PREDICTION OF EROSION EFFECT DUE TO CAVITATION ON AL-MOSUL POWER PLANT TURBINE

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ABSTRACT

In the field of hydraulic power plant, the cavitation is responsible of sever erosion which requires periodic unit shutdowns for inspection and repairs. Al-Mosul hydroelectric power plant is chosen as model in this study. Computer programs are developed by using the velocity gradient method to analyze the flow in the runner blades of the turbine (Francis Turbine) to calculate the available cavitation and compared with the critical cavitation. The erosion of the runner material (erosion rate, weight of lost material and mean depth of erosion) is also calculated to limit the operation hours of the power plant. The presented work shows that the cavitation appears on the underside of the turbine (Francis Turbine) blades in the trailing edge at distance of 82% from the leading edge due to decrease in pressure, flow separation and interference zone. This causes erosion depth of about 4 mm for the first four years of operation which represents about 17% of the blade thickness of the trailing edge. It is found that the operation hours of Al-Mosul power plant should not exceed 24000 operation hour. A good agreement is found between the prototype data obtained from the computer program analysis and experimental visualization shown in the literature and theoretical solution.

الخلاصة

ظاهرة التكهف تحدث في توربينات محطات الطاقة الهيدروليكية حيث تسبب تآكل في مروحة التوربين والتي تؤثر على أداء المحطة مما يتطلب اجراء فحص وتصليح خلال فترات زمنية متفاوتة. تم اختيار محطة كهرباء الموصل كنموذج للحسابات حيث تم بناء عدة برامج في الحاسوب بالاعتماد على طريقة أنحدار السرعة لتحليل الجريان على ريشة مروحة التوربين (Francis Turbine) لحساب معامل التكهف ومقارنته مع معامل التكهف الحرج وأخيراً حساب التآكل لمعدن المروحة (معدل التآكل، الوزن المفقود، ومعدل عمق التآكل) والذي يتم من خلاله تحديد ساعات التشغيل للمحطة. البحث الحالي يوضح ان ظاهرة التكهف تحدث في منطقة الحافة لريشة مروحة التوربين (Francis Turbine) على بعد ٨٢% من بداية الحافة تقريباً نتيجة انخفاض الضغط وأنفصال الجريان وتداخله والتي تسبب تآكل لمعدن المروحة كمعدل عمق ٤ ملم خلال السنوات الاربعة الاولى من التشغيل والذي يشكل ١٧%تقريباً من سمك الريشة عند منطقة الذيل. قد وجد أن ساعات التشغيل لمحطة كهرباء الموصل يجب أن لا تزيد على ٢٤٠٠٠ ساعة

عمل، قورنت النتائج المستحصلة من محطة كهرباء الموصل وأخرى تم الحصول عليها من بحوث سابقة وقد ظهر تقارب جيد بينها.

KEYWORDS

Erosion, Cavitation, Turbine

INTRODUCTION

Water turbines are used in hydroelectrical power stations to convert the energy of stored water at a height into mechanical work. Francis turbine (Fig.1) is understood as a water turbine where the runner receives the water under pressure in a radial inward direction and discharges it in a substantially axial direction.

Erosion is the progressive loss of original material from a solid surface due to mechanical interaction between that surface and a fluid, achieved by emission of stress pulses into the solid, which arise, for a shock wave or by the formation of a high-velocity jet of liquid both originating from bubble collapse **(Army, website)**. The collapse of the cavities can lead to an increase in the corrosion current, thus cavitation erosion accelerates corrosion **(Hammitt, 1980)**. Cavitation erosion is a complex phenomenon involving the interaction of hydrodynamical, mechanical, metallurgical and chemical factors.

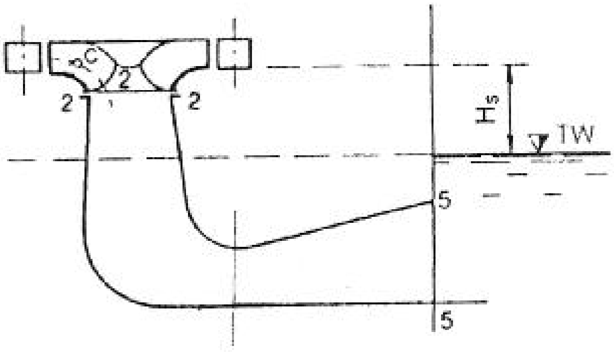
Many studies, both theoretical and experimental have been done to study the cavitation, its deleterious effects and erosion cased by cavitation collapse. **(Mikael, 2001)** represented an experimental study on cavitation in Kaplan model turbine. A periodic pattern of the cavitating tip vortex is observation, the main feature of this pattern is that cavitating vortex is bent towards the blade surface and transformed into cloud formation. **(Soyama, 2001)** proposed a new parameter in the relation between the cavitation impacts and the resistance of materials to predict the cavitation erosion, it is threshold level of materials to the cavitation impacts, a new parameter, i.e., threshold level to predict cavitation erosion is proposed as a result of the relation between the energy of impact and the erosion rate. **(Saffa, 2006)** presented a comparative studies of corrosion and erosion-corrosion resistance for two types of materials. He found that the ductile iron loss of material due to corrosion and erosion-corrosion resistance is less than gray cast iron. **(Masatake, 2003)** presented an experimental study where the real erosion progress was examined using acceleration tests. Sever erosion occurred at the predicted condition mainly under partial load conditions and high head operation. The relationship between the rate of erosion progress, which is directly evaluated by measuring erosion pit size, and cavitation intensity measured using impulse pressure sensors, is discussed.

