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Research Article

Effect of Cavitation on Hydraulic Turbines- A Review

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Abstract

Cavitation is an important problem in hydraulic machines that negatively affects their performance and may cause damages. Cavitation is a phenomenon which manifests itself in the pitting of the metallic surfaces of turbine parts because of the formation of cavities. In the present paper, a brief description of the general features of cavitation phenomenon is given and also discussed about the Thoma's Cavitation factor. Based on the literature survey various aspects related to cavitation in hydro turbines have been discussed briefly.

Key words: *Cavitation; Hydraulic Machine; Impulse Turbine; Blades; Erosion*.

1. Introduction

Among all the renewable energy sources available, small hydropower is considered as the most promising source of energy. In many parts of the country, especially hill states streams coming down the hills posses' sufficient potential energy that can be utilized. The hydraulic turbine used to convert the potential energy of water to mechanical energy. Flowing water is directed on to the blades of a turbine runner, creating a force on the blades (Kumar Pardeep *et al*, 2010). Since the runner is spinning, the force acts through a distance (force acting through a distance is the definition of work). In this way, energy is transferred from the flowing water to the turbine. The ideal power that can be derived from flowing water at a site is given by:

$$P = \gamma Q H$$

where P is power in KW , γ is specific weight of liquid in N/m^3,Q is flow rate in m^3/s and H is gross head in m.

Hydraulic turbines are divided into two groups;

- Impulse Turbine
- Reaction Turbine

Impulse Turbines are high head, low discharge, and low specific speed and operate at atmospheric pressure, while the reaction turbines operate under low and medium head with high specific speed and operate under variable pressure .Cavitation is a problem faced by reaction type hydraulic turbines. Cavitation in hydraulic machines negatively affects their performance and may causes severe damages. The management of the small hydropower plants for achieving higher efficiency of hydro turbines with time is an important factor, but the turbines show declined performance after few years of operation as they get severely damaged due to various reasons. One of the important reasons is erosive wear of the turbines due to high content of abrasive material during monsoon and cavitation (Tong D *et al*, 1981).

Cavitation was used to describe the phenomenon of liquid-to-gas and gas-to-liquid phase changes that occur when the local fluid dynamic pressures in areas of accelerated flow drop below the vapor pressure of the local fluid. Cavitation erosion is mainly a problem of hydraulic equipment and to overcome this trouble we should apply better design of moving parts and better metallurgy, which up to now seems the easiest way to solve the problems. Cavitation occurs when the static pressure of the liquid falls below its vapor pressure, the liquid boils and large number of small bubbles of vapors are formed. These bubbles mainly formed on account of low pressure are carried by the stream to higher pressure zones where the vapors condense and the bubbles suddenly collapse, as the vapors are condensed to liquid again. This results in the formation of a cavity and the surrounding liquid rushes to fill it. The streams of liquid coming from all directions collide at the center of cavity giving rise to a very high local pressure whose magnitude may be as high as 7000 atm. Formation of cavity and high pressure are repeated many thousand times a second. This causes pitting on the metallic surface of runner blades or draft tube. The material then fails by fatigue, added by corrosion (Modi PN *et al*, 2002).

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Cavitation commonly occurs in hydraulic turbines, around runner exit and in the draft tube. In general there are two ways to reduce the cavitation damage. One involves optimizing the hydraulic design of equipment; the other involves developing coatings for the substrates of wetted parts, which can prolong the overhaul interval of hydraulic components. Cavitation in general is slow process but the effect of cavitation is severe. Damaged caused by cavitation, if summarized are: erosion of material from turbine parts, distortion of blade angle, loss of efficiency due to erosion/distortion (Santa JF *et al*, 2009). Prof. D Thoma Suggested a dimensionless number called as Thoma's Cavitation factor σ (sigma), which can be used for determining the region where cavitation takes place in reaction turbines:

$$\sigma = \frac{H_a - H_v - H_s}{H} \quad (1)$$

Where H_a is the atmospheric pressure head in m of water, H_s is the suction pressure at outlet of reaction turbine in m of water or height of turbine runner above the tail water surface , H_v is vapor pressure head, H is the net head on the turbine in m of water (Modi PN *et al*, 2002). The value of σ depends on N_s (specific speed) of the turbine and for a turbine of given N_s the factor σ can be reduced up-to a certain value upto which its efficiency, η_o remains constant. A further decrease in value of σ results in a sharp fall in η_o. The value of σ at this turning point is called critical cavitation factor σ_c. The value of σ_c for different turbines may be determined with the help of following empirical relationships:

For Francis turbines: $\sigma_c = 0.625\left(\frac{N_s}{380.78}\right)^2$ (2)

For propeller turbines: $\sigma_c = 0.28 + \left[\frac{1}{7.5}\left(\frac{N_s}{380.78}\right)^3\right]$ (3)

The values of σ from equation (1) is compared with the value of σ_c from equation (2) and (3) and if value of σ is greater than σ_c, cavitation will not occur in that turbine.

