ABSTRACT

Energy is a critical factor in developing countries for economic growth as well as for social development and human welfare. Hydropower is a renewable source of energy, which is economical, non-polluting and environmentally benign among all renewable sources of energy. For efficient operation of hydropower plants, in order to meet the electricity demand, the hydro energy is stored either in reservoirs for dam based schemes or settling basins for run-of-river schemes. These reservoirs or settling basins are filled with sediments over a period of time. This problem must be taken care of by sediment settling systems in power plants. However, lot of unsettled sediment pass through the turbines every year and turbine parts are exposed to severe erosion. The erosion of hydro turbine components is a major problem for the efficient operation of hydropower plants. These problems are more prominent in power stations which are of run-of-river types. The problem is aggravated if the silt contains higher percentage of quartz, which is extremely hard.

Silt erosion is a result of mechanical wear of components due to dynamic action of silt flowing along with water. However the mechanism of erosion is complex due to interaction of several factors viz. particles size, shape, hardness, concentration, velocity, impingement angle and properties of material. The silt laden water passing through the turbine is the root cause of silt erosion of turbine components which consequently leads to a loss in efficiency thereby output, abetting of cavitation , pressure pulsations , vibrations , mechanical failures and frequent shut downs. Since silt erosion damage is on account of dynamic action of silt with the component, properties of silt, mechanical properties of the component in contact with the flow and conditions of flow are therefore, jointly responsible for the intensity and quantum of silt erosion. The hydraulic machines, working under medium and high heads are normally exposed to erosion. High head Francis and impulse turbines are highly affected by sand erosion. Even low head Kaplan turbine and propeller turbines

are also found eroded in rivers with high sediment contents. The erosion damages are to some extent different for Francis and impulse turbines. The most common type of impulse turbine is Pelton turbine, which operates under high head. The available potential energy of water is converted to kinetic energy at the nozzle, which furthermore depend on the mass of water and available head. The energy available in the water is converted into mechanical energy in the form of turbine rotation at the cost of reaction to the turbine components. During this process, the sediment present in the water exerts force on the turbine components; as a result the turbine components get deformed. The dimensional change of the components leads to efficiency loss and eventually the system failure. In case of Pelton turbines needle, seal rings in the nozzles and runner buckets, splitter are most exposed to sand erosion.

It is generally considered that erosive wear is the gradual removal of material caused by repeated deformation and cutting actions. Most common expression for the erosive wear was based on experimental experiences quantified by means of erosive wear rate and generally expressed as a function of properties of eroding particles, properties of substrates and operating conditions.

Theoretical studies were made to discuss the main causes of damage of water turbines viz. cavitation problems, sand erosion, material defects and fatigue. Based on the available studies it was found that the best efficiency point of turbine decreased in direct proportion to the increase in silt concentration. Many investigators reported their experimental results on erosive wear conducted with different base materials and different types of erodent. Based on the case studies it was reported that in run-of-river power plants in steep sediment loaded rivers caused damages to runners due to severe erosion.

Further, it is revealed from the literature survey that a number of investigators have studied the process of silt erosion in Pelton turbines, the effect of different parameters and the remedial measures to be undertaken. Based on their studies correlations were developed. These correlations are mostly based on experiments on small specimens, which do not match actual turbine components. The flow conditions created in the test rigs used in such experiments did not represent the real flow conditions in turbines. The models based test results obtained during such experimental studies in laboratories may not be able to predict the silt erosion of turbines actually in practice. It is therefore, more theoretical and experimental studies are required to incorporate the actual flow conditions inside the turbines. It becomes necessary to investigate the effect of different parameters, i.e., silt concentration, size of silt and jet velocity under different operating conditions on erosion of turbine components in order to predict silt erosion more accurately.

Silt erosion has impact on both performance and reliability of a Pelton runner. Bucket is the most affected part of the Pelton runner. The change of bucket profile alters the flow pattern causing loss of efficiency. Similarly loss of material weakens highly stressed parts increasing probability of fracture. The maintenance of buckets after erosion is costly in comparison of other components as the maintenance of the eroded turbine mainly depends upon dismantling time of the runner. The present investigation was carried out for erosive wear on Pelton turbine buckets.

Keeping this in view, the present study is carried out with respect to the following objectives;

(i) To design and fabricate the experimental setup for the actual flow condition in the Pelton turbine.

(ii) To predict the pattern of erosive wear and the wear mechanism in the different locations of the Pelton turbine buckets.

(iii) To investigate the effect of various silt parameters (concentration and size of silt particles) and operating parameters (jet velocity and operating hour) on erosive wear of Pelton turbines.

(iv) To develop correlations for erosive wear as a function of silt related parameters.

