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A Review on the Dominant Factors Affecting Silt Erosion in Hydro Turbines

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ABSTRACT: Hydro turbines requiring a high-water head for operation are often run-of-river projects situated at places like the Himalayan terrain where a high-water head is naturally available. These hydro electricity generating machines, however suffer from erosive actions of the silt impregnated run of river striking the buckets of the turbine with great force. The buckets, thus, get damaged over a period of time with the result that the down-time of the turbine is increased seriously, interfering with uninterrupted power supply. The present paper is an attempt at studying and analysing the factors affecting silt erosion of Hydro turbines. The erosion of the hydro turbine runner, as a function of various external (time, head, runner material etc.) as well as silt factors (concentration, size, angle of incidence), increases its downtime affecting its performance and efficiency adversely. This paper housing the details at one place, enumerating the factors and their effect at lowering of the turbine efficiency and performance, is expected to work as a tool in the hands of entrepreneurs concerned, to address to this burning problem in the power generation sector.

Keywords: Hydro turbine, Silt Erosion, silt concentration, silt size, impingement angle.

I. INTRODUCTION

Energy scarcity is the greatest deterrent to the growth process of a country hampering its industrial as well as agricultural growth. It will not be out of the place to mention here the importance of energy in the day to day life of the community concerning issues like drinking water, hospital and general lightening facilities. Realising the above, Govt. of India has given serious considerations to the generation of hydropower using the cheap and abundant water resources and issued its intention to establish Small Hydro Power Plants (SHP) with the aim of generating 42,783 MW [1]: total power in the route. Accordingly, many entrepreneurs have ventured to accept the challenge both in the public and private sector through independent installations and installations connected to power grids for hydropower generations. Pelton turbines are largely employed due to availability of high-water head [2].

The everlasting water in the form of streams falling from a height in the Himalayan terrain, its acquiring endless water supply from the glaciers, possession of kinetic energy, provide for a huge water power potential in the country. Despite specific arrangements for sedimentations, the run of the river in this region contains high proportions of unsettled sediments in the form of hard abrasive sand and silts round the year in general and during the monsoon days in particular. Those unsettled sediments that impregnate the run of the river strike against different parts of the turbine in course of their passage through the turbine. The impacts on the turbine-bucket which directly receive the water through a nozzle as a water jet, is most affected due to this impact. The impact due to high velocity of the water jet, therefore, damages the turbine-bucket over a period by cutting or deformation of the surface and finally renders the turbine unserviceable. The down time during repair/replacement and/or maintenance of the runner is bound to contribute adversely to the uninterrupted power generation by these hydro-power-generating machines. Thus, silt erosion mechanism and damages caused to the turbine due to silt erosion is of great importance to the engineers concerned with the design of the turbine and material selection for its fabrication and its subsequent operation and maintenance for trouble free functioning.

Keeping the above in mind many investigators are drawn to the conduct of actual experiments for the study of silt erosion of the Pelton turbine bucket. In this regard the effect of different factors and the correlations developed by the experimenters is of utmost important [3-9]. The present article is concerned with the details of the factors affecting the silt erosion.

II. FACTORS AFFECTING SILT EROSION IN HYDRO TURBINES

The factors which affect the silt erosion of a hydro turbine are

1. Operating condition which includes velocity/acceleration of a particle and impingement angle with the target material.
2. Eroding particle which include flux rate, medium of flow, size and shape.
3. Substrate Material.

A. Velocity of erosive particle and impingement angle

Erosion is said to assume a ductile mode when at low impact angles the erosion rate is maximum. Similarly, it is termed as brittle erosion when the rate is maximum at normal incidence [10]. These different modes of erosion, however, are independent of the nature of the target surface. Ductile material shows severe erosion at lower impingement angles, the maximum erosion rate being observed between 10° to 30°. For these materials at 90° impingement angle erosion rate assumes lower value. On the other hand, for the brittle materials the rate of erosion increases with the angle of erosion assuming the highest value at normal impingement. This relationship is illustrated in Fig. 1. The curves presented in the figure are normalised for maximum erosion rate pertaining to both brittle and ductile target materials.

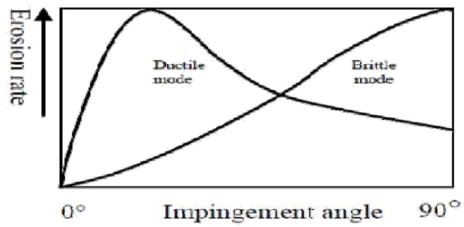

Fig. 1. Brittle and Ductile Mode of Erosion as a Function of Impingement Angle [10].

