Effect of concentration and size of sediments on hydro-abrasive erosion of Pelton turbine

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A B S T R A C T

Hydro-abrasive erosion caused by suspended sediments is a severe issue leading to frequent generation losses and failure of hydropower components especially in geologically young mountains like the Himalayas. To study the erosion behaviour of different materials under the same erosive and hydraulic conditions, experiments were performed simultaneously with different range of velocity, duration of exposure, sediment size, and concentration on a 1:8 down scaled Pelton buckets from an Indian hydropower plant (HPP) located in Himalayas. This work extends the research of Padhy and Saini (2009) for application in Pelton turbines fabricated from 6 materials such as 3 kinds of steel, 2 kinds of coatings and bronze for head up to 200 m. The values of sediment concentration for the tests were 500, 1500 and 3000 ppm, values mostly found in the HPPs. The developed erosion models were used to predict the erosion of the Pelton buckets from the study plant and are useful for proper planning of preventive measures and operation of the HPPs.

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1. Introduction

Most of the streams in geologically young mountains, like the Andes and the Himalaya, contain high sediment concentration during snow melt and rainy seasons causing hydro-abrasive erosion of hydraulic turbines and components coming in contact with sediment particles [1–3]. The hydro-abrasive erosion poses challenges for smooth and efficient operation of existing hydropower plants (HPP) as well as for the development of new hydropower plants in these regions. Recently, erosion is getting more attention because of generation loss of much needed renewable energy, experienced maintenance and high efficiency requirement. Erosion changes the profile of the turbine blades/buckets, which plays major role on efficiency of the turbine, finally leading to power generation loss [3,4]. On the one hand run-of-river plants face high erosion as less or no storage for sediment settling is available and on the other hand even small sediment particles cause acute hydro-abrasive problems in Pelton turbines due to high head [5,6]. Though researchers have identified parameters involved in erosion of Pelton turbines like sediment concentration, size, material composition, flow velocity; the quantitative information of the influence of these parameters is not fully known [3,5,7].

Hydro-abrasive erosion models are useful for designing turbine components, sediment settling basins and optimization of hydropower plant operation in rivers with high sediment contents [5,7,8]. Most often, individual particle dynamics are considered for developing erosion models [5]. Empirical and statistical relations for hydro-abrasive erosion have been developed from experimental as well as field measurements [8,9]. However, only limited erosion models in hydraulic machineries have been validated for their reliability [3]. Since erosion studies are moving towards numerical modelling and simulations, the importance of erosion models has increased recently [10].

Several researchers attempted to simulate hydro-abrasive erosion using slurry pot tester [11,12] and jet type erosion tester [10,13]. The slurry pot testers do not simulate erosion conditions of Pelton turbines due to high concentration of erodent and continuous contact of sediment with specimen. There is the static specimen in the jet type erosion tester lacks the effect of forces like centrifugal force and Coriolis force etc., which are present in rotating frame only. Moreover, factors like the Coanda effect on the backside of buckets [14] and secondary erosion (cavitation) [15] are not observed in such set-ups, but are encountered in the prototype hydropower plants.
Based on literature survey, it is found that the erosion tests give widely varying results depending on the features of different test rigs, flow velocity, impact angle, composition, concentration and size of particles [3,8]. Additionally, the existing data from experiments is difficult to be transferred to the prototype due to the fact that most of the earlier and existing test rigs do not simulate the conditions of the prototype plant. Hence, a test method resembling the conditions in a prototype plant as closely as possible is required for investigations and analysing the impact of erosion in Pelton turbine.

To include the effects of dynamic conditions, some researchers [16,17] used model impulse turbines as test rig for hydro-abrasive erosion. However, these studies involved high sediment concentration and soft material like brass specimens during experiments to get reasonable amount of erosion in less time. These conditions differ from prototype plant operation where the plant is shut down at concentrations higher than 3000 ppm to reduce hydro-abrasive erosion [18] and soft metal is not used for plants having sediment laden water. Moreover, a hard material like martensitic steel is actually used for turbines. Brekke [19] explained that different materials in similar flow conditions exhibit different erosion behaviour (also in Ref. [8]). Hence, erosion results from brass samples may not be applied to metallic 13Cr-4Ni. The hydro-turbine steel used in prototype. Moreover, attempts have not been made under the reported studies to correlate the erosion of brass and steel, being the actual turbine material, in the experimental set-up to make the outcome applicable. To obtain results applicable for prototype plants, turbine materials like 13Cr-4Ni, 16Cr-5Ni martensitic steel etc. are needed to be studied.

