Global Journal of researches in engineering
Mechanical and mechanics engineering
Volume 11 Issue 6 Version 1.0 November 2011
Type: Double Blind Peer Reviewed International Research Journal
Publisher: Global Journals Inc. (USA)
Online ISSN: 2249-4596 & Print ISSN:0975-5861

Sediment Erosion in Hydraulic Turbines

By Hari Prasad Neopane, Ole Gunnar Dahlhaug, Michel Cervantes
Luleå University of Technology (LTU), Sweden

Abstract - Sediment erosion not only reduces efficiency and life of hydropower turbines but also causes problems in operation and maintenance. Several factors are responsible for this erosion in hydro turbine components. This paper presents the sediment erosion types in hydraulic turbines and their components based upon an extensive literature review and the field observation at Cahua hydropower plant, Peru. It includes some recommended methods to minimize the effect of sediment erosion in the turbine components. An alternative design of a Francis turbine in sediment-laden water is also briefly discussed.

GJRE-A Classification : FOR Code: 091403

Sediment Erosion in Hydraulic Turbines

Hari Prasad Neopane[α] , Ole Gunnar Dahlhaug[Ω] , Michel Cervantes[β]

Abstract - **Sediment erosion not only reduces efficiency and life of hydropower turbines but also causes problems in operation and maintenance. Several factors are responsible for this erosion in hydro turbine components. This paper presents the sediment erosion types in hydraulic turbines and their components based upon an extensive literature review and the field observation at Cahua hydropower plant, Peru. It includes some recommended methods to minimize the effect of sediment erosion in the turbine components. An alternative design of a Francis turbine in sediment-laden water is also briefly discussed.**

I. INTRODUCTION

Hydraulic turbines mainly divided into two groups: Impulse and Reaction. This classification is based upon the principle of energy conversion. Pelton and Turgo are examples of Impulse turbines. Francis, Kaplan and Bulb turbine are examples of reaction turbines. The cross flow turbines are two stage impulse turbine used for smaller units.

In general, a number of factors influence the development of sediment erosion process of hydraulic machinery. These factors include mean velocity of particles, mass of the particle, concentration of the abrasive particles in a liquid flow, grain size and shape of the particles and angle of attack at which the particles collide with the surface etc. In practice, a large number of additional factors involved and further complicated the erosion of hydraulic machinery. In addition, there is no exact mathematical dependence, for the time being, to define them. Variable concentration and structural in homogeneity of suspended particles, continuous alternation and pulsation of both velocities and pressure during the motion of the flow, and variance in operation, and design features of hydraulic machinery itself, caused the actual pattern of the erosion more complicated and different (Duan et al.,2002).

Most often, it is difficult to distinguish the exact type of erosion on the hydraulic machinery. Duan et al., 2002, have described the erosion of hydraulic turbines in six categories as shown in Table 1 based upon the visual appearance. This classification could be use to evaluate the hydraulic patterns.

Table 1 : Turbine erosion categories (Duan et al., 2002)

S.N	Type	Description
1	Metallic luster	A Shining surface with no traces of paint, scale or rust
2	Fine-scaly erosion	A surface with rare, separately located and skin-deep minute scales
3	Scale erosion	A surface entirely covered with skin-deep fine scale
4	Large-sized scaly erosion	A surface entirely covered with deep and enlarged scales
5	In-depth erosion	A surface covered with deep and long channels
6	Through hole or entire erosion	Out of the material

Similarly, B.S. Mann, 1999, collected data on wear patterns of different sediment affected hydro turbine components at various hydropower stations in India in order to analyze the wear patterns. This was compared with the data available with some foreign hydropower stations from Switzerland, Pakistan, and China. It was observed that the wear patterns have a resemblance and there is a significant relevance to the flow characteristics of all the power stations. The wear pattern on a particular component is found to be similar.

As mentioned by Thapa, 2004, Matsumura and Chen, 2002, classified the erosion condition in Reaction turbines in three categories, as I, II and III, based upon difference in flow velocity and impingement angle of particle. This classification is shown in Table 2, which was developed based on erosion test of specimens located at different turbine components. From this classification, it is not possible to interpret the different type of erosion on the same component of turbine, for example, the turbine blade, can have different type of erosion at leading edge and trailing edge.

Author[α] : Assistant Professor ,Kathmandu University (KU), Nepal .
Author[Ω] : Professor ,Norwegian University of Science and Technology (NTNU), Norway .
Author[β]: Professor , Luleå University of Technology (LTU), Sweden.

Table 2 : Classification of erosion (Matsumura and Chen, 2002)

Type of erosion	Location	Flow velocity	Impingement angle	Type of erosion
I	Spiral casing Draft tube	Low	Small	I
II	Runner blade Guide vane	High	Small	II
III	Wearing ring	High	Large due to vortex and turbulence	III

Brekke, 2002, classified the sediment erosion in hydraulic machinery into three different categories, namely, micro erosion, secondary flow vertex erosion, and acceleration erosion.