Different investigators present different relationships between the erosion rate and impingement angle. Bhushan [11] presents a higher erosion rate for brittle materials as compared to ductile materials; whereas Matsumura and Chen [12] have established that the reverse is true. Similarly, Bhushan [11] shows that up to a certain low impingement angle erosion does not take place. However, Stachowiak and Batchelor [13] have established some erosion (10% maximum) rate even at 0° impingement angle. These differences may be attributed to the definitions of impingement angles of the actual particles which are in general considered as jet angle for practical purposes. This is always not true. Under practical conditions, when there is flow of liquid in a parallel pipe, the jet angle/the impingement angle should be close to zero degree. But even in this case, when turbulent flow occurs in straight pipe, the particle impingement angle would be close to 90° owing to the dancing or oscillating of particles in a direction normal to the flow direction [14, 15]. Relationship between silt erosion and particle velocity is often expressed as mentioned below:

$$\text{Erosion} \ \alpha \ (\text{Velocity})^n$$

where 'n' is velocity exponent [16]. Assuming various prevailing conditions pertaining to different concerned factors, different values of 'n' have been predicted by different researchers ranging from 1.4 to 5.1. These factors responsible for the variation in 'n' values include the following:

(a) The target material [17],
(b) Target material with coating [18],
(c) Impingement angle [19], and
(d) The test rig employed.

On the basis of the above one can emphasize that the varied values of the velocity exponent 'n' over a wide range make it difficult to predict and simulate a uniform value for the erosion rate. However, it may be appreciated that at low velocity, particles are not equipped with high values of kinetic energy to cause erosion of the target material by a cutting mechanism, though considerable elastic deformation/ fatigue effect may be evidenced even at low particle velocities [20]. As the velocity increases and reaches a value beyond a threshold or terminal velocity, the target material is considerably damaged due to both, a cutting action and plastic deformation [21]. On the other hand, however, below the critical velocity, the particles do not skid on the target surface and cutting action does not take place. For silica sand particles and carbon steel this critical velocity is predicted to be 2.5m/s [22]. Lopez *et al.*, [23] studied that the corrosion-erosion is affected by the impact velocity and impact angle on AISI 304 and AISI 420 when used as substrate material. The impact velocity has the major effect on corrosion-erosion behaviour irrespective of the impact angle. The surface damage increases with the increase in the impact velocity. The effect of impact angle on 304L stainless steel is studied by Bustein *et al.,* [24]. They developed a slurry erosion test rig to study the corrosion-erosion behaviour of 304L stainless steel and concluded that impact angle is inversely proportional to increase in current and acoustic emission. Thus, it can be inferred that under practical conditions, mechanism of target material damage due to silt erosion depends on the velocity of silt particles, together with other parameters like the impingement angle, etc. and may occur on account of either plastic deformation or cutting action.

B. Particle flux rate

Flux rate of the striking particles is the mass of the eroding particles hitting unit area of the target surface per unit time. Similarly, concentration of the striking particles in the slurry is presented by the mass or volume of the particles contained in unit mass or volume of the fluid. Up to a certain flux rate proportionality between the flux rate and the erosion rate is maintained and after that there is a reduction in the erosion rate with an enhancement of the flux rate. This may be attributed to the interference between the rebounding and the freshly arriving particles [25]. It is also evidenced that the erosion rate is affected by flux rate and size of the particles [26]. Bjordal [27] presents the erosion rate to be as low as 100 kg/m^2 for elastomers and as high as 1000 kg/m^2 for metals which are hit by large particles. Experimental findings established a relationship between the particle concentration and erosion rate given by erosion rate is directly proportional to the concentration's power value of 0.25-1.27 of the metals and coatings. However, when applied to longer periods of time of exposure, the constant of proportionality assumes a value of unity. Thus, in addition to being proportional to velocity [16], erosion is also proportional to concentration. The choicest material for fabrication of the runners (bucket and disc), as discussed above, is 16Cr5Ni stainless steel. Specifically, the most appropriate material for fabrication of the runners is 16 Cr5Ni steel that can provide good resistance against the high kinetic energy, cavitations, corrosion and sand erosion. The use of material like Stellite and Titanium is avoided owing to their cost, the use of which may not be very much cost effective.

C. Effect of media

The characteristics of the conveying medium, such as its velocity, density, corrosivity, lubricating property, cooling effect and nature of flow (laminar/turbulence) affect the silt erosion rate considerably [28]. Collision efficiency is expressed in terms of the ratio of the number of particles actually hitting the surface in the presence of the fluid medium to that theoretically hitting the surface in the absence of the medium. This provides a basis for assessment of the effect of the erosive medium on the rate of erosion.

