

# **HYDRO-ABRASIVE EROSION OF PELTON TURBINES**

**Ph.D. THESIS**

*by*

**ANANT KUMAR RAI**



**ALTERNATE HYDRO ENERGY CENTRE  
INDIAN INSTITUTE OF TECHNOLOGY ROORKEE  
ROORKEE - 247 667 (INDIA)  
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# **HYDRO-ABRASIVE EROSION OF PELTON TURBINES**

**A THESIS**

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In geologically young mountains like the Andes and the Himalayas, the most of the streams contain high sediment concentration during the snow melt and rainy seasons. The suspended sediment causes hydro-abrasive erosion in hydraulic turbines and other components of hydropower plant coming in direct contact with moving sediment laden water due to presence of hard minerals such as quartz and feldspar. Due to hydro-abrasive erosion, frequent and high level of maintenance, repair and replacements of eroded parts are required. Further on account of reduced efficiency and downtimes, there are losses in electricity generation. The problem of erosion in hydraulic machines is expected to become more severe in the future due to higher suspended sediment availability from retreating glaciers and intense rainfalls caused by climate change. Due to continuous development of untapped hydropower potential of the Asian and South American continents, the number of hydro turbines facing hydro-abrasive erosion shall increase.

For high head run-of-river (RoR) schemes, even small sediment particles can cause high hydro-abrasive erosion especially in Pelton turbines due to high impact on account of high velocity. For optimization of a hydropower plant with respect to suspended sediment and hydro-abrasive erosion, information is required on the costs of various mitigation measures and losses in electricity generation. Currently, only limited information is available due to lack of practically proven measurement techniques as well as reliable measurement data on suspended sediment properties and turbine erosion with efficiency losses. Further, quantitative relations between suspended sediment, turbine erosion and efficiency losses are rare in literature.

Based on literature survey, it was found that the abrasion tests give widely varying results depending on the features of different test rigs employed by various researchers, erosion velocity, impact angle, composition, concentration and size of particles. Commonly used slurry pot testers do not simulate erosion conditions of Pelton turbine due to high concentration of erodent and continuous contact of sediment with specimen. The static specimen in jet type erosion tester lacks the effect of forces like centrifugal force and Coriolis force, which are present in rotating frame

only. Hence, studies based on test set-up simulating the erosion conditions similar to Pelton turbines in actual hydropower plant conditions on materials used in turbine components are required. Further, the forces and accelerations inside Pelton bucket need to be analyzed to understand the main causes behind the hydro-abrasive erosion in Pelton turbines. The models developed for efficiency loss due to erosion were for specific laboratory or field conditions; hence, the application of the models require calibration specific to the hydropower plant for which erosion based losses are to be assessed. In addition to the specific calibrations, the efficiency of the hydropower plant needs to be monitored to obtain the losses for the gradual efficiency reduction caused by the erosion.

On the basis of literature survey, following objectives of the study were formulated.

- i) To investigate suspended sediment parameters (concentration, size, shape and mineral contents), turbine erosion and efficiency reduction of a prototype Pelton turbine based on field measurements in a hydropower plant.
- ii) To investigate the relation of Pelton bucket erosion with suspended sediment concentration (SSC), sediment size, velocity of erosion, roughness of buckets and operating time based on tests of commonly used grades of steel and coatings in the laboratory test rig, which allows controlled flow conditions similar to Pelton turbines.
- iii) To investigate the forces on sediment particles in Pelton bucket and their effects on the erosion of the bucket. To develop an erosion model considering various forces inside Pelton bucket.
- iv) To investigate and adapt erosion models from the literature based on the laboratory as well as field data. Further to find out the values of unknown terms of erosion model IEC 62364 (2013) for analysis of erosion in Pelton and Kaplan turbines.
- v) To assess the financial implications of the erosion on the hydropower plant based on the field investigations in the prototype plant and information from turbine manufacturers.