In the present work a mathematical model developed to study the effect of cavitation on the performance of the turbine and the life of its blades due to erosion for Al-Mosul power plant turbine which is working at the average net head (42.3 – 77.2) m and flow rate (140 - 310) m^3/s.

THEORY

Cavitation appears in some regions in the hydraulic turbine where the pressure is less than the pressure of saturated water vapour **((Caron, 2001), (krivchenko, 1986))**, the magnitude of this pressure at a certain point is known on the runner as shown in the following figure may be represented by:-

$$\frac{P_{ac}}{g}=\frac{P_{atm}}{g}-H_s-\left[a_2K_{V2}-a_5\frac{V_5^2}{2gH}-z_{draft}K_{V2}^2+lK_{W2}^2\right]H \tag{1}$$



The cavitation index (coefficient) **(Raabe, 1985)** is equal to:-

$$s=\left[a_2K_{V2}-a_5\frac{V_5^2}{2gH}-z_{draft}K_{V2}^2+lK_{W2}^2\right] \tag{2}$$

The available and critical cavitation coefficients (Jagdish, 1984) is equal to:-

$$s_{av}=\left[(a_2-z_{draft})K_{V2}-a_5\frac{V_5^2}{2gH}+lK_{W2}^2\right] \tag{3}$$

$$s_{cr}=\left[(P_{atm}-P_v)/gH\right]-H_s/H \tag{4}$$

A cavitation-safe operation of a set requires that $s_{cr} \le s_{av}$.

The shock wave radiated from collapsing bubbles is one of the main factors contributing to cavitation erosion. When a single bubble collapses, a considerable portion of the potential energy stored in the bubble is transformed into acoustic energy. Thus, the acoustic energy (E_{ac}) can be expressed as **(Zhang, 1989)**:-

$$\frac{E_{ac}}{E_{pot}}=\frac{1}{C_\infty}\left[\frac{P_\infty}{r_\infty}\right]^{1/2}F(X_{\min}) \tag{5}$$

The function $F(X_{\min})$ from classical theory is:-

$$F(X_{\min})=-\frac{1}{6}\frac{2}{3}\int_1^{X_{\min}}\frac{1-8X+16X^2}{X\{X(1-X)\}^{1/2}}dX \tag{6}$$

Where $X=(R/R_{\max})^3$ and $R_{\min}/R_{\max}\approx 3\frac{P_g}{P_\infty}$

The final relation of the acoustic energy is:-

$$\frac{E_{ac}}{(4/3)pP_\infty R_{\max}^3}=\frac{1}{27C_\infty}\left(\frac{2P_\infty}{r_\infty}\right)^{1/2}\left(\frac{P_\infty}{P_g}\right)^{3/2} \tag{7}$$

One of the most pronounced features of bubble collapse near a boundary is formation of a liquid jet within the bubble naturally **(Tomita, 1986)**. It is well known that the water-hammer pressure induced by impacting liquid jet can be expressed as:-

$$p_{WH} = r_{\infty} C_{\infty} V_j \tag{8}$$

The expression for the kinetic energy of the entire body of liquid at time is:-

$$(K.E)_{liq} = \frac{r_{\infty}}{2} \int_{R}^{\infty} u^2 4pr_b^2 dr_b = 2pr_{\infty} U^2 R^3 \tag{9}$$

An expression for the time (t) required for a cavity to complete collapse from R$_0$ to R is represented by **(Tomita, 1986)**:-

$$t = 0.91468 R_0 \sqrt{\frac{r_{\infty}}{P_{\infty}}} \tag{10}$$

The work done on the entire body of fluid as the cavity collapsing from R$_0$ to R is equal to:-

$$Work = \frac{4pP_{\infty}}{3} (R_0^3 - R^3) \tag{11}$$

If the fluid is inviscid as well as incompressible the work done appears as kinetic energy, but the cavity is filled with gas which is compressed isothermally. Then, the work done (Eq.11) is equal to the sum of kinetic energy (Eq.9), and the work of compression gas $4pP_{g0} R_0^3 \ln(R_0 / R)$ where P_{g0} is initial pressure of the gas, for that:-

$$U^2 = \frac{2P_{\infty}}{3r_{\infty}} \left[\frac{R_0^3}{R^3} - 1 \right] - \frac{2p_{g0}}{r_{\infty}} \frac{R_0^3}{R^3} \ln \frac{R_0}{R} \tag{12}$$

