AN ENERGETIC MODEL FOR CAVITATION EROSION PREDICTION IN CENTRIFUGAL PUMP IMPELLER

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ABSTRACT:

Cavitation is known to have great effects on pump hydraulic and mechanical characteristics. These effects are mainly described by deviation in pump performance, increasing vibration and noise level as well as erosion of blade and casing materials.

In the present work, only the hydrodynamic aspect of cavitation was considered. The efforts were directed toward the study of cavitation inception, cavity mechanics and material erosion in order to clarify the macro- hydrodynamic aspects of cavitation erosive wear in real machines.

As a result of this study, a rational analytical model based on energy analysis is proposed to predict the material weight loss due to cavitation erosion. An energy concept for microjet and pressure wave of bubble collapse is used in developing this model. The obtained theoretical results show good agreement with the experimental results obtained in this investigation and with results of some other investigations.

1. INTRODUCTION

In fact no other phase of hydraulic machinery design and operation has been given so much attention in technical literatures as cavitation. The reason for this was the use of higher specific speeds for both hydraulic turbines and centrifugal pumps, with the increased danger of cavitation damage. The experimental erosion results from a hydraulic machinery prototype are rare [1,2]. The problem of prototype cavitation damage prediction from deviated performance and bubble dynamics is still unsolved [3].

A survey of cavitation in hydraulic turbine by ARNDT [4] shows that the size scale exponents have not appeared to be a reliable predicator of increases in erosion rate with increases in size. The time scale effect is strongly connected to the erosion mechanism. A correlation between the parameters involved in the study of the time scale effect is presented by SELIM [5]. The results show that the wear loss rate may be predicted from the incubation period and more precisely the nominal incubation period as defined in HAMMITT [6].

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round-nosed body. It is assumed that the erosion rate is proportional to the number Z of nuclei impinging on the solid wall. The effects of liquid "microjet" impact and bubble growth problem has also not been taken into consideration.

SELIM [8] presented a model for prediction of weight loss rate, based on a hypothesised bubble energy spectrum suggested by HAMMITT [6]. He assumed the distribution of the nuclei size in the water and pressure inside the bubble. He also assumed that the damage is caused by liquid microjet that was produced by a collapsing cavity and neglected the pressure wave in liquid due to bubble collapse.

CHIVERS [9] Proposed a theoretical model to explain the development of cavitation in a centrifugal pump assuming that cavitation is a bubble growth problem. He obtained a relation between breakdown of pump performance and cavitation inception.

The objective of this work, is to study the hydrodynamic aspect of cavitation. The efforts were directed toward the study of incipient stage of cavitation, cavity mechanics and material erosion in order to clarify the macro- hydrodynamic aspects of cavitation erosive wear in real machine. A rational analytical model based on energy analysis is proposed to predict the material weight loss due to cavitation erosion. An energy concept for microjet and pressure wave of bubble collapse is used in developing this model.

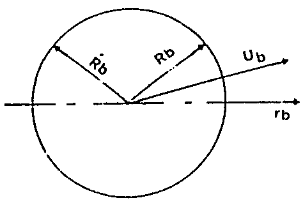
2. THEORETICAL APPROACH

Cavity Classifications; Cavitaion is classified according to its shape and origen. In centrifugal pumps there are more than one type of cavitation. Two main types of cavitaion are often presented.

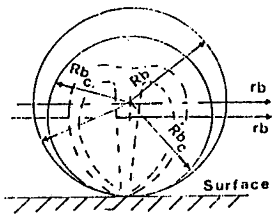
a- Fixed cavity, attached to the blade (sheet cavitaion) started at the leading edge of impeller's blades.
b- Vortex cavitaion started on the suction surface of the blades

and moves down stream. The collapses processes take place on the pressure surface of the impeller blades. This cavitaion is periodic [10,11] and unstable. The produced damage is higher than in fixed cavitaion. It occurs usually in pumps operating at lower capacity than prescribed. Most cavitaion damage is usually caused by the vortex cavitaion.