In order to achieve the objectives, the research work was carried out with following methods:

- i) Identification of a hydropower plant having high sediment laden river water and erosion conditions with Pelton turbines
- ii) Measurement of erosion, suspended sediment and reduction in efficiency at the study plant
- iii) Identification and classification of the major erosion zones in the Pelton bucket
- iv) Assessment of applicability of methods such as laser diffraction and turbidity for continuous SSC measurement at the study plant
- v) Selection of variables for laboratory tests as per field observations and available literature and carrying out the tests in the laboratory on specially designed test rig for the study
- vi) Derivation of correlation between various parameters in laboratory investigations and finding the mechanism of erosion in different parts of the Pelton bucket
- vii) Analysis of forces on sediment particles inside Pelton buckets with the assumptions to simplify the complex flows inside buckets and developing an analytical erosion model
- viii) Finding the unknown terms such as flow co-efficient ( $K_f$ ), material factor ( $K_m$ ) and exponent (p) of hydro-abrasive erosion model of IEC 62364 (2013) for Pelton turbine from the field and laboratory data
- ix) Analysing erosion in a Kaplan turbine with respect to IEC 62364 (2013)
- x) Calibration of erosion models from literature and financial analysis due to hydro-abrasive erosion assessed using the calibrated erosion models
- xi) Uncertainty analysis for parameters involved in the laboratory and field investigations

From various hydropower plants affected by hydro-abrasive erosion in the Indian Himalayas, Toss HPP (2×5 MW) having two numbers 4-jet Pelton turbines with coated buckets in one unit and uncoated buckets in second unit was selected for hydro-abrasive erosion study. Based on analysis of images of uncoated eroded buckets from the literature as well as Pelton turbine at study plant, hydro-abrasive erosion has been classified into 5 classes. The hydro-abrasive erosion was measured with an optical 3D-scanner and suspended sediment parameters were obtained with gravimetric, turbidity, laser diffraction and dynamic imaging techniques. The major findings from the field investigations of Pelton turbine erosion and monitoring of suspended sediment are as follows.

- i) The hydro-abrasive erosion in uncoated Pelton buckets has been classified in 5 different type - wavy erosion in splitter (E1), scaly erosion in curved surface inside bucket (E2), bulging/protruded erosion lines between splitter and curved surface inside bucket (E3), combination of cavitation and erosion near splitter in entry as well as the bucket root (E4) and polished smooth surface with metallic luster outside bucket (E5). Detailed measurements of each type of erosion has been explained and discussed.
- ii) Method of 3D-scanning has been found having distinct advantage over other methods of hydro-abrasive erosion measurement (using template) as it allows the measurement of the depth, profile as well as material loss. The decrease of splitter height, erosion depth in curved zones and abrasion in the cut-out portion of uncoated bucket on average were 3%, 1.5% and 5% of the bucket width. Erosion depth in curved zone of coated buckets was around 0.4% of the bucket width in few patches having coating intact in other parts.
- iii) The erosion at outlet surface inside the bucket had directed the flow towards lateral surface outside bucket. The outside of Pelton bucket was eroded on average up to 0.1% of the bucket width, which is considerably lesser than the inside surface.
- iv) The sediment properties like concentration and size have been found to vary significantly with coefficient of variation 75% and 32% respectively during the high flow season. Total suspended sediment load of 12540 tons passed through each turbine unit during study period (5 May to 15 October 2015).
- v) Sediment shape has been quantified with respect to roundness as well as elongation ratio ( $b/l$ ) and has been found to vary within a narrow range (1.5%). The sediment mineral composition was identified and quantified with X-ray diffraction (XRD), X-ray spectroscopy (EDS) and petrographic analysis. 88% of the minerals in incoming suspended sediment were harder than the material of the uncoated turbine, which was 13Cr-4Ni martensitic steel in the study plant.
- vi) The efficiency of the unit with uncoated Pelton turbine decreased by 6% due to severe erosion of nozzle rings and needles requiring shutdown for replacements mid-time of the study period.

For laboratory investigations, the testing conditions were selected to simulate flow conditions similar to a Pelton turbine as shown in the following Table. The

Pelton turbine of the test rig with 24 buckets was designed with model buckets as 1:8 geometric scaled of the tested Pelton buckets in the field. The buckets were designed with detachable feature for ease of dismantling to measure erosion and fixing disks were used for reassembly in well reproducible manner. The model Pelton turbine had 6 different materials (4 number of each type) namely 13Cr-4Ni, 16Cr-5Ni, 16Cr-4Ni martensitic steel, bronze, 13Cr-4Ni with plasma sprayed Cr<sub>2</sub>O<sub>3</sub> coating and 13Cr-4Ni with WC-Co-Cr HVOF coating.

#### **Range of parameters**

<b>Parameters</b>	<b>Range</b>
Erosion velocity	4 values - (32.11, 28.97, 25.62 and 22.05) m/s
Operating head	4 values - (200, 180, 160 and 140) m
SSC	3 values - (750, 1500 and 3000) ppm
PSD ranges	4 values - (0-90), (90-180), (180-250) and (250-355) $\mu$ m
Time	4 values - (3, 6, 9 and 12) hrs

The erosion after each test was measured with weight loss of buckets and 3D-scans. The roughness of the buckets was also measured in different zones. Based on laboratory tests, the major findings are as follows.