The bubble impact pressure P_j due to sudden collapse as water hammer can be expressed as **(Raabe, 1985)**:-

$$P_j = r_{\infty} C_{\infty} U \tag{13}$$

Cavitation erosion is sometimes assessed by counting the number of craters produced per unit surface area or per unit time **(Sayama, 1998)**. The mathematical relation model for the dynamics of the cavitation erosion using a differential equation applied to forced oscillations with damaging is:-

$$\frac{d^2u}{dt^2} + 2a_s \frac{du}{dt} + b_s^2 u = 1 \tag{14}$$

By introducing the parameters $d = a_s / b_s$ and $t_t = b_s t$, the general solution of the above equation can be written as:-

$$u = af_0(d, t_t) + bf_1(d, t_t) \tag{15}$$

The functions $f_0(d, t_t)$ and $f_1(d, t_t)$ are determined for various parameters by using the following expressions:-

For $-1 < d < 1 \;\; ; \;\; d \neq 0$

$$f_0(d, t_t) = 1 - \left(\exp(-dt_t)\right) \left[\frac{d}{\overline{w}} \sin(\overline{w} t_t) + \cos(\overline{w} t_t) \right] \tag{16}$$

$$f_1(d, t_t) = 1 - \frac{2d}{t_t} \left(1 - \exp(-dt_t)\right) \left[\cos(\overline{w} t_t) + e \sin(\overline{w} t_t) \right] \tag{17}$$

Where $\overline{w}$ and e are represents the following abbreviations:-

$$\overline{w} = (1 - d^2)^{1/2} \tag{18}$$

$$e = \frac{d^2 - 0.5}{d(1-d^2)^{1/2}} \tag{19}$$

For $d > 1$

$$d_0 = d + (d^2 - 1)^{1/2} \tag{20}$$

$$f_0(d,t_t) = 1 - \frac{1}{d_0^2 - 1}\left[d_0^2 \exp(\frac{-t_t}{d_0}) - \exp(-d_0 t_t)\right] \tag{21}$$

$$f_1(d,t_t) = 1 - \frac{1}{t_t}\left[2d - \frac{1}{d_0(d_0^2 - 1)}\left(\exp(-d_0 t_t) - d^4 \exp(\frac{-t_t}{d_0})\right)\right] \tag{22}$$

For $d = 0$

$$f_0(d,t_t) = 1 - \cos(t_t) \tag{23}$$

$$f_1(d,t_t) = 1 - \frac{\sin(t_t)}{t_t} \tag{24}$$

For $d = 1$

$$f_0(d,t_t) = 1 - (1 + t_t)\exp(-t_t) \tag{25}$$

$$f_1(d,t_t) = 1 - \frac{2(1 - \exp(t_t))}{t_t} + \exp(t_t) \tag{26}$$

The observed erosion rate expressed in terms of depth of penetration per unit time ($\dot{Y}$), can be related to the energy absorbed per unit time and area **(Roger, 1989)**:-

$$I = \dot{Y}S \tag{27}$$

RESULTS AND DISCUSSION

The cavitaion behavior along the suction and pressure sides of the runner blade for different sections such as, the hub, mean, and the shroud is studied for different flow rates in the range of the data of Al-Mosul hydroelectric power plant. The available cavitation coefficients along the blade length at the shroud on suction and side pressure sides are presented in Figs. (2 to 4). For **Fig. (2)** the discharge 175 m^3/sec, net head 42.3 m and suction head 4.22 m, for **Fig. (3)** the discharge 226 m^3/sec, net head 66.4 m and suction head 1.75 m and for **Fig. (4)** the discharge 283.3 m^3/sec, net head 77.2 m and suction head 0.32 m, it is found that the value of available cavitation at the shroud section of the blades decreases as the relative velocity of flow increases (pressure will be fall). The critical cavitation coefficients are calculated to find the optimum working conditions, these values are presented in **Fig. (4)**. The comparison between **Figs. (2 to 4)** and **Fig. (5)** shows that the cavitation starts to form at distance 82%,88% and 90% from the leading edge. This fact was presented by **(Gordon, 1989)** who stated that the first evidence of cavitation in Francis unit usually appears on the underside of the blades, near the trailing edge. Also it is found that increasing the net head and decreasing the suction head, will increase the available cavitation coefficient from (-0.25) to (-0.09) while the critical cavitation coefficient which is nearly constant will give an optimum working conditions.

The shock wave radiated from collapsing bubbles is one of the main factors contributing to cavitation erosion. **Fig. (6)** shows that the acoustic energy emitted from the collapsed bubbles increases with the increase in the radius of the bubble. The duration of the bubble collapse which is shown in **Fig. (7)** is proportional to the radius of the bubble. **Figs. (8 and 9)** show that the impact pressure at specified radius has destruction action, treating the bubble impact pressure due to the sudden collapse as water hummer, after jet impact on a solid boundary, an impulsive pressure with a very short duration is produced.