Pump Performance; A centrifugal pump is essentially a device capable of generating a specific head of fluid for a particular volumetric flow rate.



a) Velocity vector of bubble motion



b) Velocity vector of bubble collapse attached surface

Fig. (1) Coordinate bubble systems

Fig. (1) shows spherical co-ordinate at the center of bubbles with radial co-ordinate *rb*. Fig. (1) also represents the expected bubble view in growth and collapse.

The vapour to liquid volume ratio (r_v) for cavitating flow is obtained experimentally using the following equation: $r_v = (Q_n - Q_c)/Q_c$ (1)

There is single phase flow between the inlet of the pump and the impeller eye. Two phase flow is generated between the impeller eye and blade inlet. Although the flow in the impeller passage is two phase, the flow can be reasonably considered as one phase flow along each side of blade since no new cavities (bubbles) are generated in the high pressure region.

To determine the pressure at the blade inlet point, Bernoulli's equation is applied between impeller eye and the blade inlet point, neglecting potential difference and head losses. The energy equation is in the form:

$$P_u v_f - \frac{C_u^2 - C_{fi}^2}{2} = P_{ib} v_f (r_v + 1) + \frac{v_f}{v_g} r_v (h_g - h_f) \qquad (2)$$

Bubble Dynamics; In the present model bubble radius (R_b), rate ($\dot{R}_b$) and acceleration ($\ddot{R}_b$) of growth are studied. For simplicity, the following assumption are considered:

a) The cavity starts with one nucleius between two adjacent blades at the lowest pressure point. This assumption has been discussed and proved by LUSH [12].
b) During the cavity generation the bubble radius grows with its maximum speed ($\ddot{R}_b = 0$).

The extended Raligh's equation of motion for a spherical cavity in an infinite medium with substituting the equivalent value of P, is given by:

$$R_b \ddot{R}_b + \frac{3}{2}\dot{R}_b^2 = \frac{1}{\rho}\left(P_g + P_v - \frac{2\delta}{R_b} + 4(\mu_L + \mu_g)\frac{\dot{R}_b}{R_b} - P_\infty\right) (3)$$

During the collapsing process the following assumptions are considered:

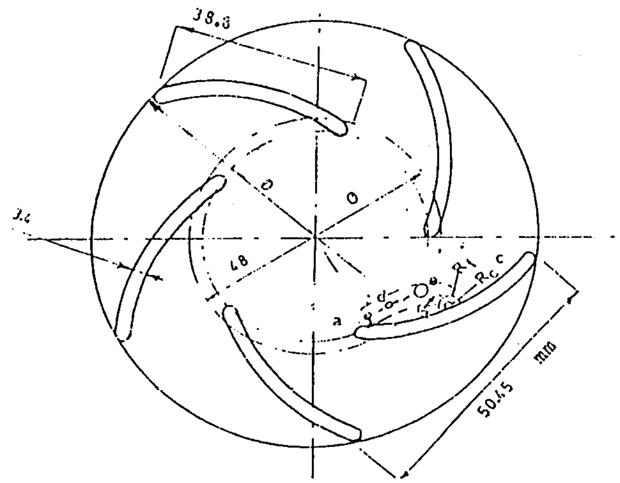


Fig.(2) Bubble stream line intersecting point (c).

a) The process of collapsing cavities is simplified by the consideration of static, wall-attached bubble. RAABE [7] proved that the speed of the bubble wall at the moment of collapse of attached cavity is [$\dot{R}_b$]. The final impact pressure P_i of the collapsing bubble acting on the solid wall in point (c) follows from the annihilation of (R_b) according to JUKOVSK's formula of water hammer, $P_i = \rho_L a_L \dot{R}_b$ (4)
b) In the bubble collapse, the bubble splits isentropically into two spherical divisions with equal volumes as demonstrated in HAMMITT [6]. All bubbles have the same trajectory (see Fig. 2).

Under the above assumptions the final bubble radius R_{b_c} follows from the radius at point (f), taking into account, an isentropic pressure and bubble division.

$$R_{b_c} = \frac{R_{b_f}}{x^{1/3}}\left(\frac{P_{g_f}}{P_{g_c}}\right)^{1/3\gamma} \qquad (5)$$

where , x = number of bubble divisions.

Substituting R_{b_c} for R_b in Rayleigh's equation, then the new values of $\dot{R}_b$, $\ddot{R}_b$ and the impact pressure wave can be determined.