1.1 Cavitation -- erosion in hydroturbines

Also known as "pitting" erosion, cavitation on hydro-turbines occurs as a result of the steady erosion of particles from the turbine surface, Pitting depth exceeding 40mm in depth has been observed on hydro-turbine runner surfaces. Typical metal losses experienced in the hydro-generating industry can average approximately 5kg/m^2 /10,000 hours (generally repair is scheduled at 40,000 hours). For a turbine runner over a period of several years, metal losses up to 200kg is not uncommon (Simoneau R *et al*, 1999). Up to 90% of hydro-turbines suffer cavitation damage to some extent (Simoneau R *et al*, 1999). To study the cavitation erosion, three types of devices have usually been used. These are the rotating disk, the hydrodynamic tunnel and a vibratory device which produces cavitation (Preece C.M *et al*, 1979). Cavitation-erosion is most likely to occur on the low pressure side of the turbine runner blades. Damages caused by cavitation if summarized are: erosion of material from turbine parts.

- Distortion of blade angle
- Loss of efficiency due to erosion/distortion

1.3Theoretical investigations

Cavitation can be observed in a wide variety of propulsion and power systems like pumps nozzles, injectors, marine propellers, hydrofoils and underwater bodies (Knapp R T *et al*, 1970). Cavitation can appear in hydraulic turbines under different forms depending on hydraulic designs and the operating conditions. In Francis turbine the main types are leading edge cavitation, travelling bubble cavitation, Von Karman vortex cavitation and draft tube swirl, Leading edge or inlet cavitation is usually a very aggressive type that is likely to erode the blades deeply. Traveling bubble cavitation is noisy type of cavitation that reduces machine efficiency and provokes blade erosion.

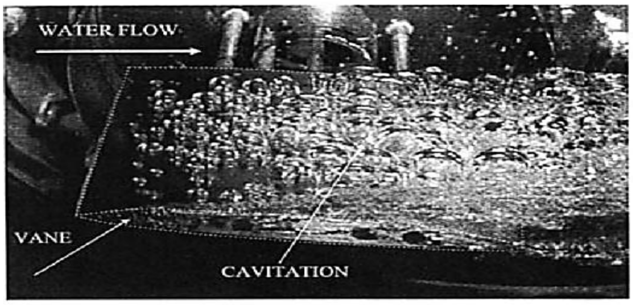


Fig. 1 Fluid flow on a blade under cavitation (Baldassarre Antonio *et al*, 1998)

Draft tube swirl generates low frequency pressure pulsations that in case of hydraulic resonance can cause strong vibrations on the turbine and even on the power-house. Von Karman vortex cavitation produces structural vibrations at the trailing edge of vanes (Baldassarre Antonio *et al*, 1998). Duncan (Duncan Jr Wet *et al*, 1998) provided information about cavitation, cavitation repair, cavitation damage inspection, cause of pitting, runner modifications, cavitation pitting locations, methods of cavitation pitting repair and areas of high stress runner. Typical areas of cavitation pitting were found as shown in Figure. 2.

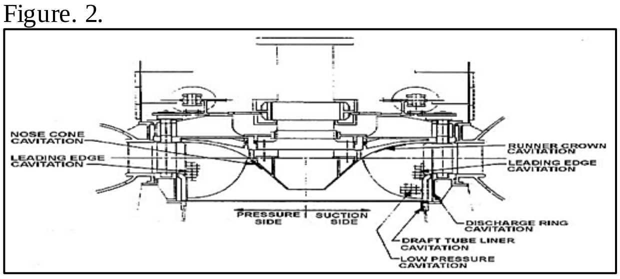


Fig. 2 Francis turbine- typical area of cavitation pitting (Duncan Jr Wet *al*, 1998)

Karimi and Avellan (Karimi A *et al,* 1996) presented a new cavitation erosion device producing vortex cavitation. A comparative study between various cavitation erosion situations was carried out to verify the ability of this vortex cavitation generator to produce realistic cavitation erosion with respect to that observed in hydraulic machinery. Hardened superficial layers in specimens exposed to flow cavitation were found a thicker than those in vibratory cavitation, which leads to higher erosion rates. Farhat et al. (Farhat M *et al,* 1999) illustrated the benefits of the cavitation monitoring in hydraulic turbines using a vibratory approach. This technique was used in a large Francis turbine in order to validate as light modification of its distributor, which was intended to reduce the cavitation aggressiveness and related erosion.