Micro erosion is found on the surface of turbine components where fine particles with grains size less than 60 ƒÝm are moving at very high velocity. High shear stress in the boundary layers gives high rotational motion to these particles causing several ripples in the direction of flow. The patterns with such erosion are also compared as fish scale or orange peel. Such type of erosion can appear in guide vane and runner blade in a Francis turbine towards outlet and in the needle of a Pelton turbine.

Obstacles in the flow field or secondary flow in the corners of conduits causes secondary flow vortex erosion. Any obstruction in the flow field causes secondary flow and horseshoe vortex is generated around the cylindrical obstacles like guide vane leading edge. Similarly the needle of the Pelton wheel have vortex behind the ribs supporting needle and hence vortex erosion takes in the straight line downstairs the ribs. The vortices in the corner of conduits like guide vanes-facing plates and blades-band also cause this type of erosion. Such vortices and secondary flow are caused by combined effect of boundary layer and change in flow acceleration. The design of hydraulic machinery working in the range of high Reynolds numbers, (106 - 108) will normally be exposed all three types of erosion.

II. IMPULSE TURBINE: PELTON

Generally, Pelton turbines are designed for low speed number, range from 0.1 to 0.2, the velocity in the jets will be higher than 100 m/s. The acceleration of the particles in the buckets will normally be more than 50,000 m/s2, which depends on the size of the buckets and head of the turbine. The high velocity and acceleration of particles at the buckets are main reasons for the sediment erosion. Brekke, 2002, categorized the Pelton turbine components into four groups in order to study the sediment erosion phenomenon. Those are inlet system, nozzle system, turbine runner and the wheel pit.

a) Inlet system

Inlet system consists of manifold and valve. The velocity at inlet system is normally maintained low. Brekke, 2002, provided the following velocity relations in order to design the inlet system of the Pelton turbines

At inlet manifold, $C = k_i \cdot \sqrt{2 \cdot g \cdot h}$ $[0.08 < k_i > 0.1]$ Equation 1

At valve, $C = k_v \cdot \sqrt{2 \cdot g \cdot h}$ $[0.095 < k_v > 0.12]$ Equation 2

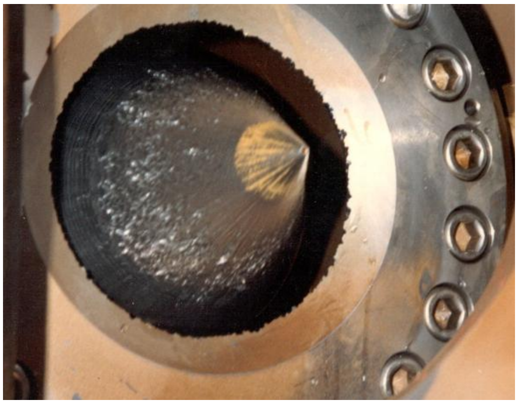
At nozzle, $C = k_n \cdot \sqrt{2 \cdot g \cdot h}$ $[k_n > 0.99]$ Equation 3

Because of the low operating velocity at the inlet, the inlet system or pipes will have only moderate effect of sediment. Hence, application of high erosion resistance rubber, and epoxy based coating or paint may prevent erosion in such pipes. Slight erosion of this system does not affect the performance of the turbine by any means, but severe erosion in bifurcation and bends is likely to increase the leakage and in worst-case rupture of pipe. Regular inspection and maintenance should be carried out to prevent any catastrophic effect.

b) Nozzle system

Nozzle system includes nozzle ring and needle. High head Pelton turbine, for example, 1,200 m head can have jet velocity up to 150 m/s. Such a high velocity can damage both the nozzle and the needle. The flow is accelerated from the outlet of fins supporting needles up to nozzle tip and all the pressure energy available in the water is converted into kinetic energy. High velocity combined with the needle geometry creates strong turbulence in the boundary layer close to needle tip. The fine particles bombarding due to turbulence strikes the needle surface several times and severe erosion can be seen in short time. Cavitation can follow in a short interval of time and severe damage of the needle can take place. The nozzle tips are relatively sharp and less than 1 mm contact between nozzle and needle are maintained to reduce cavitation damage and to obtain highest possible efficiency. This makes the nozzle tip vulnerable to sand erosion. If nozzle diameter increases by 5 % due to erosion at tip, the turbine will run at 10 % load even if needle is at closed position. It may affect entire control system of the power plant.

The photographs presented in Figure 1 illustrate the extent of sediment erosion in Pelton turbine nozzle and needle. These photographs were taken from the lecturer notes provided by professor Ole Gunnar Dahlhaug, NTNU.