The relative wear resistance of different materials may vary under varying test conditions. Therefore, the wear resistance index of the materials, obtained under different tests, may vary. In the present study, a test method resembling to the prototype conditions as closely as possible is developed and used for analysing the impact of erosion. For the purpose, a 1:8 geometrically scaled down model of Pelton buckets from a HPP severely affected by hydro-abrasive erosion was selected in laboratory investigation. The model Pelton turbine was fabricated with detachable buckets made of different materials and tested with sediment particles obtained from the same HPP. Four major parameters, specifically SSC, size, erosion velocity and duration of operation, were varied during tests in laboratory. Surface roughness of the various buckets was also analysed.

2. Methodology

The details of the set-up, parameters considered, procedure adopted, measurement methodology and data reduction methods for the study are presented in this section.

2.1. Experimental set-up

A 10 kW Pelton turbine with 24 buckets, a pitch circle diameter (PCD) of 192 mm and a nozzle diameter of 12 mm was used to study the erosion in Pelton buckets (Fig. 1). All the 24 buckets were detachable for ease of measurement after each test run. Six different materials were used to measure the erosion variation in various materials under the same erosive conditions, as detailed in Table 1. Both the coatings were 200 μm thick and applied over the base material 13Cr-4Ni. The buckets of same material were arranged diametrically opposite to each other (Fig. 2) and were grouped with numbers given to each bucket in 6 groups as shown in Table 1. The design and fabrications details of set-up are provided in Rai et al. [20].

2.2. Parameters

The hydro-abrasive erosion due to sediment laden water is a complex process and depends on many factors, broadly clustered in three groups [3,5,7–10].

a. Operating conditions: velocity, acceleration, impingement angle, type of fluid, temperature
b. Eroding particles (sediment): concentration, size, shape, hardness, mineral composition
c. Target material properties: chemistry, elastic property, hardness, surface morphology

Although the parameters for hydro-abrasive erosion have been identified, the effect of these parameters on the hydro-abrasive erosion is not fully understood. Due to the complexity associated with measurement of hydro-abrasive erosion and associated parameters like sediment properties, limited literature is available for hydraulic turbines, especially for Pelton and Kaplan turbines. The parameters considered for erosion study were suspended sediment concentration (SSC), suspended sediment median diameter d50 of a given particle size distribution (PSD), relative flow velocity and exposure duration with their range provided in Table 2 along with the values from Padhy and Saini [16]. One of the objectives of the set-up was to test different materials under similar hydraulic and erosive conditions.

2.3. Procedure

A digital pressure transducer was mounted on the penstock pipe at the inlet to the turbine to measure the water head. A calibrated digital balance having least count of 0.1 mg was used to measure the weight loss of the buckets. Another calibrated digital balance having a least count of 0.5 g was used to measure the weight of sediment. The sediment was graded to different size ranges by sieving through 355 μm, 250 μm, 180 μm and 90 μm sieves. After each experimental run, the buckets were dismantled from the Pelton hub and washed with a soap solution. The cleaned buckets were dried and weighed. After weighing, the roughness was measured in each bucket and a 3D scanning was performed. After the measurements, the buckets were reassembled on hub for another experimental run.

2.4. Measurement methods

Various parameters selected for investigation are measured using following methods.

2.4.1. Erosion measurement

The erosion was measured with a 3D-scanner and weighing balance. The changes in roughness of all buckets were also measured to analyse the effect of change in roughness on erosion. These values i.e., changes in the 3D profile, weight loss and roughness variations were measured after each test run. A 3D-scanner (COMET L3D 1M, Carl Zeiss), made of a light emitting diode (LED) and a camera, was used to measure the erosion of the Pelton buckets using the triangulation principle.

2.4.2. Measurement of sediment properties

The sediment samples, sieved into four size classes — (a) 0–90 μm, (b) 90–180 μm, (c) 180–250 μm and (d) 250–355 μm, were used for different test runs with three SSC values — (a) 750 ppm, (b) 1500 ppm and (c) 3000 ppm. For every test run, the amount of water in the tank with dimension 1 × 1 × 1 m³ was selected as 700 L, i.e. 0.7 m depth and the required amount of
sediment is calculated using eqn. (1). Here, the density of water is assumed as 1000 kg/m³, i.e. 1 L of water weighs 1 kg.

\[
Q_s = \frac{700}{\left(\frac{10^6}{\text{SSC}} - 1\right)} 
\]  

(1)

where,

\[Q_s\] the amount of required sediment, kg, and

\[\text{SSC}\] = suspended sediment concentration by mass, ppm.