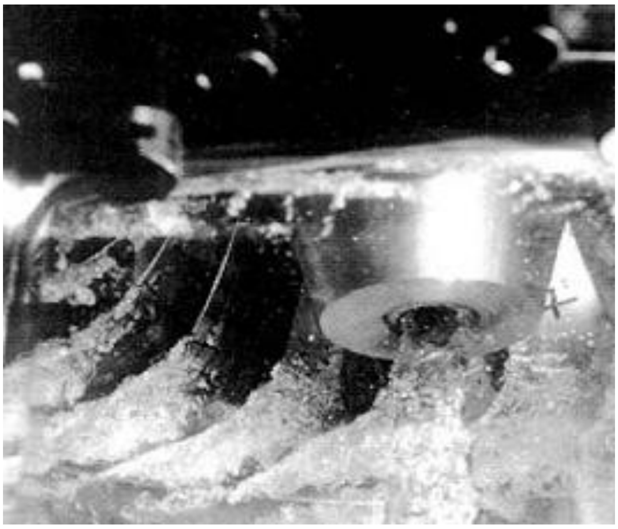
2. Experimental studies

Escalera *et al* (2006) carried out experimental investigation in order to evaluate the detection of cavitation in actual turbines. The methodology was based on the analysis of structural vibrations, acoustic emissions and hydrodynamic pressures measured in the machine. The results obtained for the various types of cavitation found in the selected machines were presented and discussed in detail. Various types of cavitation in Francis turbines were found are as shown in Fig. in travelling bubble, the generalized Rayleigh-Plesset equation was found valid approximation of the bubble growth and it can be solved to find the radius of the bubble,$R_B(t)$; provided that the bubble pressure, $P_B(t)$; and the infinite domain pressure, $P_\infty(t)$; are known. The equation is expressed as:

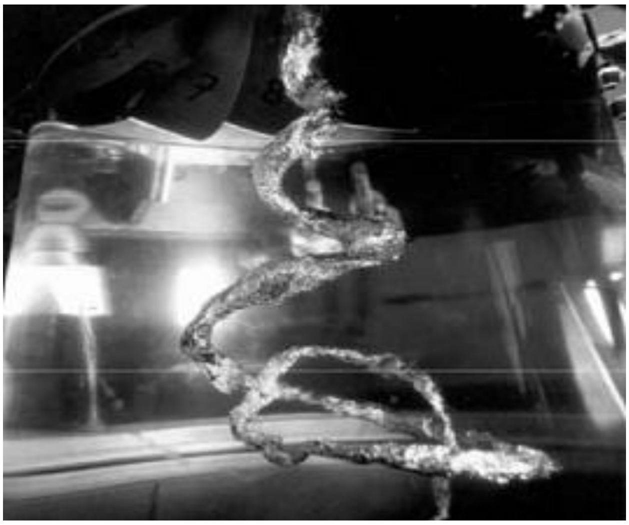
$$\frac{P_B(t)-P_\infty(t)}{\rho}=R_B\frac{d^2R_B}{dt^2}+\frac{3}{2}\left(\frac{dR_B}{dt}\right)^2+\frac{4\nu}{R_B}\frac{dR_B}{dt}+\frac{2\gamma}{\rho R_B}$$

where ν is the kinematic viscosity, ρ is density and γ is surface tension.

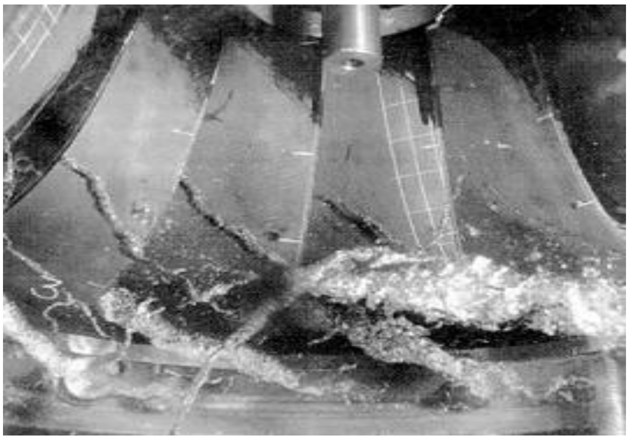
(a)