Number of bubbles generated at the blade inlet which were taken away by the flow can be estimated as follows:

$$Z_0 = \frac{3 \cdot r_{v_2} \cdot Q_c}{4\pi R_{b_0}^3 \cdot n} \qquad \text{nuclei/s} \qquad (6)$$

The time of bubble collapse is also calculated by the following formula which was suggested by RAYLEIGH [6].

3. CAVITATION EROSION:

According to some investigation the major cause of cavitation induced erosion may be one of the following:

a) Shock waves in the liquid due to bubble collapse [7].
b) Liquid "microjet" impact upon the eroded surface [8].

The number of bubbles impact per second is not the presumed cause of cavitation erosion, a combination of shock waves in the liquid and liquid "microjet" impact upon the eroded surface due to bubble collapse is considered to represent, in this model, the most likely detailed mechanism for cavitation erosion.

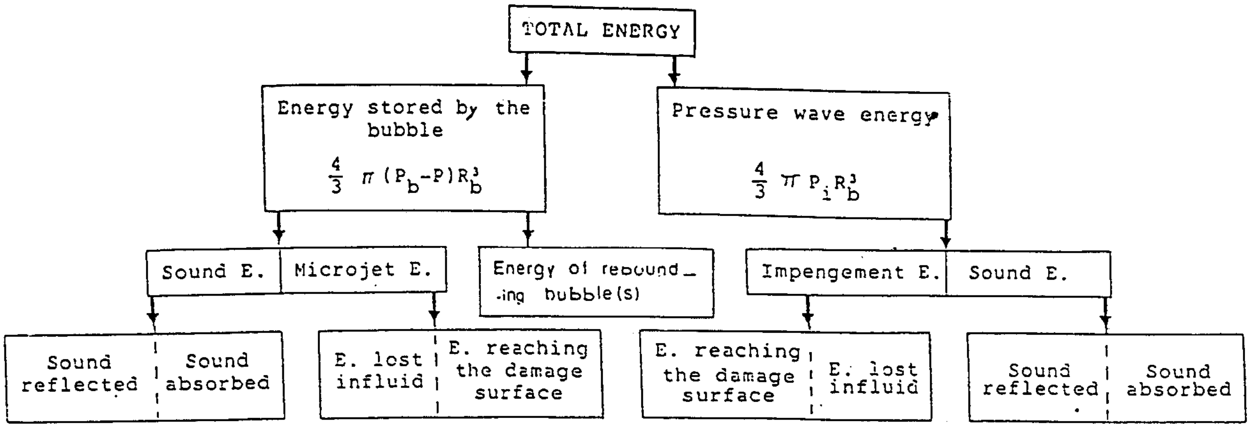


Fig. (3) Energy flow process.

Various groups of parameters have different effects upon cavitation erosion. There are mainly two groups (a) Fluid parameters which are velocity, pressure, gas content and temperature. (b) Material properties as ultimate resilience, strain energy,.... etc. Material properties effects are represented in a predominate mechanical property factor which is discussed by HAMMITT [6].

An Energy Concept for The Scaling of Cavitation Erosion; The energy concept has been proposed by several investigators [3,8]. Hammitt postulated that there is a statistical distribution of bubble energies that varies with the degree of cavitation. The total energy scheme is shown in Fig.(3). It is given by the following form:-

$$E_T = E_D + E_P \tag{7}$$

where

E_D the energy remaining in the bubble after the initial collapse, including the energy of rebounding bubbles $= \frac{4}{3}\pi(P_b - P)R_b^3$

E_P Pressure wave energy

The energy remaining in the bubble can be further divided as follows:

$$E_D = E_{S.S} + E_{MJ} + E_R \tag{8}$$

where

E_R Energy of rebounding bubble.

$E_{S.S}$ Sound energy reflectd and absorbed (generated from energy stored in the bubble).

E_{MJ} Microjet total energy (includes energy lost in the fluid and reaching the damage surface).

Then, the energy of rebounding is also divided as follows:

$$E_R = E_I + E_{S.P} \tag{9}$$

where

E_I Impingement energy (includes energy reaching the damage surface and lost in fluid).

$E_{S.P}$ Total sound energy (includes energy reflected and absorbed from pressure wave energy).