For preparing SSC value 3000 ppm, 2.1063 kg of sand was mixed with 700 L of water in the tank. The sediment particles were analysed for shape and mineral composition [1]. As the tests were conducted in closed loop, the sediment particles were disintegrated into smaller particles during the tests. Thus, the water-sediment samples were collected at a 30 min interval to obtain the actual value of the particle size for each test. These 7 set of samples (first sample at the start of the test) for each test of 3 h duration were analysed for size and shape parameters. The average values of sediment size and shape were used for erosion calculations.

\[
Q_s = \frac{700}{\left(\frac{10^6}{\text{SSC}} - 1\right)} 
\]  

(2)

\[
Q_s, \text{ SSC} \] 

(3)

\[
V_{jet} = \text{jet velocity obtained converting pressure into kinetic energy, m/s,} 
\]

\[
U = \text{circumferential velocity of the buckets at the PCD, m/s,} 
\]

\[
C_T = \text{co-efficient of velocity,} 
\]

\[
D = \text{PCD, m,} 
\]

\[
N = \text{rotational speed of the Pelton runner, rpm,} 
\]

\[
H = \text{head, m,} 
\]

\[\pi = \text{constants pi,} \] and

\[g = \text{acceleration due to gravity, m/s}^2. \]

To measure the variation in erosion depth, the standard deviation and the coefficient of variation were calculated.

2.5. Data reduction methods

The erosion of each bucket group BG1 – BG6 was obtained by taking an average of erosion in all 4 buckets of the same bucket type after each test. It is equivalent of 4 times erosion testing of every material during one test. It was possible only because 4 numbers of

![Schematic of experimental test set-up](image-url)
same material buckets were tested simultaneously in the Pelton turbine test set-up. The average erosion after each test for a bucket group is calculated from eqn. (5).

\[
\langle E_{BGi} \rangle_j = \frac{1}{4} \sum_{k=1}^{4} \left( \langle W_{BGi}^k \rangle_{j-1} - \langle W_{BGi}^k \rangle_j \right)
\]

(5)

where,

\[
\langle E_{BGi} \rangle_j = \text{Erosion after } j\text{th test for } i\text{th bucket group, } g,
\]

\[
\langle W_{BGi}^k \rangle_{j-1} = \text{Weight of the } k\text{th bucket of } i\text{th bucket group after } (j-1)\text{th test run, } g,
\]

\[
\langle W_{BGi}^k \rangle_j = \text{Weight of the } k\text{th bucket of } i\text{th bucket group after } j\text{th test run, } g, \text{ and,}
\]

\[
k = \text{number of bucket of same bucket group (total = 4).}
\]

The plots were obtained for various parameters used for test runs such as suspended sediment median size \((d_{50})\), SSC, flow velocity and time as independent variables versus erosion weight loss. After these initial findings, a relationship in the form of eqn. (6) is obtained for parameters involved as it is evident from the literature [16,17] that the normalised erosion has multi-variate power relation with operating and sediment parameters. The normalised erosion makes the correlation independent of the initial weight of the turbine bucket and it was calculated with eqn. (7).

\[
\langle E_{BGi} \rangle_j = K \cdot (\text{SSC})^a \cdot (d_{50})^b \cdot (V)^c \cdot (t)^d
\]

(6)

\[
\langle (E_{n})_{BGi} \rangle_j = \frac{\langle E_{BGi} \rangle_j}{\langle W_{BGi} \rangle_{j-1}}
\]

(7)

where,

\[
\langle (E_{n})_{BGi} \rangle = \text{normalised erosion for } i\text{th bucket group}
\]
\((E_n)_{BG_i}\) = normalised erosion for ith bucket group after jth test run, 
\(W_{BG_i,j-1}\) = initial weight of bucket before jth test run or after (j-1)th test run, g, 
K = constant, 
SSC = suspended sediment concentration, ppm, 
\(d_{50}\) = median sediment size in a particle size distribution (PSD), mm, 
\(V\) = relative flow velocity, m/s, 
\(t\) = time duration of erosion, hours, and, 
\(a\), \(b\), \(c\) and \(d\) = exponents of SSC, \(d_{50}\), \(V\) and \(t\) respectively.

The relation shown in eqn. (6) was obtained using a least square multivariate regression analysis on logarithmic values of the normalised erosion and other parameters. Once the linear relation between those was obtained, antilog was taken to obtain the constant \(K\) and the exponents.

