pressure pulses increases too, b) the velocity changes the energy of collapse (this energy is the product of initial volume of the bubble and the pressure causing collapse, and will increase with the square of velocity according to Rayleigh's derivation of the collapse time of a spherical cavity). This is because when the velocity is increased at constant cavitation number the ambient pressure to cavity has also to be increased to conserve the cavitation number. As a sequence, the difference between the liquid pressure and the bubble inner pressure may be quite large and able to provide a large acceleration to the collapse bubble wall. Therefore, the impulsive collapse pressure resulting either from the impact of the micro-jet (the jet velocity increases with the square root of the collapse driving pressure [41,42] or from the impact of the shock waves is quite large; c) the increase of the flow velocity induces an increase in pit size. This trend was reported by Franc et al. [24]. The increase in pit size due to the collapsing of bubbles indicates that the cavitation intensity is increased. , d) The average size of the bubbles seems unchanged with changing velocity. Knapp [43] concluded that the average size of the cavity remains sensibly unchanged with changes of velocity. According to Rayleigh, differential equation for the pressure-inertia equilibrium of collapse bubble, the growth time (t) is related to the time a water particle with water velocity at the vena contracta of cavitating source (U) requires to pass through the cavity length λ by means of $t \alpha \ \lambda/U$. Combining the growth time expression with Rayleigh equation reveals that the maximum size of the growth bubble is independent of the flow velocity at constant cavitation number (σ) and is controlled by σ and geometrical shape alone, e) The standoff distance of the collapse process to the wall of specimen seems changing with flow velocity. Jiang and Shu [44] and Soyama [45] reported that for bubbles not too close to the wall the pressure along the bubble wall surface is a function of the standoff distance. The pressure along the bubble wall changed with the flow velocity, therefore, the flow velocity affects the standoff distance, and f) the flow velocity may change the acoustic impedance of the water. Wilson and Graham [46] and Garcia and Hammitt [47] reported that the erosion rate in various liquid increases exponentially with the acoustic impedance. The combination of these five phenomena results in a strongly non-liner effect of the flow velocity on cavitation weight loss rate.

Figure 10 presents the variation of velocity exponent with cavitation source size.

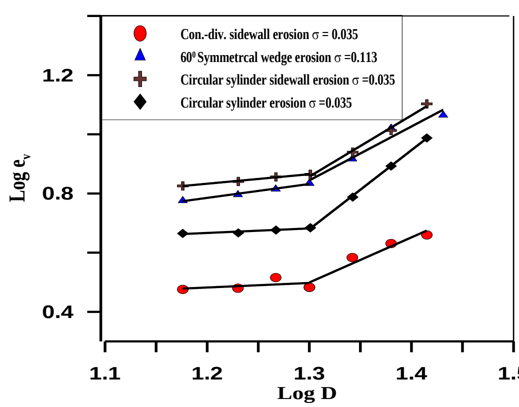


Fig. 10. Variation of velocity exponent with cavitation source.

This Figure show that the velocity exponent shows increasing trend with increasing size of the source and the velocity exponent is proportional to the size raised to two characteristic exponents. The two size exponents obtained from experiments show marked difference between their values depending on the range of the cavitation source size and place of erosion measurements. The values of the two exponents are about 1.85 for size of 20-27 mm for these shapes of cavitation source with sidewall specimens. However, in case of using circular cylinder itself as specimen, the two size exponents are found to be about 0.15 for size range of 15-20 mm and 2.67 for size of 20-26 mm. An examination of the two characteristic size exponent's magnitudes indicates that the size exponent for the size range 20-27 mm is larger than the size exponent for the size range 15-20 mm. The reason for this high sensitivity of the velocity exponent to changes in source size is not obvious and it is difficult to understand why the velocity exponent should vary with some power of the cavitation source size as shown by the results of the experiments. Nevertheless, the difference in the two exponents can be interpreted as a change in the class of cavitation as each size range produced different regimes of cavitation, i.e. cavity lengths, shapes, mechanism of cavity formation and inception and breakdown cavitation numbers. In addition, these differences between the size exponent values may be interpreted as a result of test section wall effects. The difference in the two exponent's value with the erosion place may be attributed to the difference in erosion mechanism for the cylinder itself and the side wall spectrum. In fact, the sidewall erosion seemed to be due to the collapse of a cluster of bubbles which breaks away from the cavitation source and travels downstream with the flow before collapsing completely. The reason of the cylinder itself seemed to be the collapsing of numerous small bubbles at the formation site of the cavity and the collapsing of bubbles carried backwards through the cavity by the re-entrant jet which is generated in the cavity closure region.

The above discussion indicated the general difficulty in scaling cavitation phenomena according to the simple similarity laws. This is because the phenomenon of cavitation erosion is very complex.

The results obtained in the present work have certainly raised some interesting points because further experimental studies are obviously needed to find answers to many questions which the research suggests. The answers would aid the hydraulic designers. Thus work reported here represented an addition to knowledge of this aspect which could lead to the prediction of cavitation damage for flows encountered in practice.

IV. CONCLUSIONS

The following are the more important conclusions of the present work:

1. The experimental results of the weight loss rate (WLR) in the steady- state zone showed that the flow velocity was found to have a marked effect upon the magnitude of the (WLR). It was found that the (WLR) increased rapidly with increasing the flow velocity.
2. The experimental results of all cavitation sources showed that the variation of the WLR with velocity could be expressed as a power law for velocities ranging from 24 to 42.5 m/s with constant cavitation number. The values of velocity exponent varied between 3 to 12.62 depending on the cavitation source shape, size and the erosion place. Therefore, the assumption that a single power law of cavitation erosion is applicable to all cavitation erosion tests is doubtful.
3. The results showed that the relation between the velocity exponent (n) and the cavitation source size (D) was power law with two characteristic exponents in the size range 15-20 mm were 0.47 and in the size range 20- 27 mm of about 1.85 for different source shape with side wall specimens. However, for measurements of WLR on the circular cylinder source itself the two exponents were 0.15 for size up to 20 and 2.67 for the size range of 20-26 mm. The values of the two exponents were independent of the shape of the cavitation source shape but dependent on the place of erosion measurements.
4. The experimental results indicated that for the same up-stream flow conditions the WLR produced by various cavitating source shapes varied widely, the extremes of the range being in the ratio of about 700:1. The (WLR) produced by 60^0 symmetrical wedges was the most dangerous for sidewall erosion and of the WLR produced by circular cylinder and that produced by con.-div. wedge. The damage pattern produced by 60^0 symmetrical wedge and circular cylinder may be analogous to the damage from cavitation on the leading and trailing edges of impeller blades. Accordingly, more than one type of cavitation is likely to occur in the same machine and, therefore, the designer should design his machine with the most dangerous type to minimize the dangers.
5. The results obtained have certainly raised some interesting points because further experimental studies are obviously needed to find answer to many questions which these results suggest. The answers will be helpful for the hydraulic designer.

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