(v) To investigate the Pelton turbine performance and develop correlations for turbine efficiency parameters as a function of silt related parameters.

An experimental set up was designed and fabricated to investigate the effect of the silt and operating parameters on erosive wear. It consisted of a Pelton turbine with spear valve, water tank, service pump-motor, connecting pipes, stirrer, pressure transducer, open channel, weir, generator, control valves and other accessories.

An extensive experimental study has been carried out to collect the experimental data in order to discuss the wear mechanism and to develop the correlation for normalized erosive wear as a function of particle size, concentration, jet velocity and time of operation of Pelton turbine. Experimental data have been generated taking into account all the parameters contributing their effect on erosion of Pelton turbine bucket. The silt samples were collected from the river Bhagirathi basin (India), where a severely silt affected powerhouse is situated. The range of parameters considered under the present experimental study is as given in Table1.

Table 1 Range of parameters

No.	**Parameter**	**Range**
1.	Concentration	5000 to 10000 ppm
2.	Silt size	Upto 355 micron
3.	Jet velocity	26.62 to 29.75m/s
4.	Operating time	8 hrs run for each set

The experimental investigation was carried out in two stages viz. i) Identification of hot spots and analyzing the wear mechanism - Pelton turbine buckets were coated with easily erodible material and wear hot spots were identified after operating the turbine over a short period of time and ii) Determination of quantum of erosive wear and analyzing the efficiency loss of Pelton turbine due to erosive wear.

In order to study the mechanism of erosive wear, small pieces of soft material were glued at the hot spots, identified under the first part of the experimental study. The pattern of erosive wear has been examined by taking photographs of buckets. Scanning Electron Microscope (SEM) micrographs placed at wear hot spot were obtained.

Based on the observations it is predicted that coarser particles travelling at higher velocity relative to the velocity of water jet created pits and craters along the depth of the bucket at higher value of impact angle. However, the particles traveling at higher velocity in the vicinity of the splitter cause the erosion. This may be due to the shearing action of the surface of the silt particles. Smaller particles flow along the water jet causing abrasive type of erosion along the depth and at the outlet of the bucket. These particles seem to be embedded into the surface at inlet of the bucket due to lower kinetic energy and are flown out from the surface by the incoming jet.

The micrographs of splitter tip and along the depth of the Pelton bucket after erosive wear were obtained. The splitter tip has been found to be eroded by plastic deformation and indentation, overlapping craters are found on the splitter tip while along the depth of the bucket erosion takes place by plastic deformation as well as plowing.

The quantum of erosive wear was determined by measuring the mass of individual bucket before and after the experimentation at proposed time intervals. Silt concentration is found to be the strong parameter for mass loss of the Pelton bucket.

The normalized wear varies with silt concentration. Mass loss increases linearly with operating hour and other parameters viz. silt size, silt concentration and jet velocity. On the basis of experimental investigation, it has been found that the normalized erosive wear increases with an increase in the value of silt concentration for all the value of silt size. However, for a given value of silt concentration, the erosive wear rate has been found to be higher for larger size particles as larger particles have higher impact energy.

The bucket erosion has been found to be varied with the jet velocity and it implies that the jet velocity is the strongest parameter in bucket erosion. As jet velocity is the function of head, the high head turbines are more vulnerable to silt erosion. It has been observed that the power output of the turbine decreased in a rapid rate at initial stage and after some time period of operation, the power out put decrease rate achieved asymptote. The inlet or splitter, depth of the bucket and the outlet edges are found to be the prominent parts of bucket erosion. Based on the qualitative study it was found that the sharp edge of the splitter became blunt and the depth of the bucket increased due to silt erosion.

Based on the experimental data collected, a correlation has been developed for normalized erosive wear of Pelton turbine bucket as a function of the silt parameters and operating conditions. Correlation for percentage of efficiency loss has also been developed as a function of silt parameters and operating condition. Based on the experimental data obtained under different conditions following correlation were developed;

(i) Correlation for normalize mass loss

$$W = 7.91\times10^{-13}(t)^{0.99}(S)^{0.13}(C)^{1.23}(V)^{3.79} \qquad (1)$$

(ii) Correlation for percentage efficiency loss

$$\eta_{\%} = 2.43\times10^{-10}\,(t)^{0.75}\,(S)^{0.099}\,(C)^{0.93}\,(V)^{3.40} \quad (2)$$

A comparison between actual value of mass loss and the value predicted from the correlations are made and the results are found to be in good agreement.

Summarizing, on the basis of experimental investigation it has been concluded that the normalized erosive wear increases with an increase in the silt concentration, silt size and jet velocity. The developed correlations may be useful for turbine manufacturing industries in order to predict the quantum of erosion in Pelton turbine bucket at manufacturing stage.