The average erosion rate presented in **Fig. (10)**, it is found that the erosion rate increases through the first year of exposer time, which is in agreement with the results obtained by **(Rao, 1984)** as shown in **Fig. (11)**. The erosion curve shown in Fig. (11) is divided into three stages: first an accumulation period, second a steady state period and third an attenuation period.

Fig. (12) shows a comparison between the experimental data obtained from Al-Mosul power plant due to maintenance period and the theoretical results for presented work for a material loss in the exposer time. A good agreement is found with a typical material loss curve varies with time **(Zhou, 1983)** as shown in **Fig. (13)** especially for the first two year. Material loss (S-shape) curve shown in **Fig. (13)** is characterized by an initial period of negligible or low damage rate, then a period of approximately constant maximum erosion rate and finally a period of decreasing or sometime oscillating rate.

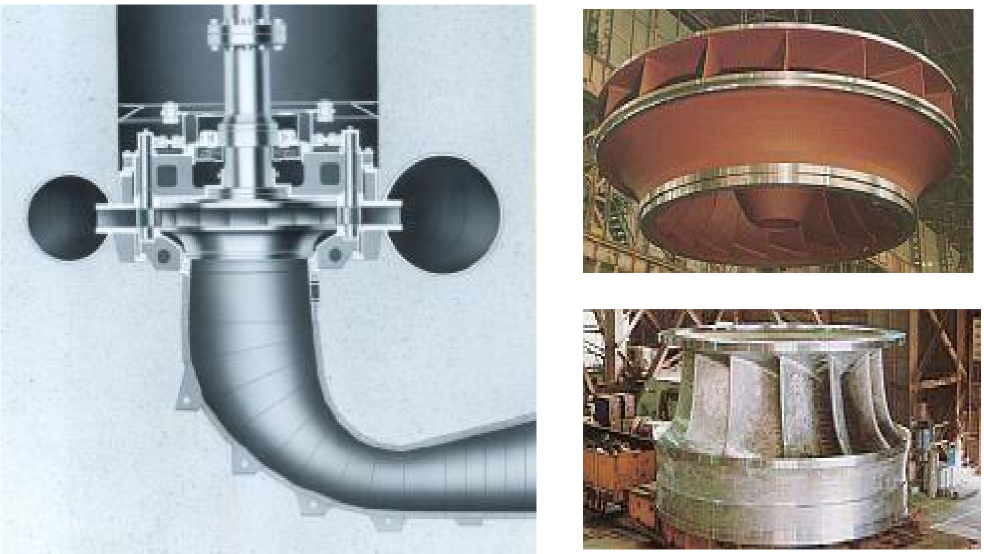
Fig. (14) shows a relation between the exposer time of Al-Mosul power plant and the mean erosion depth of the runner surface. This curve shows that, for the first four year, the mean depth about 4 mm which is about 17% of the blade thickness at the trailing edge whose thickness is 24 mm.

CONCLUSIONS

1- The cavitation phenomena appears in the underside of Francis turbine runner blades and in the trailing edge due to the irregular blade shape which reduces pressure up to vapour pressure.

2- The best performance of Al-Mosul power plant requires the optimum working condition, depending on the data of Al-Mosul power plant as well as the optimum frequency of turbine repair. Therefore the operation hours should not exceed 24000.

3- The destruction action of collapsing bubbles is strongly depending on a bubble volume, and the acoustic energy increases with the increases in radius of the bubble.



(A) (B)

Figure (1) Francis Turbine (A) part of casing and show the interior parts. (B) Runner **[Hydraulic Turbine, website]**

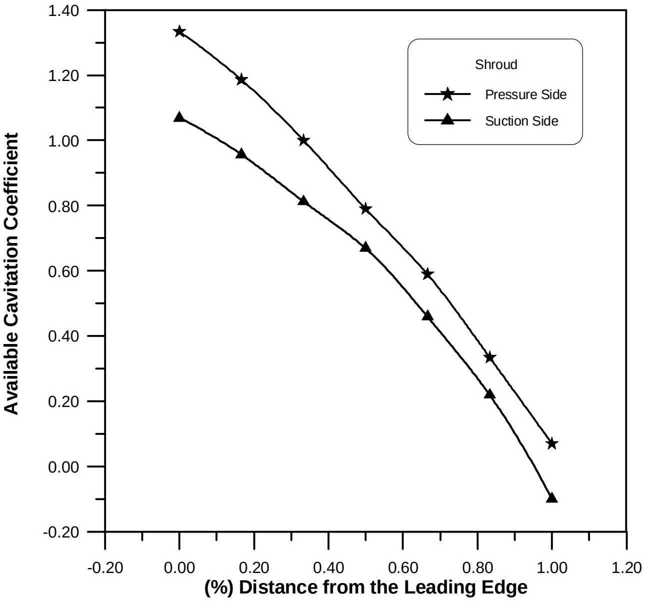


Figure (2) Variation of available cavitation coefficient along the blade length (H=42.3m)