(a) Nozzle needle, Mel, Norway

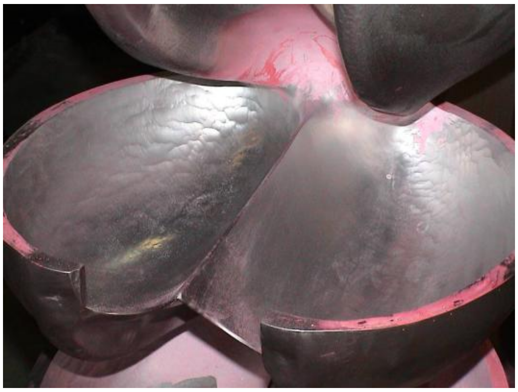
(b) Nozzle ring, Andhi Khola, Nepal

Figure 1 : Sediment erosion at Pelton turbine nozzle and needle

The protection of needle and nozzle surface by applying ceramic-metallic coatings may help to improve erosion resistance. Ceramic coating is not very effective in case of larger size particles. There is very little scope to improve the erosion resistance of needle and nozzle by hydraulic design, but maintainability can be improved by designing replaceable nozzles tip.

c) Pelton turbine runner

Peltion turbine runner consists of splitter, bucket tip and bucket surface. Sediment erosion can be found in all components however, the nature of erosion is different. In high head Pelton turbines, the absolute acceleration range normal to the surface could be 50,000 - 100,000 m/s2. Such a high acceleration is the main reason of sediment erosion in turbine buckets, which has a strong effect on separation of particles from streamline. The characteristics of damage due to fine and coarse sediment are different. With coarse particles, most of the damages are in the area where the jet directly hits at the bucket surface. Surface damage is observed due to the hammering action and not due to the cutting action by sharp edge. Long scars are also seen in the flow direction in each side of the bucket splitter but no damage is observed at the root of the bucket. Splitters and entrance lips are most severely damaged portion of the buckets, because of direct hitting of particles. The photographs presented in Figure 2 illustrate the extent of sediment erosion in Pelton turbine buckets and splitter.



(a) Bucket surface, Khimti, Nepal

(b) Splitter, Rangjung, Bhutan

Figure 2 : Sediment erosion at Runner buckets

The acceleration of particles normal to the flow direction separates the particles from the flow direction and such accelerating particle strikes the surface causing collision in the water conduit surface. Large particles, for instance higher than 0.5 mm, cause severe damage in the Pelton turbine bucket.

Fine particles may glide along with water inside the bucket and strike the surface toward outlet edge, causing severe erosion around the outlet. Due to distortion of bucket profiles near the outlet, but not at the edge where the acceleration is zero, the direction of flow changes bending inward and strike backside of following bucket with braking effect. This phenomenon is schematically explained in Figure 3.

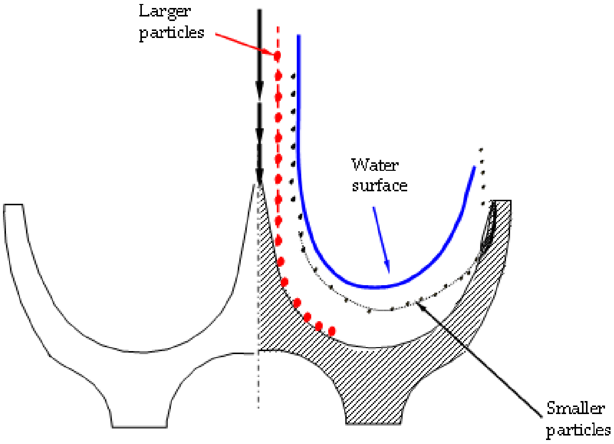


Figure 3 : Illustration of separation of particle in a Pelton bucket (Thapa and Brekke, 2004)

Thapa and Brekke, 2004, have drawn some conclusions based upon the different hydropower plants erosion patterns observations:

- If the particles are fine (silts), then there will be erosion on the needle but not much erosion in the buckets.
- If the particles are coarse (sand), then there will be erosion in the buckets and there is less erosion of needles.
- With medium size particles, both needle and bucket will be eroded.

d) Criteria for Pelton turbine design

Sediment erosion problem cannot be solved completely by hydraulic design alone however, this can be minimised to some extent. The three basic criteria for the design of Pelton turbine to minimize the effect of sand erosion are as follows (Brekke, 2002).

- The radius of curvature should be as large as possible at the location where flow direction changes.
- The number of jets should be as low as possible.
- The hydraulic radius of the bucket and nozzle size should be large. This brings minimum sand particles in contact with the surface.