(b)



(c)



(d)

Fig. 3 Different types of cavitation in francis turbine (a) leading edge cavitation (b) travelling edge cavitation (c) draft tube swirl (d) interblade vortex cavitation

Hart and Whale carried out work on improved weld surfacing alloy which was developed and tested to resist cavitation erosion in hydro turbines. During their study they experinced the typical wear charactersitics in laboratory testing and then correlated to actual service conditions. A metallurgical evaluation showed that a high strain, work hardening auestenitic stainless steel produces superior resistance to cavitation erosion. During their study several industrial alloys were evaluated using the vibratory and high velocity cavitation test to produce a new alloy development in weld surfacing. Field testing showed an improvement in cavitation- erosion resistance of up to 800% relative to 308 stainless steel. The cumulative weight loss of various industrial alloys are shown in Figure. 4.

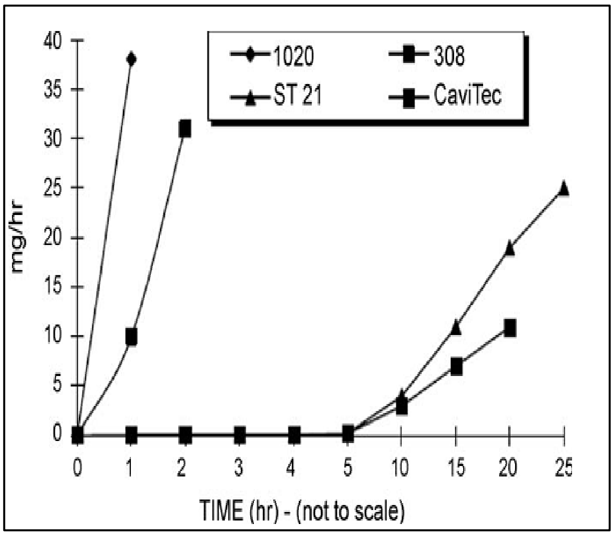


Fig. 4 Cumulative weight loss of various industrial alloys

3. Case studies

Kuppuswamy and Rudramoorthy (2005) have reported the deformation of outer distributor cone in the bulb turbine due to cavitation. Top and bottom sides of the outer distributor cone enlarged in size from the initial dimensions at the time of erection of the turbine. The left and right hand side dimensions reduced from the erection data. For the cavitation erosion phenomenon, the pressure waves- impact mechanisms is responsible for damage. During his study author has found the correlation between the distortion of outer distributor cone and number of hours worked in the equations.

3.1Cavitation damage repair

The Repair of Cavitation pitting Damage on turbines is considered an essential part of a hydro plant maintenance program. Repair of damage turbines from Cavitation can be done by welding which is considered to be most common and most successful method of repairing (Iftikhar *et al*, 2007). One promising technique being utilized in recent times is spraying of metallic and non-metallic materials over surface. The cavitation and erosion resistance of thermal spray coatings has been investigated and presented by Santa et.al. (Santa JF *et al*, 2009). Therefore in order to detect and prevent them it is necessary to apply adequate detection techniques that could be easily used in real hydropower plants. An on-line monitoring system is now considered as an important part of modern control system of hydropower plant. Vibration measurement is important with respect to cavitation detection also. Increased vibration level along with abnormal noises is the fingerprints of cavitation. Kumar *et al*. (2005) investigated that Stellite 6 deposited by high velocity Oxyfuel (HVOF) process had the lowest cavitation rate as compare to 308 stainless steel weld metal. Escaler *et al*.(2005) reported that the steady erosion rate of a cermet coating composed of tungsten carbide particles in a cobalt matrix was lower than that of ASTM A743 grade CA6NM martensitic stainless steel. Sugiyama *et al*. (2005) found that the cavitation erosion resistance of a number of thermally sprayed cermets increased with the reduction of pore density of the samples, which explained that 41 WC/Ni/ Cr/Co flame thermally sprayed coating showed better resistance than the stainless steel and the rest of coatings evaluated. Espitia and Toro (2010) tested experimentally the cavitation resistance of a stainless steel and two flame thermal spray coatings and from their study they observed that the best cavitation resistance was shown by the uncoated ASTM A743 grade CA6NM stainless steel, followed by WC/CoFeNiCr and Cr_2O_3

4. Elements of an effective repair program for cavitation

4.1 Damage in hydraulic turbines

An effective integration of the on-line vibration monitoring program with the cavitation damage repair can be achieved. Vibration data collected at various levels of plant operation is collected, analyzed and stored by vibration monitoring system. A simple software approach is proposed which obtains the input from vibration monitoring system by identifying abnormal vibration levels. These abnormal values can then be separated from the record and further analyzed, all parameters related to this abnormal value are sampled and the severity of cavitation damage can be based on historical data. A comprehensive data base of possible repair options can be stored in the software for analogy (Ahmad Iftikhar,*et al*, 2007).