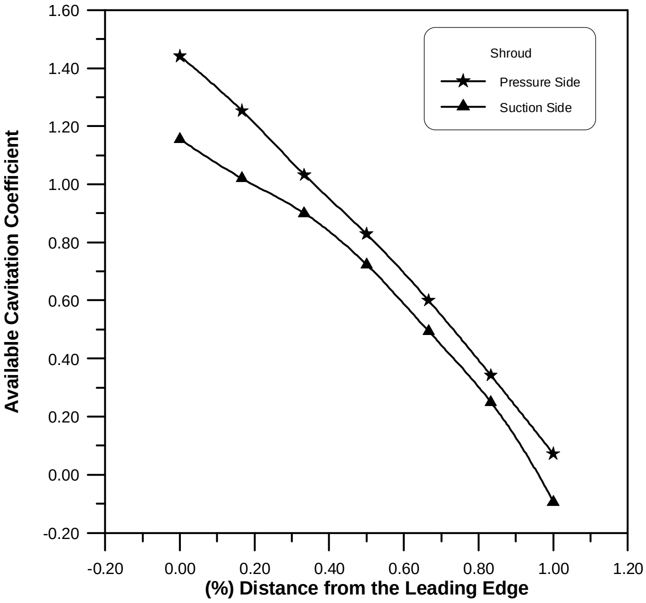


Figure (3) Variation of available cavitation coefficient along the blade length (H=66.4m)

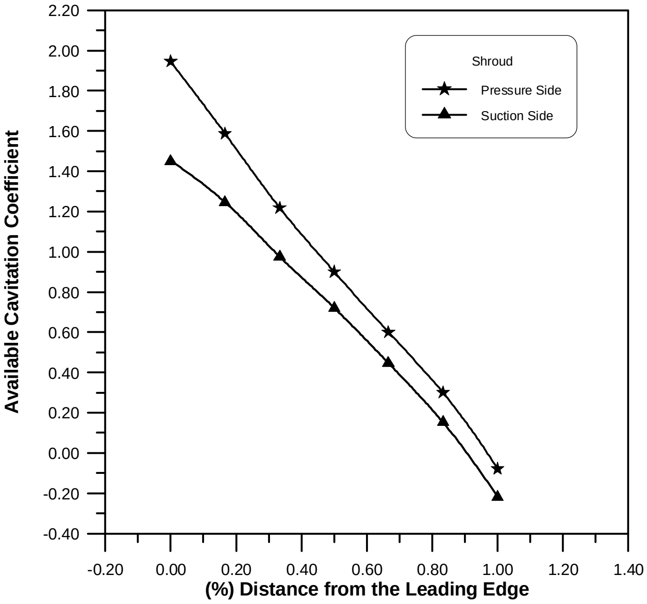


Figure (4) Variation of available cavitation coefficient along the blade length (H=77.2m)