III. REACTION TURBINE: FRANCIS

Generally, Francis turbines are designed for speed number, range from 0.2 to 1.5. High head Francis turbines are mostly affected by sediment erosion. For the high head type of Francis turbine, approximately 50 % of energy is converted in to kinetic energy at guide vane and remaining 50 % is retained as pressure energy. The inlet velocity could reach up to 85 - 95 m/s on high head turbines. Hence, guide vane faces high absolute velocity. The runner outlet has highest relative velocity. The velocity at the runner outlet is normally selected around 40 m/s during design to ensure flow of water out of the turbine. Brekke, 2002, categorized the Francis turbine components in to four groups in order to study the sediment erosion phenomenon. Those are inlet system, guide vanes system, runners and labyrinth seals, draft tubes, and shaft seals.

a) Inlet system: Stay vane

Inlet system of Francis turbine consists of manifold, valves, bypass system, spiral casing and stay vanes. Compared to inlet valve of Pelton turbine, its inlet valve will face 50 % less pressure during closing due to pressure created by spinning runner. Hence inlet valve of Francis turbine have rubber seal against movable steel seal, which has better erosion resistance. It is important to make bypass system larger in order to create higher possible pressure in the spiral casing before opening the valve seals because lower pressure in the spiral casing during opening will increase the damage of the valve seals and bypass valve seals. Hence, bypass system in the Francis turbine has to be stronger than Pelton turbine to create higher pressure in spiral casing. The starting pressure in the guide vane system gives indication of leakage due to sand erosion. The velocity at spiral casing is higher than Pelton turbine manifold because of shorter distance between inlet valve and guide vanes. The velocity at the inlet of the spiral casing is almost same as the meridional velocity at the runner outlet and inlet of valve.

The stay vanes have the main purpose of keeping the spiral casing together. The dimensions have to be given due to the stresses in the stay vanes. The vanes are designed so that the flow is not disturbed, and they direct the flow into the turbine. Because of the secondary flow in the spiral casing, an incorrect flow angle towards the top and the bottom region of inlet of stay vanes in traditional design often cause secondary flow erosion in high head turbines. Similar phenomenon has been observed at Cahua power plant, where paint and material are removed due to the erosion at the stay vane inlet as shown in Figure 4 (a).

(a) Inlet of stay vane

(b) Typical ring grooves near leading edge

Figure 4 : Erosion at stay vane at Cahua power plant

The corrosion followed by removal of paint accelerates the erosion rate. However, modern parallel stay rings reduces incorrect flow and minimizes erosion at stay vane inlet. Under normal condition, erosion resistant paints can be used in spiral casing and stay vane, but for high head turbines, stainless steel stay vanes can be used to reduce the effect of sediment erosion. The mid height of the leading edge part is exposed to less erosion intensity. Near the upper and lower cover at the inlet, ring-shaped erosion grooves, as shown in Figure 4 (b), were observed (Mette Eltvik, 2009).

b) Guide vane system

The guide vane system is highly affected by sediment erosion due to highest absolute velocity and acceleration. For high head turbines, the relative velocity head (C2/2g)/Hn for guide vane increases from 10 % at guide vane inlet to 50 % at runner inlet. At normal speed, pressure drop across the guide vane will be approximately 40 % of net head at full load and 50 % at small opening, which is one of the reason for cross flow and hence erosion takes place at the junction of guide vanes and facing plates. The main reason for cross flow is the pressure difference. The erosion of guide vane due to sand laden water can be classified in following four categories (Brekke, 2002):

- Turbulence erosion at the outlet region and facing plate due to high velocity of fine grain sand
- Secondary flow erosion in the corner between guide vane and facing plates due to fine and medium size particles, which makes horseshoe grooves in the facing plates following contours of guide vanes
- Leakage erosion at the clearance between guide vane and facing plate due to local separation and turbulence increasing the horseshoe vortex in the suction side. The leakage also causes local separation and turbulence at the pressure side at inlet and suction side at outlet of guide vanes causing even a deep groove at the bottom and top of the guide vanes
- Acceleration erosion is caused by separation of large particles from the streamlines of main flow due to rotation of water in front of the runner. This acceleration of particle I s normal to the streamline and strikes guide vane surface causing sevre eroion. This acceleration also creates secondary flow causing erosion at the corner between the guide vanes and the facing plates by fine particles

In Cahua power plant, as shown in Figure 5 (a), more erosion is observed near the transitional zone to the lower cover, due to the high acceleration and absolute velocity in the guide vane cascade. The acceleration erosion in the guide vane in reaction turbine can be reduced by designing the flow with smoothest possible acceleration. The stay vane outlet angle should be carefully chosen so that guide vane will be in neutral position in normal operation condition. Similarly, reduction of clearance between guide vane and facing plate avoid cross flow and secondary flow. Metal sealing are used to reduce gap between guide vane and facing plates with the intention to improve efficiency, but this could be more destructive once damage of such seal commence. The turbulence and secondary flow create dangerous galling in facing plates. It destroys flow pattern and reduces turbine efficiency. The covers will be exposed to erosion since the acceleration normal to the streamline creates secondary flow, especially at the corners between the facing plates and guide vane as clearly seen in Figure 5 (b). This effect occurs because of the horseshoe vortex and heavy erosion grooves are observed.