- i) The WC-Co-Cr HVOF coating was found to have the best erosion resistance among the materials tested in the laboratory. Among different parameters, the erosion velocity was found contributing maximum to the erosion of the buckets.
- ii) Among sediment parameters, SSC was found to have the linear relation with erosion. Correlations between normalized erosion and test parameters were developed for all the materials tested.
- iii) The roughness of the uncoated surface has been found to have no significant relation with erosion. However, the surface roughness decreases in case of coated surfaces until the coating is completely removed from the surface and the surface starts behaving like an uncoated surface.
- iv) The mechanism of erosion in different parts of Pelton buckets was found to be strongly related to the flow pattern in that part. The mechanism of erosion in the splitter region was mainly due to the impact of sediment particles on the surface forming craters whereas scratching was the main mode of material removal in the curved region.

Due to rotation of Pelton runner and flow in curved path inside buckets, different types of centrifugal forces and Coriolis force act on sediment particles in Pelton buckets. These forces were determined with a series of assumptions and simplifications. The main reason for the susceptibility of Pelton buckets to erosion was found high accelerations caused by the curvature of the bucket separating the sediment particles from the streamlines, and leads to the grinding of the particles on the surface of bucket. Further, an erosion model has been developed with considerations of impact and frictional forces inside the bucket. The erosion model developed for Pelton buckets with respect to the forces was found in agreement with the available literature. The findings from the analytical study are summarised as follows:

- i) The angle between the particle path and the fluid streamline resulting from the forces on particles was considered as major similarity parameter for the erosion potential in the Pelton buckets.
- ii) The hydro-abrasive erosion can be decreased by increasing pitch circle diameter (PCD) and bucket width at the design stage itself.
- iii) The largest resulting separation angles and the largest separation velocity occur in the outer zone of the buckets and lead to the highest resultant forces on the particles.
- iv) The exponent of erosion velocity for hydro-abrasive erosion has been found between 3 and 4, similar to the value obtained from laboratory investigations. Exponents of other parameters in the derived erosion model have been found to be similar to the values reported in literature and obtained from laboratory investigations.

In the theoretical erosion model proposed by IEC 62364 (2013), the value of terms like the flow coefficient ( $K_f$ ) and exponent ( $p$ ) of reference size (RS) are not prescribed for Pelton and Kaplan turbines due to lack of field studies. From the field and laboratory data, the values of  $K_f$  and  $p$  of RS were obtained as  $5.43 \times 10^{-6}$  and 0.3 respectively for curved zone of the bucket. For splitter height reduction, these values were found as  $1.76 \times 10^{-5}$  and 0.15 respectively. The erosion in Kaplan turbine of a hydropower plant from Himalayan region is also analysed as per IEC 62364.

The models available in the literature for calculating gradual loss of efficiency of turbine were explored and applied for calculating the same for the study hydropower plant. The details on the loss of revenue due to erosion of material from turbine surface and restoring back the surface to initial uneroded profile were obtained from the turbine manufacturers and analysed for the study plant. The financial analysis for study plant has been carried out for 3 months duration starting from the date of installation of new runner and sediment laden inflows during monsoon/rainy season. It has been found that the losses in operating the uncoated turbine for the duration accounted for 15.7% of the initial cost of uncoated turbine, major portion contributed by gradual efficiency loss. Hence, the operation of eroded turbine for longer duration adds significantly to revenue losses. Further, the cost of preventive measures has been obtained for the study plant and a criterion for decision making is developed. The cost of coating was 11% of the uncoated turbine cost; however, it minimized the downtime and other losses as observed from other unit of the plant with coated bucket. From this limited financial analysis, it may be concluded that the option of coated turbine would be more economical for the study plant.

The present study provides data and information to hydropower plant managers and researchers for measuring the erosion and to develop strategies for handling erosion issues effectively. However, more systematic erosion studies with advanced instruments and methodologies are required, especially in Pelton and Kaplan turbines, with simultaneous measurement of erosion in turbines, suspended sediment and efficiency reduction. To assess the complete loss due to erosion and optimum measures to minimize the losses, data needs to be obtained for longer duration of few years say 3 to 5 years at a hydropower plant.