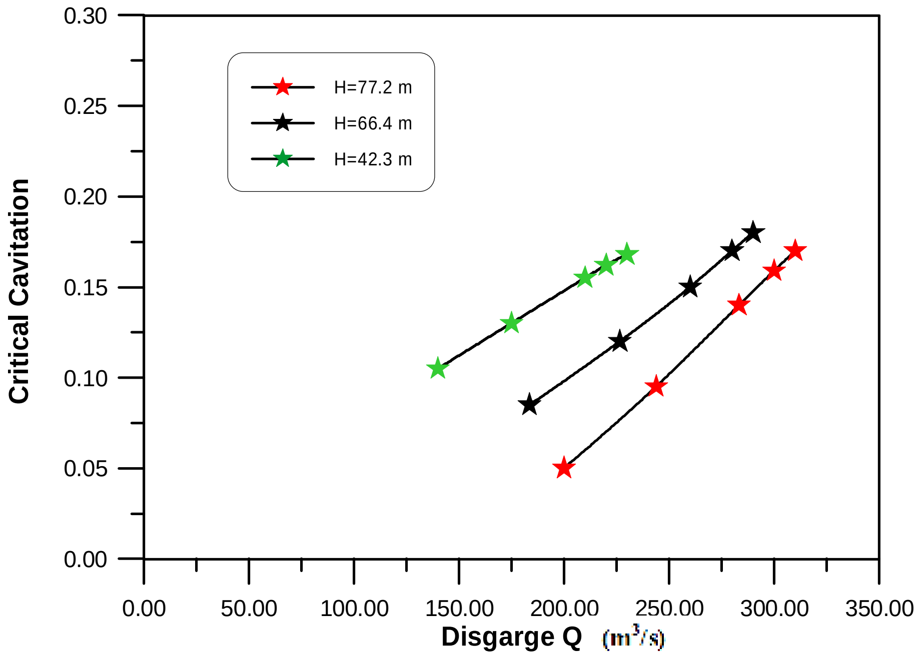


Figure (5) Samples of critical cavitation coefficient at different operation

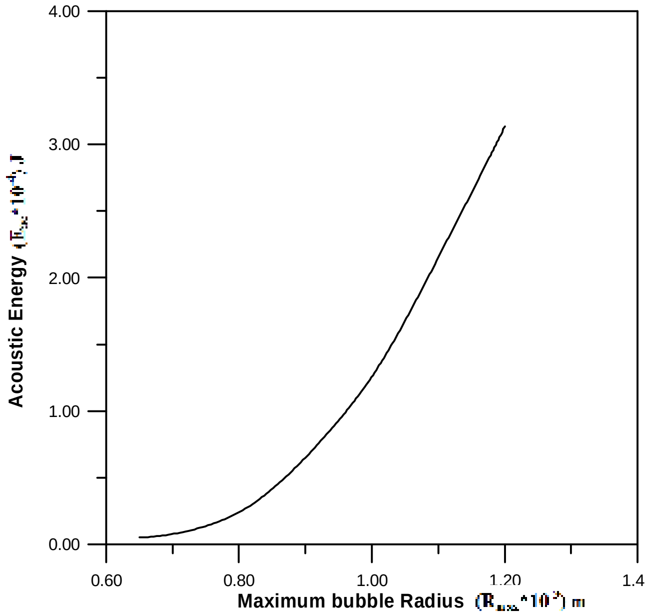


Figure (6) Acoustic energy versus maximum bubble radius

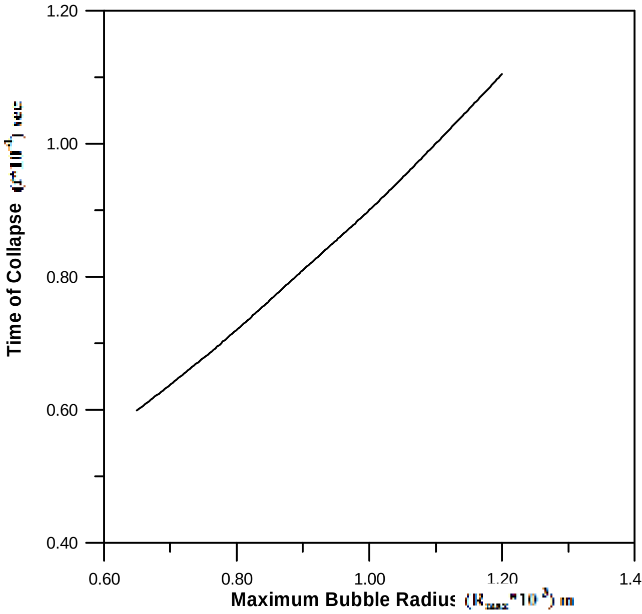


Figure (7) Time of collapse versus maximum bubble radius

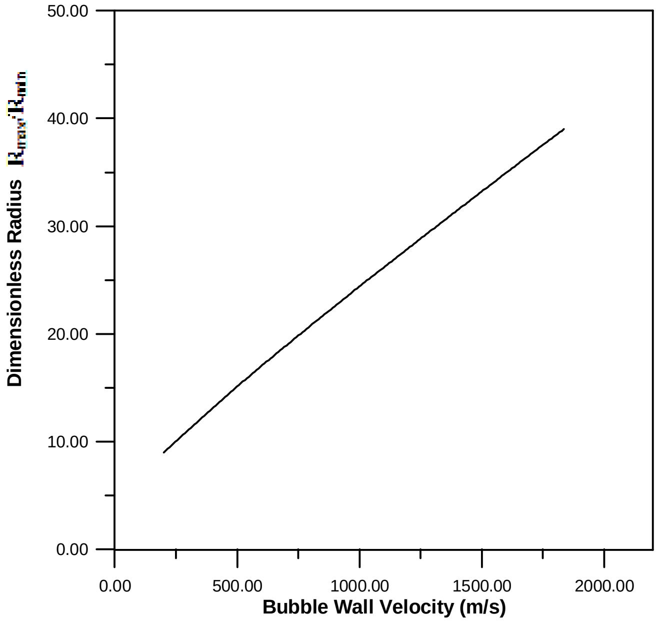


Figure (8) Dimensionless radius versus bubble wall velocity

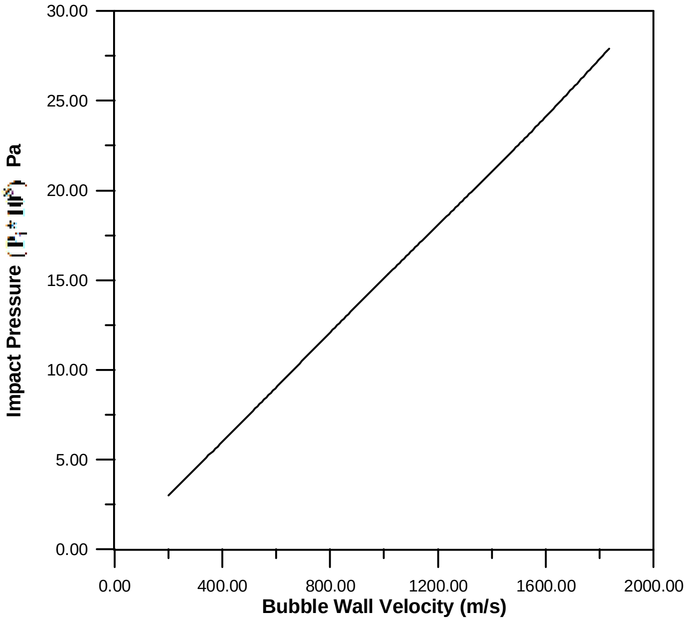


