Contending erosion in hydro turbine for moderate temperature applications

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Abstract -The mystery of erosion phenomenon is not yet fully understood in terms of extent of its dependence on various parameters and the relative importance of these parameters in different situations. The hydro power projects, especially those located nearby Himalayan region, suffer a serious setback due to silt erosion. Erosion of key underwater components leads to increase the down time of the project for preventive maintenance. Thus, there is an urgent need to solve this problem or at least minimize its deleterious effects. Many remedial measures have been suggested to control the problem. However, dependence of erosion on numerous parameters adds to the complexity of the problem. Therefore, along with all the efforts to minimize the occurrence of erosion, the erosion resistance of the material must primarily be improved. Presently, 13/4 martensitic stainless steel or CA6NM, is being widely used for the critical underwater components of hydro turbine. However, 13/4 steel is reported to be less resistant to silt erosion and having poor weldability. This led to the development of alternative materials. Recently, the new grades of nitronic steel are reported to be more erosion resistant than 13/4 steel.

***Keywords*: silt erosion, hydro turbine, erosion variables, erosion resistant materials, nitronic steel**

I. Introduction

The battle against erosion is being fought from the long time wherever hard particles entrained in a gas or liquid medium are impinging on a solid at any significant velocity. Many researchers have contributed to investigate the ways it destroys the integrity of the surface of the key components in various applications [1, 2, 3]. There has been lot of deliberations on the pros and cons of erosion. Various aspects of this complex phenomenon are studied from the long time for different materials and under different conditions. Much information has been presented about the erosion mechanism, effect of various parameters on erosion in particular conditions, effectiveness of measures taken to protect the material from erosion and the factors to be considered for the design of erosion resistant materials. However, the most important outcome of the extensive study of more than five decades is that there is still wide scope to learn more and more about erosion. The severity of the damage caused by erosion is increasing day by day in many applications, especially hydroelectric power plants in Himalayan region. Considering the necessity of efficient management of hydropower plants in India to ensure progressive development in the power generation sector, the silt erosion problem to underwater parts of hydro projects needs to be solved urgently.

This paper aims to address the severity of erosion, dependence of erosion on variety of parameters, effectiveness of various remedial measures applied so far and development of erosion resistant materials for hydro turbine application.

II. Menace of Erosion in Hydro Turbines

Hydro power plant is considered to be a key factor in realizing the energy dreams of India. However these projects, especially those located nearby Himalayan region, suffer a serious setback due to silt erosion. It has been observed frequently that large amount of sediment (as high as 20,000 ppm) is present in water during the rainy season. The silt mainly consists of quartz (70–98%), having hardness of 7 on Moh's scale. The process of slit erosion resembles to saw-cutting of material with continuously hitting of angular particles of high hardness. The impact of these silt particles causes the erosive damage which is greatly governed by magnitude and direction of flow in relation to material surface.

The popularly used turbines in hydro power plants are impulse (e.g. Pelton) and reaction (e.g. Francis, Kaplan) turbines. Many underwater parts of the these hydro turbine components, namely buckets, nozzle(s) and needle(s) in case of impulse turbines and runner blades, guide vanes, labyrinth seals and faceplates in case of reaction turbines, are vulnerable to silt erosion. Subsequently it results in severe damages to the turbine components in the form of leakages, forced outages, increased vibration and drop in turbine efficiency. The pits formed on the surface or thinning of the components due to erosion make the turbine structurally weak [4]. Erosion of key underwater components leads to increase the down time of the project for preventive maintenance. The frequent overhauling decreases the total energy production. Erosion rate of 3.4 mm/year has been reported for the needle and the buckets of Pelton turbine which resulted in reduction of 1.21% in the efficiency of hydro turbine located in Himalayan region [5]. Thus, there is an urgent need to solve this problem or at least minimize its deleterious effects.

III. Remedial Methods

In order to solve or minimize the silt erosion phenomenon, it is necessary to understand the damage mechanisms and the parameters influencing this phenomenon. This requires multi dimensional approach which includes technical know-how of various fields of engineering studies. Erosion consideration may influence selection of type of turbine in their overlapping range on the basis of ease of replacing or repairing worn components. In case of Pelton turbine, damaged runners, needles and nozzles rings can be easily repaired by welding or replaced in few hours. Hence it may be preferred over Francis turbines. As suggested by Clark [6], the rate of erosion of critical components can be reduced by reducing the impact velocity of particles and the collision efficiency at susceptible regions in the flow regime. The design of components subject to high erosion rates should be based on determination and control of particle trajectories in the components. The various measures adopted to minimize/control the silt erosion and its deleterious effects in hydro power plants are listed as follows

- Improving water sedimentation by using continuously flushed sand removers.
- Using only the upper layer of water which contains less solids and fewer abrasive particles.
- Improving plant design and layout, equipment design and operating conditions to reduce silt damages
- Using highly erosion resistant materials for hydraulic components
- Applying protective hard coatings on the base material.
- Employing technology of quick repair and replacement of components affected by silt erosion
- Continuous monitoring to further improve the operations on the basis of feedbacks.