The energy which produced damage is

$$E_{P.D.} = E_{MJ} \text{ reaching the damage surface} + E_I \text{ reaching the damage surface} \tag{10}$$

Energy of Bubble Collapse; Considering a single cavitation bubble impinging the blade and then collapsing, according to the energy flow process as illustrated in Fig. (3). The total energy of bubble collapse (E_T) is the sum of the energy due to shock waves in liquid and the energy due to liquid "microjet" impact, that is:

$$E_T = \frac{4\pi}{3} P_i R_b^3 Z_0 + \frac{4\pi}{3} R_b^3 Z_0 (P_b - \underline{P}) \tag{11}$$

Energy Produced Damage ($E_{p.d.}$); The value of the threshold energy is obviously a function of test material. The total energy flux of the collapsing bubbles required to produce damage is given by integrating the energy distribution curve ($n(e)$) from the threshold (e_{th}) energy to infinity, i.e., (Hammitt 1980), that is:

$$E_{p.d.} = \int_{e_{th}}^{\infty} n(e) \cdot e \cdot de \tag{12}$$

Energy produced damage can be computed by substituting the energy distribution with total energy flux of bubble collapse into equation (12) and integrating from e_{th} to infinity (details of derevation in ref [14]), one obtains:

$$E_{p.d.} = Z_0 \left\{ e_{th} \exp\left[-\left(\frac{\sqrt{\pi} e_{th} Z_0}{2 \cdot E_T} \right) \right] + \frac{E_T}{Z_0} \operatorname{erfc}\left(\frac{\sqrt{\pi} e_{th} Z_0}{2 \cdot E_T} \right) \right\} \tag{13}$$

Energy Balance of Erosion; Energy produced damage is proportional to the energy necessary to remove unit material volume (ψ) times the volume loss rate ($\dot{V}$). The constant of proportionality is the efficiency of energy transfer between bubble and eroded surface (η). This relation can be represented as follows:

$$E_{p.d}\, \eta = \psi \cdot \dot{V} \tag{14}$$

The efficiency of energy transformation will be a function of many factors such as liquid and material properties.

Predominant Mechanical Property (ϵ); HAMMITT (1980) showed that the most likely form for an energy parameter would be a combination of ultimate resilience (U_R) and strain energy (S_E) (i.e. $\epsilon . C_3 = \psi$). It can be arranged as follows:
$$\epsilon = C_0 + C_1\ U_R + C_2\ S_E \quad (15)$$

Where, C_0, C_1 and C_2 are constants which can be determined from HAMMITT [6]

It can be assumed that the threshold energy (e_{th}) is proportional to the quotient of the energy parameter which represents the energy per unit volume necessary to produce damage and the efficiency of energy transformation. Thus, the threshold energy is given by the following expression: $e_{th} = C_4 \epsilon / \eta$ (16)

Where , C_4 is the constant of proportionality.

Mass Loss Rate; Weight loss rate can be predicted by substituting from equation (13) into equation (14), one obtains:

$$WLR = \frac{t\eta\rho g}{\epsilon C_3} Z_0 \left\{ \frac{\epsilon C_4}{\eta} \exp\left[-\left(\frac{3\epsilon \cdot C_4}{8\eta\sqrt{\pi} R_b^3 (P_c + P_b - \underline{P})} \right) \right] \right.$$
$$\left. + \frac{4}{3}\pi R_b^3 (P_c + P_b - P)\ \mathrm{erfc}\left[\frac{3\epsilon \cdot C_4}{8\eta\sqrt{\pi} R_b^3 (P_c + P_b - \underline{P})} \right] \right\} \quad (17)$$

Then the total weight loss rate (TWLR) in the impeller from each collapse and for all impeller blades, will be as follows:

$$TWLR = n \sum WLR \quad (18)$$

The parameters C_3, C_4 can be determined experimentally as function of THOMA cavitation factor and running impeller speed.