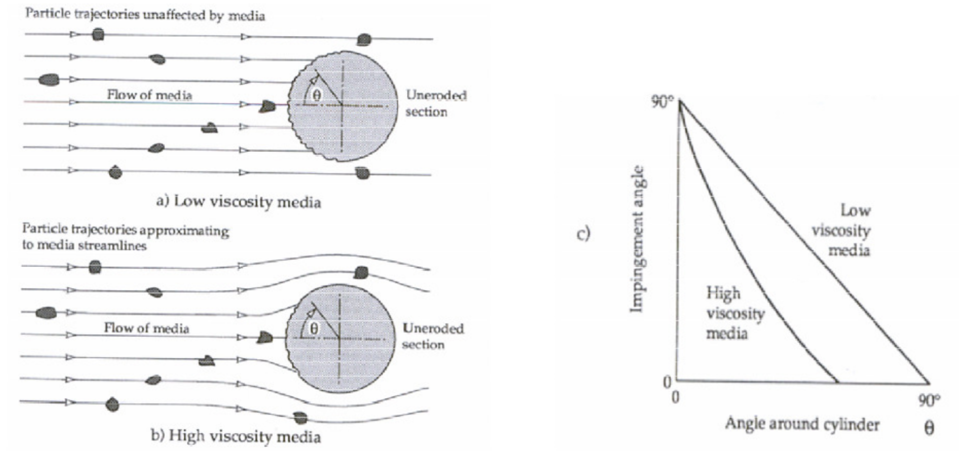

Fig. 2. Effect of Medium on Impingement Angle [13].

The particle trajectory is influenced by the viscosity of the medium altering the angle of impingement [12, 29]. The particle trajectory and effect of viscosity of the medium on the impingement angle is presented in the Fig. 2. It may be noticed that careful analysis of the particle trajectory helps determine the erosion rate and the exact location of damage. For example, erosion at the back side of Pelton hydro turbine buckets is caused by the particles that rebound from the preceding buckets. Erosion rate is influenced by both the flow direction and type of flow of the medium. For an instance, when the target surface and the direction of flow of medium are parallel, turbulent flow accounts for a greater rate of erosion compared to laminar flow; as under turbulent flow conditions more numbers of particles tend to hit the target, some of the particles hitting repeatedly.

However, under laminar flow conditions particles try to adopt a stream-line flow pattern. Many of them escape without striking the surface. This condition will be responsible for reducing the erosion rate. However, when the flow direction of the fluid is normal to the target surface erosion rate is higher for laminar flow as compared to turbulent flow conditions. The erosion rate is significantly reduced when a small amount of lubricant is added to the medium that contains the striking particles. The lubricants restrict any change in material properties by providing a cooling effect during impingement, thus reducing the erosion rate. It has been demonstrated [13] that the added lubricant reduces the erosion in elastomers by reducing the surface tensile stress associated with particle impact.

The characteristic properties of the particle like size, shape and hardness influence the erosive wear of the target surface. Also, the viscosity and velocity of the fluid which influence its flow characteristics governing the transport mechanism of the particle play a role in silt erosion [28, 30]. River sediments consisting of clay, silt, gravel, sand cobbles, boulders etc. can be classified either as the bed load which travel on the bed of the river stream or suspended load which are suspended in the river water and get transferred along with the river water acquiring a velocity more or less equal to that of river water. Basically, it is the fraction of sand particles in the size range of 0.06 mm to 2.0 mm present in the sediment that cause turbine erosion [31].

D. Particle size

The role of particle size in the silt erosion of hydro turbines has been reported in great details by many investigators [32-35]. They report that ductile mode of erosion changes to brittle mode with the particle size changing from small to large. According to these researchers the erosion rate and ranking of erosion resistance also change with the mode of erosion when the size of the eroding particles is changed (Fig. 3). It is also opined by these researchers that the rate of erosion and the erosion rankings depend on the hardness of the particles and the toughness of the material of construction of the hydro turbine components when it is being eroded by small sized particles. In their experiments the maximum erosion rate was obtained at an impact angle of 30° with smaller particles and 80° with larger particles. It was further observed, while small sized particles in the water stream have a cutting effect on the material, large sized particles account for plastic deformation and fatigue of the material concerned [33-35].

Erosion rate of hydro turbine material is the function of the shape of the impinging particle along with its size though data available in this aspect are limited. However, shape factor of the eroding particles constitutes an important factor in the silt erosion of the hydro turbines since most of the erosion models proposed by several investigators have a mention of shape of the particles [35-37] in their respective models. It can be stated that blunt particles with round edges exhibit a lower erosion rate whereas angular particles with a sharp edge cause a higher erosion rate. Computer aided modelling using micro scale dynamic model (MSDM) was conducted by Chen and Li *et al.*, to investigate into three basic shape, viz., triangular, square and circular shapes on the erosion rate. The results obtained with a single particle impact and when 50 particles are involves in simultaneous impingement on the target material, is presented in Fig. 4 [38].