IV. Current Scenario

As discussed earlier, many remedial measures have been suggested to control the problem. It is practically not feasible to arrest all the silt particles flowing with the water to improve water sedimentation. Therefore interaction of these particles with the surface of the surrounding components is unavoidable. Measures can be taken to make these interactions less hostile by controlling the velocity and impact angle of the impacting particles. However such efforts fetch very limited relief owing to design considerations preventing major changes in these parameters. For example, the velocity of impacting particles automatically decreases with the decrease in flow velocity of water. However this leads to decrease in power produced by the turbine. Similarly flow of water is directed over the runner blade with a specific angle which ensures maximum conversion of hydraulic energy into mechanical energy. Therefore changing the direction of flow to change the angle of impacting particles will ultimately lead to reduction in hydraulic efficiency of turbine. Therefore some other ways need to be adopted / discovered to control these parameters.

The important point to be noted is that the erosion of underwater parts is primarily controlled by metallurgical factors. The ongoing research work is focused on prevention and prediction of erosion and can be broadly organised into three domains [7]. The theoretical aspects of the various issues involved in erosion are being studied and interlinked to fully understand this phenomenon. The laboratory and field tests are being conducted to confirm various theoretical predictions, quantify the effect of various parameters and evaluate the performance of new erosion resistant materials. The mathematical modelling and computer simulation are being increasingly used to perform complicated computational experiments under controlled conditions.

Today literature on erosion observes dependence of erosive wear on numerous variables which has been categorized [8] as:

- *Impingement variables* e.g. particle velocity (v), angle of incidence (α), flux or particle concentration, particle loading and the rotational speed of the eroding particles.
- *Particle variables* e.g. particle shape, size, hardness, friability (ease of fracture)
- *Material variables* e.g. mechanical properties such as hardness, ductility, work hardening behaviour, physical properties like specific heat, melting point and density and microstructure.

From the literature survey it appears that there is general consensus amongst the researchers over the effect of impingement angle, velocity and shape of the impacting particles [9, 10, 11]. The dependence of fundamental mechanism of material removal on particle kinematics, as predicted by theoretical models, was verified by some investigators by impacting single angular particles [12]. On the contrary, the issues like particle size, material hardness are widely debated. The factors like microstructure, ductility, tensile toughness and work hardening coefficient of the material are considered to be highly significant while the properties like tensile and impact strength are not highly rated for erosion behaviour of the material. Attention is drawn to some factors like effect of temperature and effect of carrier fluid in slurry and its viscosity and lubricity. The new perspective in regards with the better understanding of the erosion phenomenon emphasizes on its correlation with high strain rate material properties [13], dynamic strength, thermophysical properties (density, Sp. Heat etc.) and large strains.

The material removal mechanism in erosion has been studied in details by many researchers. Several theories/ models suggested by them are micromachining mechanism, deformation wear, fatigue model, mechanical energy density, localization model, lip formation, platelet mechanism etc. Thus it is evident that erosion takes place with different mechanism under different testing conditions for the variety of materials used. Hence, the erosion behaviour needs to be clarified under suitable testing conditions for systems of interest.

Some researchers tried to protect the target surface to reduce the erosive loss by way of surface treatment and/or suitable coatings like weld overlays, thermally sprayed coating, hard chrome plating, D-gun spraying, HVOF coatings, PVD-TiN coating, plasma nitriding and boronising [14, 15, 16, 17, 18]. The interesting results were reported for low impact velocity. However, it turned out that there are various issues which add to the difficulty of developing effective coatings. For example, the defects in the coating, such as cracks and porosity accelerate the erosion process considerably.

It therefore becomes clear that the mystery of erosion phenomenon is not yet fully understood. Involvement of numerous parameters influencing the problem adds to the misery of the research community. It is now urgently needed to plan systematically for the strategies to attack the problem on all fronts.

V. Development of Erosion Resistant Materials

It is often said that prevention is better than cure. But when complete prevention is impossible, the resistance power must be increased by some way or the other. Similarly, along with all the efforts to minimize the occurrence of erosion, the erosion resistance of the material must primarily be improved. Alloy designing and heat treatment are the two important methods of improving properties of materials. Sufficient data is available on erosion resistance of various materials under specific conditions. Accordingly, various kind of stainless steels are preferred for various underwater parts of hydro turbines (Table 1).