Figure (9) Impact pressure versus bubble wall velocity

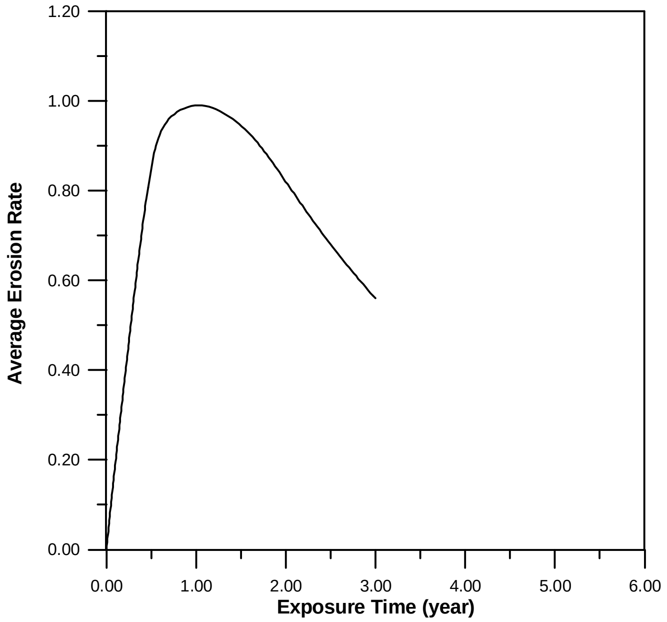


Figure (10) Average erosion rate versus Exposure time (Erosion Rate curve)

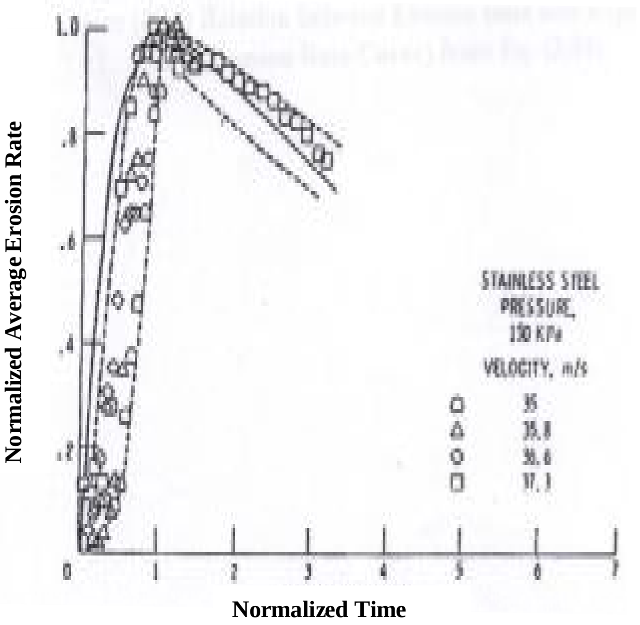


Figure (11) Normalized average erosion rate versus normalized time for stainless steel examined in a rotating disk device **[Rao,1984]**

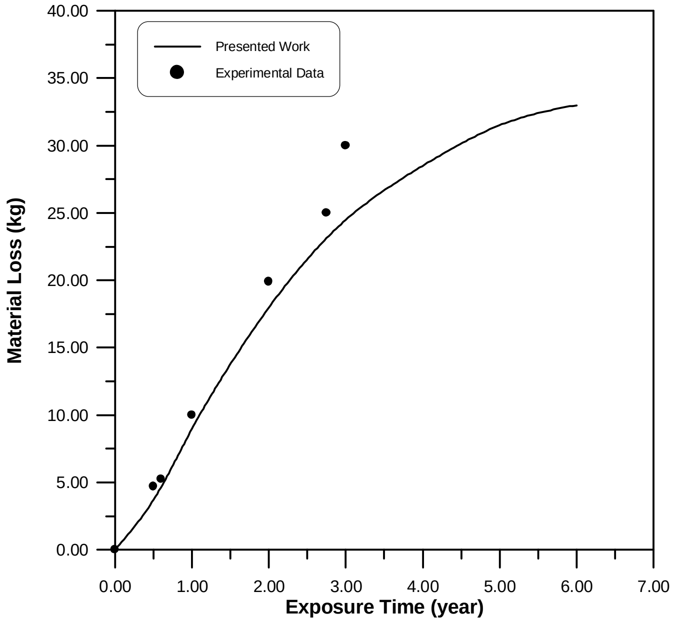


Figure (12) Material loss versus exposure time
(Material Loss curve)