(a) Eroded guide vanes

(b) Horseshoes vortex of facing plates

Figure 5 : Erosion at guide vane and facing plates at Cahua power plant

The guide vane clearance for new turbine is recommended roughly 0.1 - 0.3 mm in pressurized condition, which is dependent on deflection of the head cover. Low initial dry clearance in the order of 0.05 to 0.1 mm may give low clearance in pressurized condition, but such a low dry clearance may cause abrasion and adhesion between guide vane and facing plates. The facing plates can be improved by cladding underneath the guide vanes, but the difference in hardness between guide vanes and facing plates should be maintained to avoid galling of the surface. The hardness of 16Cr5Ni Guide vanes with 350-400 HB and facing plate of 17Cr1Ni with 300 HB is an example of appropriate combination, which avoids galling and abrasion. The necessary tolerance and surface finish at the mating part of guide vane and facing plate should also be maintained to get rid of these problems. The maintainability of the facing plate is often improved by designing replaceable layer to save maintenance time and expensive bulk material.

c) Runner

In the runner, the highest relative velocity occurs at outlet region while the highest absolute velocity and accelerations may be found at the inlet of the blade. Hence, impact due to kinetic energy is small compared to force exerted by large accelerating particle. Contrary to this, the relative velocity is the highest at the outlet of the runner blade. Hence, turbulence erosion due to fine sand is always susceptible at the trailing edge of the blade. Also because of high relative velocity, most of the particles will move towards outer diameter in the runner outlet and hence more effect of erosion is seen there. Inlet region of the runner is sensitive to incorrect pressure distribution between pressure and suction side and any separation caused by this may cause severe local erosion at the inlet due to fine grain sand. Cross flow from the hub to the shroud caused by incorrect blade leaning will also increase the so-called horseshoe vortex in the blade roots. The erosion at runner outlet of Cahua power plant is shown in Figure 6.

(a) Erosion at runner outlet

(b) Erosion at pressure side of blade

Figure 6 : Erosion at runner at Cahua power plant

The improvement of blade leaning and correct blade loading at inlet may improve performance of Francis turbine against erosion. The splitter blades at the inlet of runner help to reduce damage of flow around leading edge at off design operation, which ultimately improves the resistance to sand erosion and cavitation. Incorrect blade leaning may lead to cross flow between hub to band and such cross flow may intensify erosion effect together with other loss associated with it.

d) Labyrinth seals

The velocity in labyrinth is in order of 45 m/s for high head turbine. Labyrinth seals having small clearance and working with coarse sand may also have erosion as well as abrasion effect. The efficiency of a labyrinth seal is inversely proportional to clearance gap. Hence, gaps should be made the smallest possible to have minimum leakage, but it has to be sufficiently large to avoid any direct contact between rotating and stationary part. The clearance between the stationary and rotating parts is varied between 0.25 to 1.0 mm depending on the size of the turbine. The turbulence erosion due to fine sand is always susceptible in the labyrinth seal because of high velocity in its surrounding. The rotating labyrinth seals are made up of steels to achieve longer life, while stationary seals are normally made of softer materials such as bronze. The replacement cost for the stationary seal is cheaper. However, in the case of high sediment concentration, even the stationary seals can be made up of steel, which has higher erosion resistance than softer material.

e) Draft tube

The draft tube section closer to runner will be exposed to the highest velocity because of high absolute velocity of water coming out of runner and some sediment erosion effect can be anticipated. Apart from this portion, sediment erosion is normally no problem in draft tube.

f) Shaft seal

Mechanical shaft seal will be damaged if the sand-laden water is exposed to it. The damage could be due to more abrasion than erosion. Shaft seals are normally made up of carbon rings, bronze and steels with lower hardness compared to shaft material. Apart from selection of erosion and abrasion resistance material for seals, insertion of pressurized clean water in the shaft seal also avoids wear.

IV. TURBINE DESIGN

The following IEC guidelines explain some recommended methods to minimize particle abrasion and the effects thereof, by modifications to design for clean water. It should be understood that every hydraulic power plant is a compromise between several requirements. While it is possible to design a unit to be more resistant against particle abrasion, this may adversely, affect other aspects of the turbine. Some examples are :

- Thicker runner blades may result in decreased efficiency and increased risk of vibrations from von Karman vortices.
- Fewer runner blades (in order to improve the access to the blade surfaces for thermal spray surface treatment) may result in reduced cavitation performance.
- Abrasion resistant coatings may initially result in increased surface roughness, which may reduce the efficiency.
- Reduced runner blade overhang may result in reduced cavitation performance, which in turn may reduce the output that can be achieved for a turbine upgrade.
- Many abrasion resistance design features will increase the total cost of the power plant.