4.EXPERIMENTAL APPARATUS AND INSTRUMENTATION

To study the cavitation erosion due to bubbls collapse experimentally, a test rig has been designed and constructed. To achive this task the loop is equipped with a centrifugal pump. The pump is equipped with an impeller of aluminium which has the following specifications; total weight 96.6 gm, inlet diameter = 38mm, outer diameter = 81mm, height = 11mm. The impeller is designed with five blades turned backwards at an angle 30°. The pump is driven at different speeds by two motors, through a system of pulleys. Suction and discharge pipes are made from glass to allow full visualization. The cavitating flow condition is reached with decreasing NPSH by the two following methods; 1- The partial closing of suction valve. 2- Increasing of the impeller velocity. Fig (4) shows the shematic diagram of the system.

The weight loss in the impeller is accurately measured using digital precision scale, self calibrated with accuracy of 0.1 mg. U-tube manometers were used to measure pressures with accuracy of ±1 mm. The discharge is measured with calibrating tank. The fluid (water) temperature is measured with thermocouple located in the suction tank.

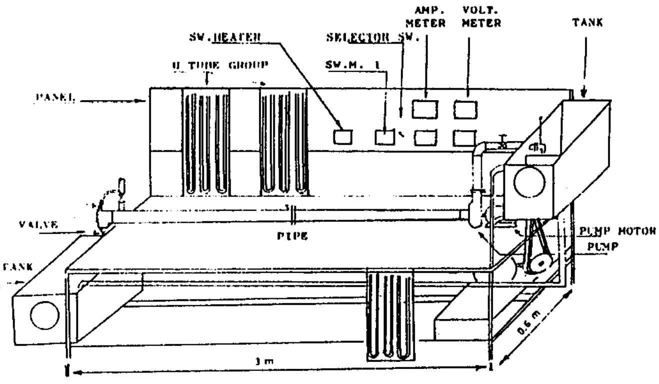


FIG.(4) TEST RIG TO STUDY CAVITATION PHENOMENON.

5. RESULTS AND DISCUSSION

Pressure Distribution Along The Circular Blade; The pressure distribution on suction and pressure surfaces as a function of radial distance from blade inlet to blade outlet is shown in Fig. (5) for an impeller speed of 2860 rpm. The pressure drop in the pressure distribution indicated between the two peaks in the curve has been also observed by MOORE [15]. This sudden pressure drop in circular arc blade of centrifugal impeller may be due to the effect of next blade [16], fluctuation in the blade shape or the centrifugal force applied to the rotating flow.

Bubble Behaviour in Centrifugal Impeller; The relation between initial bubble generated radius and inlet blade pressure is found to be linear, which depends on impeller speed. It is clear that as the inlet pressure decreases the bubble radius increases as physically expected. At the same inlet blade pressure lower than 60.15 KN/m^2 abs. ,bubble radius decreases with increasing impeller speed, as shown in Fig. (6). For the considered impeller bubble collapse starts at the second element which is followed by a series of collapsing in the next element where pressure is higher as shown in Fig. (7).

The solution of the equations (3) with the assumption previously mentioned is shown in Fig. (7). The initial bubble radius at impeller inlet was calculated with regardless of cavitaion origen and type. This is based on vapour to liquid ratio. The bubbles collapse are in indirect relation with σ - Low σ (critical σ) means low NPSH -. The break-down characteristics is sharp. When σ is larger than the critical value the number Z_0 is decreased and the collapse bubbles will grow as pressure wave generates from the first collapse acting as water hammer. According to Jukovsk's formula depression will occure and the bubble diameter will increase untill it reaches a high pressure region where it collapses. This type of cavitaion presentes a clear periodicity, simillar to that observed by Yamamasu and Yokomiyo [10] under non cavitating condition. The performance of such a pump is of a normal curve but when cavitaion appears the performance curve is staggered.

Predicted Erosion Rate; Based on the pressure distribution for cavitating conditions, bubble dynamic data, material constants and energy constants, the erosion rate is estimated. The energy - erosion constants mentioned before are obtained from the experimental data results.