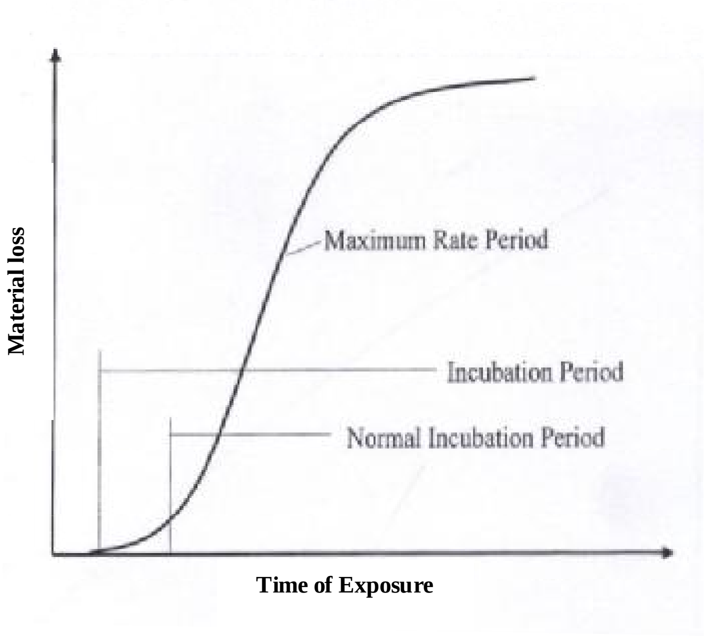


Figure (13) Typical cavitation or liquid impact
(S-Shape Erosion Curve) **[Zhou, 1983]**

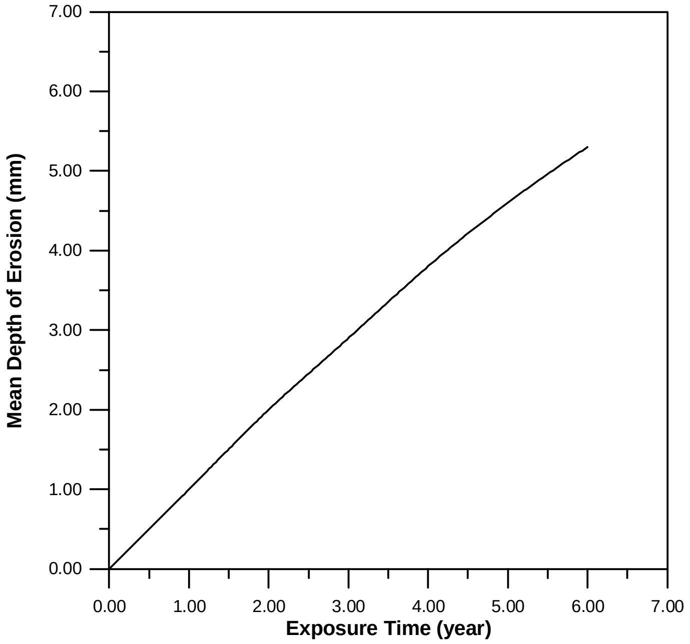


Figure (14) Mean depth of erosion versus exposure time
(Mean Erosion Depth curve)

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NOMENCLATURE

C_∞	Velocity of sound	m/s
E_{ac}	Acoustic energy	J
E_{pot}	Potential energy	J
G	Acceleration	m/s^2
H	Net head of turbine	m
H_s	Suction height (distance from the tailrace level to runner axis)	m
I	Erosion intensity	-
K_{V2}	Coefficient of absolute velocity at exit of runner	-
K_{W2}	Coefficient of relative velocity at exit of runner	-
P_{ac}	Minimum absolute pressure	Pa
P_{atm}	Atmospheric pressure	Pa
P_g	Gas pressure in the bubble	Pa
P_v	Vapour pressure	Pa
P_{WH}	Water hammer pressure	Pa
P_∞	Local pressure in flow field	Pa
R	Radius of bubble	m
R_0	Initial radius of bubble	m
R_{max}	Maximum radius of bubble	m
R_{min}	Minimum radius of bubble	m
r_b	Radius measured from center of bubble	m
S	Characteristics strength of the material	-
U	Bubble velocity	m/s
U	Peripheral velocity	m/s
V	Velocity at exit of turbine	m/s
V_2	Velocity at the outlet of the runner	m/s
V_5	Velocity at the outlet of the draft tube	m/s
V_j	Impact velocity of a liquid jet	m/s
$\dot{Y}$	Depth of penetration per unit time	-
a_2 & a_5	Coriolis coefficient allowing for non-uniform velocity distribution	-
a_s	Internal friction coefficient of material during plastic deformation	-
b_s	Coefficient inversely proportional to material strength	-
g	Specific weight of water	N/m^3
l	Pressure number	-
z_{draft}	Draft tube losses coefficient	-
r_∞	Density	kg/m^3
s	Cavitation coefficient	-
s_{av}	Available cavitation coefficient	-
s_{cr}	Critical cavitation coefficient	-

t	Bubble collapse time	sec
u	Metal loss rate	1/sec