The optimum combination of abrasion resistant design features must be considered and selected for each site based on its specific conditions.

a) Hydraulic design of turbine

i. *Selection of type of machine*

It is advantageous to select a type of machine that has low water velocity that can easily be serviced and that can easily be coated with abrasion resistant coatings. Some general guidelines are; in the choice between a vertical shaft Kaplan and a Bulb; the Kaplan will normally have lower velocity. The serviceability and ease of coating is approximately equal between the two. In the choice between a Kaplan and a Francis, the Francis will normally have lower velocity. On the other hand, the Kaplan runner has better access for applying abrasion resistant coatings. The serviceability is approximately equal between the two. In the choice between a Francis and a Pelton, the Francis will normally have lower maximum velocity. However, the parts in a Pelton turbine that are subject to the maximum velocity (i.e. the needle tips and seat rings) are small and have better access for applying abrasion resistant coatings. The Pelton turbine is also easier to service.

ii. *Specific speed*

For the same plant, lower specific speed machines are normally bigger and have lower water velocities in the runner outlet. However, the water velocities are not lower in the guide vanes and in the runner inlet. For Kaplan, Bulb and low head Francis turbines, most of the abrasion damage will be in the runner, so the specific speed is important. For high head Francis turbines, much of the abrasion damage will be in the guide vane apparatus, so the specific speed is not so important. For Pelton turbines, the water velocity does not depend on the specific speed. However, a lower number of jets is beneficial for a Pelton turbine since the buckets will be larger which in turn gives less water acceleration in the buckets and thus less abrasion damage. A lower number of jets will automatically result in a lower specific speed.

iii. *Variable speed*

Even though variable speed machines are not frequent, they are less prone to cavitation, even under a wide head range operation. Due to this characteristic, the variable speed machine may better resist particle abrasion.

iv. *Turbine submergence*

Cavitation and abrasion will mutually reinforce each other. For this reason, it is recommended that the turbine submergence is higher for plants where abrasion is expected.

v. *Runner blade overhang*

In case of Francis runner refurbishment, there is sometimes a need to increase the turbine output significantly. One way to do that is to extend the runner band inside the draft tube cone, in order to increase the blade area and to improve the cavitation performance. However, this creates additional turbulences at the top of draft tube cone that will increase metal removal if particles are present in water. A secondary effect of the overhang blades is to create a lower pressure zone downstream of the runner band seal, thus creating higher seal leakage and more particle abrasion at the band seal.

vi. *Thicker runner blades and guide vanes*

Increased runner blade thickness, particularly at the outflow edge, gives some extra margin before the removal of material on the runner blades becomes critical for the structural integrity of the runner. A thicker blade design should be done with care. The thicker blade may result in decreased efficiency and increased risk of vibrations from von Karman vortices. In addition, the risk of cavitation damage on the runner band, downstream of the blade, may increase.

b) Mechanical design of turbine

If abrasion is expected and the turbine type is defined, not only the hydraulic design but also the mechanical design can take some precautions to reduce the abrasion rate and to allow easy maintenance or replacement of the abraded parts. Generally, for the design, the area exposed to the abrasive wear should be as small as possible. As well, discontinuities and sharp transitions or direction change of the flow should be avoided. The turbine shaft seal should have rubber rigs in place of carbon rings and its design should be such as to allow dismantling and replacement in the shortest possible time. The thickness of the runner blade in the area prone to erosion should be increased. These areas are mainly at runner outlet. Increasing the wall thickness is a method to increase the overhaul interval of a component due to abrasion. For structural components, which do not influence the efficiency, the wall thickness can be increased in critical areas to avoid early failure of the component due to higher stresses.

The material selection for components, which are subject to abrasive wear, is another important criterion. Generally, weldable stainless steel materials are preferred. If both corrosive and abrasive attack anticipated then stainless steel is preferred. Considering the larger hardness, martensitic steel is preferred over austenitic steel. Furthermore, shaft seal with clean sealing water is recommended. Normally, shaft seals in units, which are operated with water and, which contains abrasive particles, have to be fed with clean sealing water. It must be avoided that the contact surface or the wearing surface gets contact with the abrasive particles.

c) Operation of turbine

Operation of a turbine at part load and full load is marked by reduced efficiency, increased flow turbulence and higher relative flow velocities at turbine runner outlet. Presence of secondary flows and accompanying vortices lead to increased local velocities. Since such flow conditions are conducive to increased sediment erosion, attempt should be made to avoid such operations when water carries excessive sediment. The following actions are recommended for consideration during operation of the units.