Varga *et al*, (1969) has presented cavitation in hydraulic machines is always associated with vibration and noise having features and intensity depending on cavitation conditions some methods based on acoustic investigations. De Lucia *et al* (1994) conducted experiments on automatic analysis zones by means of image processing. Kenkermath D *et al*, (1974) analyzed the particles produced by cavitation erosion, and reported that many particles were quite irregular in shape. They also observed spherical particles among cavitation erosion debris.

Ahmed *et.al*.(1993) observed both the eroded surface and removed particles by cavitation erosion of SUS 304 during the incubation period and concluded that the dominant mode of cavitation erosion is fatigue failure. Moreover they classified the collected particles into three groups according to their shapes, namely, longitudinal, triangular, and mixed quadrangle hexagon. Susan-Resiga *et al*.(2002) showed the predicted results of the initial cavitation number of a francis turbine runner.

Cavitation is defined by Knapp *et al.* (1970) as the condition when a liquid reaches a state at which vapor cavities are formed and grow due to dynamic-pressure reductions to the vapor pressure of the liquid at constant temperature. The violent process of cavity collapse takes place in a very short time of about several nanoseconds and results in the emission of large amplitude shock-waves, as demonstrated by Avellan F *et al*, (1989). Baiter HJ *et al*, (1986) and Ceccio S Let *al*, (1991) have shown that the measurement and analysis of hydraulic noise are useful for investigation the feature of cavitation phenomenon. Rasmussen REH *et al*, (1949), Lichtman J.Z. *et al*(1964), Wood G.M *et al* (1949) have used RDA to investigate cavitation. Cavitation repair methods by welding and thermal spray coatings have been well studied and presented by Kumar *et al* (1964).

Cavitation erosion problems are found in turbine runner as well as in other parts of the turbine system as a result of rapid changes in pressure, which lead to the formation of small bubbles or cavities in the liquid. These bubbles collapse near the component's surface at a high frequency in such a way that the elastic shock wave created is able to cause erosion of the material straight afterwards (Rasmussen REH *et al*, (1949).J.F. Santa *et al* (2009 studied slurry and cavitation erosion resistance of six thermal spray coatings.

At present, prevents and reduces the cavitation damage the main measure to include:

1) Correct design hydraulic turbine runner, reduces the hydraulic turbine cavitation coefficient
2) Enhancement manufacture quality, the guarantee leaf blade's geometry shape and the relative position are correct, guarantee leaf blade surface smooth bright and clean.
3) Uses the anti-cavitation material, reduces the cavitation to destroy, for example uses the stainless steel runner.
4) Calculates the installation elevation of hydraulic turbine correctly.
5) Improves the running condition, avoids the hydraulic turbine for a long time running under the low head and the low load. Usually does not allow the hydraulic turbine to transport under the low output (For example: Is lower than 50% fixed outputs), regarding the multi Taiwan unit's hydroelectric power station, should avoid the single Taiwan unit long-term low load and the excess load running.
6) Prompt maintenance, and pays attention to the patching welding the polish quality, avoids the cavitation the malignant development.
7) Uses the air supplemental equipment to send the air into the draft tube, eliminates possibly has the cavitation oversized vacuum.

5. Conclusions

Cavitation is a phenomenon of formation of vapor bubbles in low pressure regions and collapse in high pressure regions, high pressure is produced and metallic surfaces are subjected to high local stresses. Cavitation can present different forms in hydraulic turbines depending on the machine design and the operating condition. As a result, high vibration levels, instabilities and erosion can occur this invalidates the machine operation and cause damage. It is difficult to avoid cavitation completely in hydraulic turbines but can be reduced to economic acceptable level. Some of the investigators have reported that in spite of design changes in the turbine components and providing different materials and coatings to the turbine blades, the improvement in most cases is not quite significant. It is therefore; required experimental and theoretical studies for studying the impact of cavitation in hydro turbine.

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