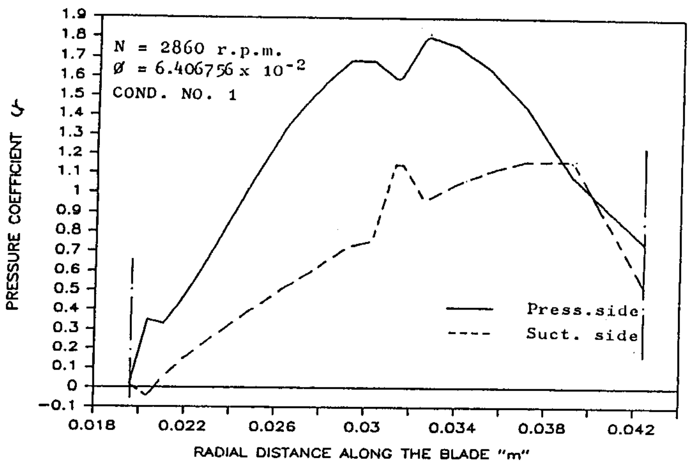


Fig. (5) Press. coefficient along the blade (N = 2860)

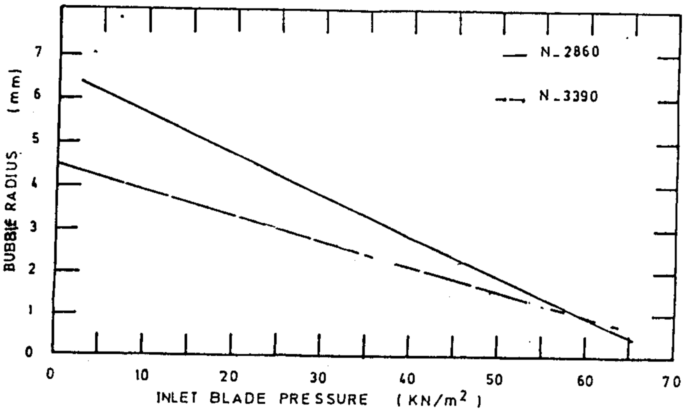


Fig.(6) Bubble radius as a function of inlet blade pressure.

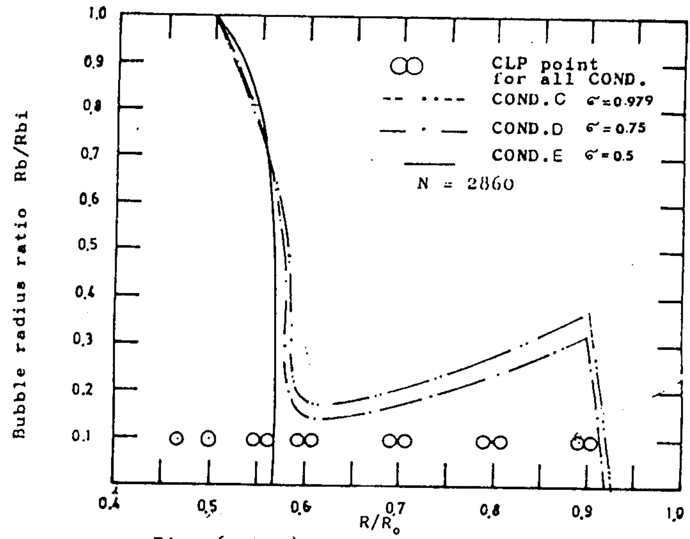
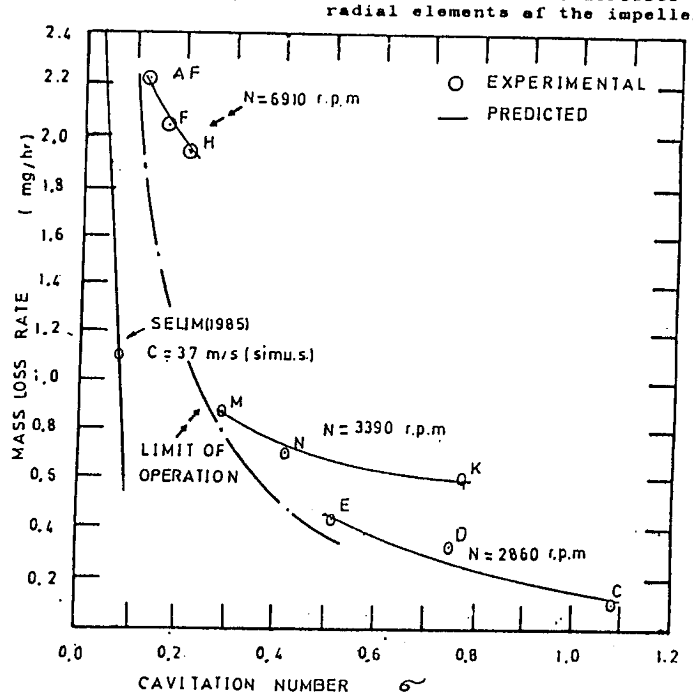