TABLE I
Stainless steels currently used for the critical underwater components [Naidu 2001]

Sr. No.	Component	Material
1.	Runner	13%Cr, 4% Ni stainless steel
2.	Labyrinth seals	13%Cr, 4%Ni or 18%Cr, 10%Ni stainless steel
3.	Guide vane	13%Cr, 4% Ni stainless steel
4.	Liners for top cover and pivot ring	18%Cr, 10%Ni stainless steel
5.	Fasteners in water path	Stainless steel
6.	Tubes for bearing coolers	Cupro-Nickel (80% Cu-20%Ni)
7.	Rubber seals	Neoprene synthetic rubber

Presently, 13/4 martensitic stainless steel or CA6NM, is being widely used for the critical underwater components together with austenitic steel selectively. The high hardness of 13/4 steel (of the order of 300-400 VHN) is considered to be the main cause of its good erosion resistance. However, 13/4 steel is reported to be less resistant to erosion, especially to silt attack [1]. The pits formed on the surface or thinning of the components due to erosion are rectified by applying welding techniques. This is another area where the currently used 13/4 steel is facing lot of problems due to its poor weldability. The weld metal and heat affected zone (HAZ) is prone to cracking. Further, the formation of carbides and intermetallic compounds in the HAZ makes it vulnerable to excessive erosion due to silt laden water. Therefore, this steel requires pre and post welding treatment. Practically it becomes difficult to follow the precise welding treatment on the shop floor. In order to overcome these problems, various other grades of steel have been developed so far for the fabrication of underwater parts, as shown in Table 2.

In erosion resistant applications, austenitic matrix is preferred because of its high toughness and ductility and better work hardening ability. However, relatively low yield strength and hardness of conventional austenitic stainless steels may be the main obstacles for their use in erosion resistant applications. The erosion resistance of both nitronic and PH stainless steels was observed to be inferior to 13/4 steel. This was attributed to softer matrix of these steels. Various studies have underlined the importance of material hardness which provides resistance to indentation and scratching by hard particles. However after certain level of hardness, ductility plays a crucial role in improving the erosion resistance of the material. Thus for high erosion resistance, high hardness coupled with good ductility is perhaps the better choice. Therefore it calls for the use of improved austenitic stainless steel grades having sufficient strength, hardness and ductility. The hardness of the earlier grades of nitronic steel (low carbon grades) was less. Therefore in the new grades of nitronic steel, as shown in Table 3, the carbon percentage (wt%) has been increased which resulted in increase in hardness.

TABLE III

Various grades of austenitic stainless steels for underwater parts of hydro turbine (Composition in wt.%) [Goel 2008]

Designation	C	Mn	Si	Cr	Ni	N
21-4-N	0.55	8 – 10	1	21	4	0.4
23-8-N	0.35	2 – 3	1	23	8	0.3

Both the nitronic steels showed better erosion resistance than 13/4 steel in as received condition (i.e. hot rolled) [19, 20, 21]. Better erosion resistance of nitronic steels is attributed to sufficiently high hardness of the matrix due to presence of carbides coupled with its higher ductility. However, it is also observed that the erosion resistance of both the steels has improved by more than 20% after heat treatment. As stated above, weldability of the steel is another important parameter for the easy repair of the erosion resistant material. At present no attempts have been made to study the weldability aspect of the nitronic steels. However, the repair welding of the nitronic steel is not expected to be much problematic. Therefore, new grades of nitronic steel may claim top ranking as an alternative erosion resistant material for hydro turbine application.

TABLE IIII

NEW GRADES OF NITRONIC STEELS FOR UNDERWATER PARTS OF HYDRO TURBINE (COMPOSITION IN WT.%) [GADHIKAR 2011]

Designation	C	Mn	Si	Cr	Ni	Others
PRECIPITATION HARDENING (PH) STAINLESS STEEL						
PH 14-4Mo	0.05	1	1	13.7-15.0	7.7-8.7	2-3 Mo, 0.75-1.50 Al
PH 15-7Mo Type 632	0.09	1	1	14-16	6.5-7.7	2 -3 Mo, 0.75-1.50 Al
AM 350 Type 633	0.07-0.11	0.5-1.25	0.5	16-17	4-5	2.5-3.25 Mo, 0.07-0.13 N
AM 355 Type 634	0.10-0.15	0.5-1.25	0.5	15-16	4-5	2.5-3.25 Mo, 0.07-0.13 N
NITRONIC STEEL						
Nitronic 50	0.02	4 - 6	1	20.5-32.5	11.5-13.5	0.2-0.4 N, 1.5-3.3 Mo, 0.1-0.3 Nb, 0.1-0.3 V
Nitronic 60	0.10	7 - 9	4.5	16-18	8 - 9	0.25-0.5 N, 2-3 Mo
Nitronic 40	0.08	8 - 10	1	19-21.5	5.5-7.5	0.15-0.4 N
Nitronic 33	0.08	11.5 - 14.5	1	17-19	2.5-3.75	0.2-0.4 N
Nitronic 32	0.15	11-14	1	16.5-19.5	0.5-2.5	0.2-0.4 N

VI. CONCLUSIONS

Erosion still remains an unresolved mystery to a great extent. Various measures adopted to minimize/control the silt erosion in hydro turbine have fetched limited relief. Therefore, there is now urgently needed to plan systematically for the strategies to attack the problem on all fronts.

The limitations of currently used hydro turbine steel i.e. 13/4 have led to the development of alternative material. The new grades of nitronic steel are found to be suitable for erosion resistant applications. The erosion resistance of both the nitronic steels i.e. 21-4-N and 23-8-N steels is better than 13/4 martensitic stainless steel which is currently used for fabrication of underwater parts of hydro turbine. Therefore it seems that nitronic steels can be a future material for fabrication of the components subjected to silt erosion.

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