- Shut down units at higher particle concentration periods. This may avoid considerable wear on the unit for a small amount of lost production. Especially for run of river schemes, where large variation in particle concentration can happen very fast this strategy can be useful.
- Minimize amount of debris passing through unit. Large solid items, for example logs, gravel (larger than 2 mm), etc. may damage the hydraulic surfaces and any abrasion resistant coatings. Damage to hydraulic surfaces may increase the turbulence of the flow, which will increase the abrasion damage. This is especially important for high head Francis and Pelton units, since the water velocities are very high and these units rely on smooth hydraulic surfaces to keep the turbulence low.
- Do not operate the unit in case the abrasion damage jeopardizes the safety of operation. As the abrasion damage progresses, the unit will eventually become unsafe to operate. This could for example be due to seal leakage increasing so much that the axial thrust exceeds allowable limits or that the remaining material thickness of some component falls below acceptable minimum thickness. Regular inspections of critical components should be made at least every year and inspection results must be compared with predefined acceptance criteria.
- Avoid low load operation as much as possible. Low load operations are the worst operating conditions with respect to abrasion for most components and turbine types.
- Close inlet valve at shutdown. With a turbine at standstill and the water shut off only by the guide vanes, the water leaking past the guide vane clearances will have very high velocity, close to the free spouting velocity. This will cause abrasion wear in the guide vane apparatus. By closing the inlet valve, this abrasion is eliminated. To close the inlet valve is especially important for high head units.
- Hard coatings are very sensitive to cavitation. Thus, in machines with such coatings all operating conditions that lead to cavitation must be avoided and strictly stick to the recommended operating range for the turbine.

V. ALTERNATIVE DESIGN OF FRANCIS TURBINE

A few instances have been noticed where under identical conditions of sediment, the intensity of damages at different hydropower stations were not identical. While components at a particular power station eroded very fast, damages to components at other power stations were insignificant. This leads one to believe that equipment design has a role to play in influencing the intensity of erosion (Naidu, 1999).

The author earlier designed a Francis turbine for sediment-laden water that considering the erosion of the Francis turbine occurs mainly at the outlet of the guide vanes and at the outlet of the runner blades. In order to reduce the erosion rate of the turbine, the absolute velocity at the inlet of the runner and the relative velocity at the outlet of the runner have to be reduced. In this study, the flow and head were kept constant while the speed, inlet peripheral velocity and outlet runner blade angle were changed according to Table 3.

Table 3 : Variable input parameters

Speed	rpm	n	750	600	500	433	375	333	300	275
Inlet peripheral Velocity, reduced	-	$\underline{U_1}$	0.71	0.74	0.77	0.8	0.83	0.86	0.89	0.92
Outlet blade angle	degree	β_2	17	19	21	23	25	27	29	31

The results show that the outlet diameter changes relatively little while the inlet diameter changes drastically. The reduction of the erosion at the outlet is more than at the inlet. This is shown in Figure 1.7. The inlet angle of the turbine has changed so that the design looks more like a pump-turbine. This means that the turbine will be larger than the traditional design. The reduction of the erosion is linked to the reduction of the velocity and therefore the size of the turbine increases. This result in a higher price of the turbine, but it will reduce the maintenance costs during its lifetime. It has been shown from the calculation that the design of the runner can decrease the sand erosion but it is not possible to avoid this problem completely by design alone.

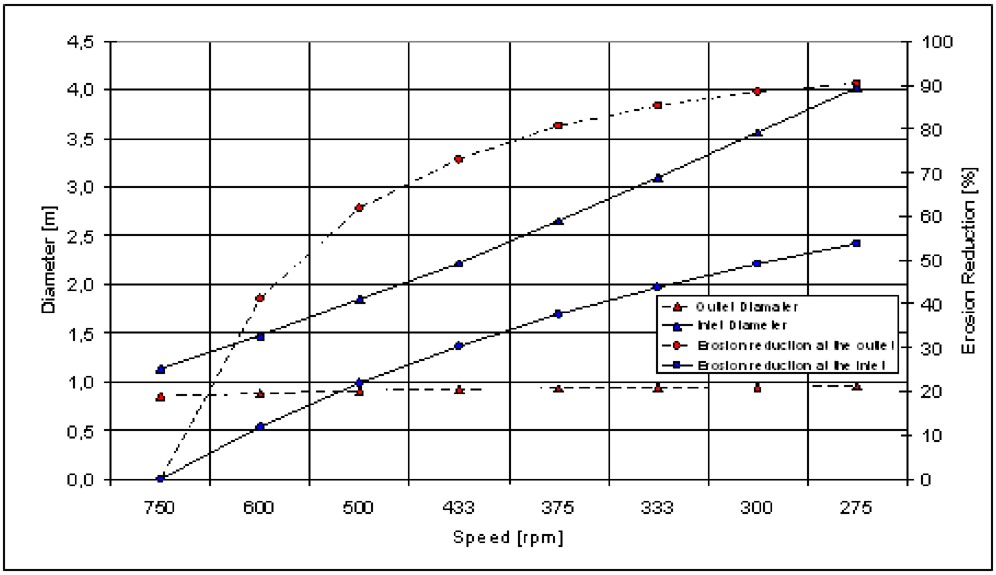


Figure 7 : Variation of diameter for reduction of erosion

However, if a Francis turbine designer combines the hydraulic design and coating of the critical parts, a significant reduction of erosion can be achieved.