Fig. (7) Bubble radius ratio acrosses radial elements of the impeller



Fig(8) MASS LOSS RATE AS A FUNCTION OF THOMA CAVITATION FACTOR (σ)

The erosion as Weight Loss Rate is calculated using equation (17) where the energy produced damage is assumed to be originated from the microjet impingement in addition to pressure wave. The efficiency of energy transfer between bubble and eroded surface is given by equation (14). In fact, this efficiency as well as coefficients C_3, C_4 in equation (17) are determined experimentally. A further study is needed in order to predict these coefficients, based on pump hydraulic parameters.

The model considered total bubble's number calculated from equation (6), which, it is independent of cavitaion type whatever cavitaion sheet or vortex.

The mean value of the instantaneus *WLR* over (150 hr) was taken in the evaluation of the Weight Loss Rate (WLR). Since WLR is not constant with time, it is of S shape type with an incubation period, followed by a period of increasing WLR. This cycle may be repeatable with time [2] so that a mean value can be obtained over large period of operation.

The results show also that erosion is dependent on running speed, so that the formula given in [2] to correlate erosion with velocity in a power law was not in complete agreement with the experimental data. At low running speed, WLR tends to be constant.

Comparison between the predicted and experimentally obtained weight loss rate is shown in Fig. (8). The figure indicates that there is a good agreement between the predicted and experimental values.

In comparison to the results obtained by other authors, it is found that the results obtained by SELIM [8] for a model system is not in the range of the present study. This is because the prototype system usually operates at different conditions. It is clear that the weight loss rate decreases with increasing Thoma cavitation factor for a certain impeller speed. This is because the inlet pressure increases (less chance for bubble generation) as Thoma factor increases. Also, the figure indicates that cavitation damage is very sensitive to running speed.

CONCLUSION

The cavitation erosion rate can be predicted as a result of an energy liberated from the combined effect of shock wave in the liquid and liquid microjet impact upon the eroded surface due to the bubble collapse. The models for cavitation erosion prediction in the impeller machine deal with the macro-hydrodynamic aspects of cavitation , pump performance deterioration, real fluid parameters, bubble dynamics and pressure distribution for different operating conditions.

The proposed model is a good tool for prediction of blade damage due to cavitation.

Initial bubble radius has a linear relation with inlet pressure which depends on the impeller speed.

NOMENCLATURE

A = Area of impeller blade.
a = Sound speed
C_{fi} = Absolute fluid velocity at impeller inlet
C_u = Upstream fluid velocity
e = Single blow energy
h_f = Specific enthalpy of liquid
h_g = Equilibrium specific enthalpy of vapour
$n(e)$ = Cumulative number of bubbles corresponding the energy
n = Blade number
$\underline{P}$ = Pressure at bubble wall i.e. at liquid-vapour interface
P_c = The uniform critical pressure across the impeller inlet i.e, or, collapse pressure
P_{ib} = Pressure at blade inlet
P_u = Upstream pressure
P_∞ = Pressure at $r_b = \infty$
Q_n = Volumetric flow rate
Q_c = Actual volumetric flow rate in cavitating region
r = Radial distance
U_t = Peripheral velocity at impeller blade outlet.
v_f = Specific volume of liquid
v_g = Specific volume of vapour
μ = Absolute or dynamic viscosity
ρ = Density, mass per unit volume /OR, angular angle in the Z plane.
δ = Surface tension
σ = THOMA cavitation factor
ϕ = Flow coefficient of pump flow rate $= \frac{Q}{A_t U_t}$
ψ = Pressure head coefficient $= (p - P_t)/(\rho U_t^2/2)$
ν = Isentropic exponent

SUBSCRIPTS

b = Bubble; i= Impeller inlet; g = Gas
c = Collapse; o= initial
f/L = Liquid; t=Impeller outlet

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