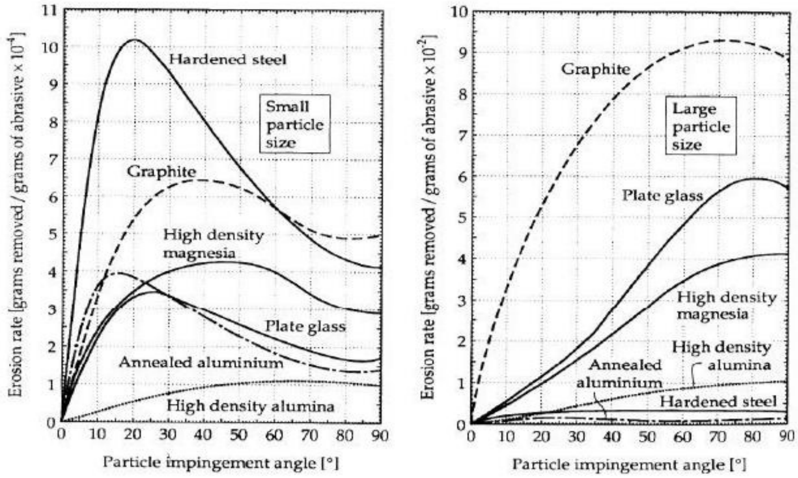

Fig. 3. Erosion Resistance of Different Materials [35].

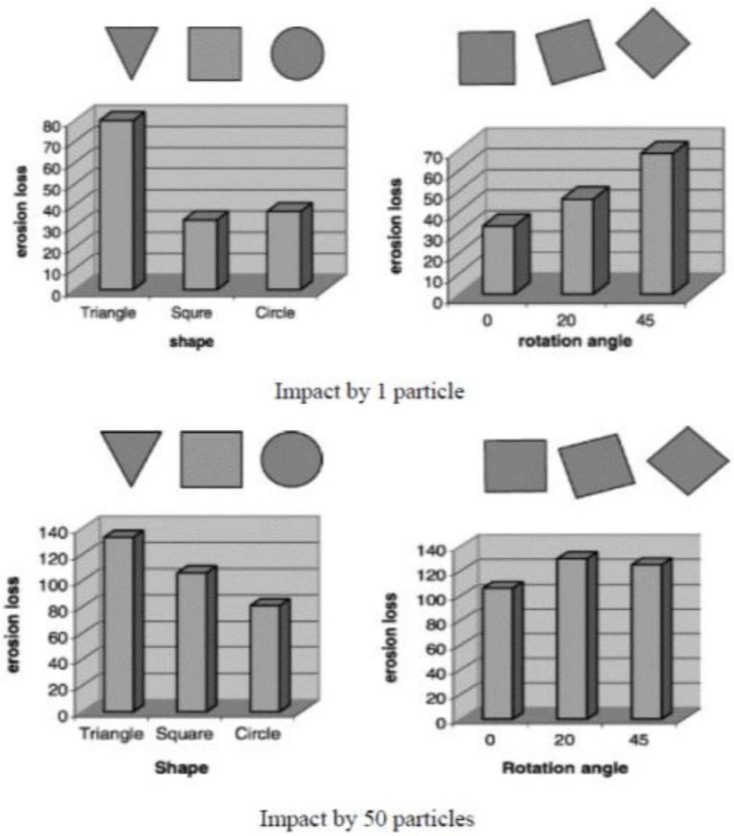

Fig. 4. Erosion Rate due to Different Shapes of Particles [38].

The concept that hard particles cause greater erosion does not always hold good. For example, a hard particle with rounder edges may not cause severe erosion [37]. However, edges of soft particles round off even with a small impact whereas, in general, hard particles are characterised by sharp edges. Erosion rate is greatly influenced by the ratio of hardness of the substrate to that of the particle. Erosion becomes severe when the particles are harder than the substrate [39, 40]. Arabjnejad *et al*., [41] gave the correlation between particle hardness and erosion ratio considering particle velocity and particle angularity. The concluded erosion ratio is proportional to particle hardness. The roughness of the substrate due to erosion is dependent on hardness of particle and substrate together with the shape and size of particles [42]. Particles softer than substrate materials appreciable erosion occurs when the substrate material has relatively lower fracture toughness [43, 44].

III. CONCLUSION

Erosion of hydro turbine parts due to silt attack is a major problem in hydro power plants. This problem cannot be avoided completely but can be reduced by analysing the different factors involved in silt erosion.
The various factors that cause silt erosion in hydro turbines are operating conditions which include velocity/acceleration of the particle and impingement angle with the target material, eroding particle which include flux rate, medium of flow, size and shape and substrate material. Many researchers have made a thorough study of these factors affecting silt erosion which helps in analyzing the erosion procedure taking place in hydro turbines.

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