VI. CONCLUSION

Sediment content of water can no more be overlooked in any phase of hydropower project implementation. This includes all the phases like, investigation, design, operation and maintenance, and refurbishment and upgrading. Due consideration of the problem at every stage, would affect economies on one hand and long-term solutions would emerge on the other hand. However, one solution in order to decrease the sediment erosion is to increase the size of the turbine, thereby increases the hydraulic radius of curvature, and thus decreases the accelerations. Furthermore, while it is possible to design a Francis turbine to be more resistant against sediment erosion, this may adversely, affect other aspects of the turbine. It should be understood that every hydraulic turbine is a compromise between several requirements.

REFERENCES RÉFÉRENCES REFERENCIAS

1. **Bajracharya, T. R., B. ,Acharya, C. B. Joshi, R. P. Saini, and O. G. Dahlhaug**, “Sand erosion of Pelton turbine nozzles and buckets: A case study of Chilime hydropower plant”, Wear Vol. 264, No. 3 - 4, 2008, pp. 177 - 184.
2. **Brekke, H., H. Wu, Y. L., and B. Y. Cai,** “Design of hydraulic machinery working in sand laden water”. Book series on Hydraulic machinery, Vol. 2 edited by Duan C. G. and Karelin V. Y., 2002.
3. **Edwards, J. K., and B. S. Mclaury,** "Modelling solid particle erosion in elbows and plugged tees", Journal of Energy Resources Technology Vol. 123, 2001.
4. **Finnie, I.**, "Some observations on the erosion of ductile metals", Wear Vol. 19, No. 1,1972,pp.81-90.
5. **Finnie, I.,** “Erosion of surfaces by solid particle”, 1960, Wear Vol. 3, pp. 87-102.
6. **Naidu, D. B. K. S.,** "Developing Silt Consciousness in the minds of Hydro Power Engineers", Silting Problems in Hydro Power Plants, New Delhi, India, 1999.

7. **Neopane, Hari Prasad, Ole. G. Dahlhaug, and M. Eltvik**, "Numerical prediction of particle shape factor effect on sediment erosion in Francis turbine blades", 6th International conference on hydropower, Tromsø Norway, 2010.
8. **Neopane, Hari Prasad, Ole. G. Dahlhaug, and B. Thapa,** "Alternative Design of a Francis Turbine for sand-laden water", International Conference on Small Hydropower - Hydro Sri Lanka, (22 - 24 October) Sri Lanka, Kendy, 2007
9. **Neopane, Hari Prasad, Ole. G. Dahlhaug, and B. Thapa,** "Experimental examination of the effect of particle size and shape in hydraulic turbines", Waterpower XVI, Spokane, Washington, USA: HCI 2009.
10. **Neopane, Hari Prasad,** "Sediment erosion in hydro turbines, PhD thesis", Norwegian University of Science and Technology (NTNU) Trondheim, Norway, Faculty of Engineering Science and Technology, Department of energy and process engineering, 2010.
11. **Ole Gunnar Dahlhaug, and P. E. Skåre,** "Development of a sediment resistive Francis runner", Hydro 2009: Progress - Potential - Plans, Lyon, France: The International Journal on Hydropower & Dam, 2009.
12. **Ole Gunanr Dahalhaug, P.E. Skåre, V. Mossing, and A. Gutierrez,** "Erosion resistant coatings for Francis runners and Guidevanes", The International Journal on Hydropower & Dams, Water Resources and Renewable Energy Development in Asia, Vol. 17, Issue 2, 2010.
13. **Padhy, M. K., and R. P. Saini,** "Effect of size and concentration of silt particles on erosion of Pelton turbine buckets", Energy Vol. 34, No. 10, 2009, pp. 1477 - 1483.
14. **S. Kurosawa, T. Suzuki, and L. Shyang Maw**, "Numerical model testing to enhance performance and reduce cost of Francis units", The International Journal on Hydropower & Dams, Water Resources and Renewable Energy Development in Asia, Vol. 17, Issue 2, 2010.
15. **Thapa, Bhola,** "Sand erosion in hydraulic machinery, PhD thesis", Trondheim: Norwegian University of Science and Technology, Faculty of Engineering Science and Technology, Department of energy and process engineering, 2004.
16. **Truscott, G. F.,** "A literature survey on abrasive wear in hydraulic machinery", Wear Vol. 20, No. 1, 1972, pp. 29 -50.