3. Results and discussions

In this section, the effect of various parameters such as SSC, PSD, erosion duration, erosion velocity and roughness of buckets on hydro-abrasive erosion are presented. Further, a correlation of normalised erosion with these parameters is developed for turbine designers to predict erosion of Pelton turbine in sediment laden flow conditions. The major eroded portions are splitter, cut-out and outer zone of curved portion of buckets similar to the patterns reported in literature [6,10,16]. The erosion behaviour of all three layers of Pelton buckets is similar to the patterns reported in literature [6,10,16]. The erosion behaviour of all three materials (BG2, BG3 and BG4) is similar whereas bronze (BG1) shows the most erosion for every operating condition. Among the two tested coating materials (BG5 and BG6), HVOF sprayed Cr2O3 coating revealed that the coating started to erode faster in the early test runs and the substrate material was exposed. The 13Cr-4Ni with WC-Co-Cr HVOF coating had the minimum amount of erosion among all tested materials; hence, it can be concluded that this coating is the better suited and more resistant to erosion among the two tested coatings. The performance of 13Cr-4Ni with plasma sprayed Cr2O3 coating revealed that the coating started to erode faster and the cavitation behaviour of this coating is poor. Among all the steels tested, the deviation of erosion was low. Hence, there is no substantial evidence to find a better response of various steel materials with respect to erosion. As the response to erosion was similar for all three tested types of steel, the selection should be based on other properties like response to corrosion, cavitation, weldability, cost etc. The relation of erosion with time and SSC was found in this research to be almost linear. Similar findings were also obtained by various researchers [16,17].

3.3. Effect of erosion exposure duration (t)

In order to find the effect of the exposure time on erosion, test runs were conducted in the laboratory for four different durations of 3, 6, 9 and 12 h at constant values of other parameters like 1500 ppm SSC value, (90–180) \(\mu\)m size range and flow velocity of 32.11 m/s. The erosion increased approximately linearly with the operating time for all materials; however, the rate of increase in erosion with respect to time was different for different materials (Fig. 5). This finding of linear variation of erosion with time is in accordance with findings in literature [8,16,17].

3.4. Effect of flow velocity (V)

In order to find the effect of velocity on erosion, test runs were conducted in the laboratory for four different velocities of 32.11, 28.97, 25.62 and 22.05 m/s at constant values of other parameters like 1500 ppm SSC value, 250–355 \(\mu\)m size range and operating duration of 3 h. Various velocities were obtained by varying the head of the pump from 200 m to 140 m of water column during the test runs. The erosion increased rapidly with velocity for all materials; however, the rate of increase in erosion with respect to velocity was different for different materials (Fig. 6). This finding is in accordance with the finding described in literature [8,16,17].

3.5. Correlation of normalised erosion

For normalised erosion, the obtained values of the constant and the exponents of eqn. (6) for various bucket groups i.e., BG1 to BG6 are given in Table 3.

The exponent of velocity for 13Cr-4Ni was obtained to be 3.47, a value similar to the value 3.4 proposed in IEC 62364 [8]. The correlation for coatings, especially BG5, should be interpreted with caution because the coating was removed after around half of the tests and the substrate material was exposed. The 13Cr-4Ni with WC-Co-Cr HVOF coating had the minimum amount of erosion among all tested materials; hence, it can be concluded that this coating is the better suited and more resistant to erosion among the two tested coatings. The performance of 13Cr-4Ni with plasma sprayed Cr2O3 coating revealed that the coating started to erode faster after a few tests, meaning that the erosion behaviour of this coating is poor. Among all the steels tested, the deviation of erosion was low. Hence, there is no substantial evidence to find a better response of various steel materials with respect to erosion. As the response to erosion was similar for all three tested types of steel, the selection should be based on other properties like response to corrosion, cavitation, weldability, cost etc. The relation of erosion with time and SSC was found in this research to be almost linear. Similar findings were also obtained by various researchers [16,17].

The deviations of observed and predicted erosion from the above equations were below 10% for most of the cases and followed a linear trend around 45\(^\circ\) as expected and shown in Fig. 7(a–b). However, few outliers fall around 15%. For coated buckets, the outliers have the maximum deviation about 20% as shown in Fig. 7b. This is because the substrate/base material also got eroded in those cases in which coatings were partially removed from few patches during last tests. The initial full coated buckets and completely removed coatings from few patches after a series of tests is shown in Fig. 8(a–b) for both coatings.

3.6. Relation of erosion and roughness

The measurement of the roughness was carried out after each
test and quantified with an arithmetic average line parameter (Ra), commonly used for roughness [24]. In this study, it was observed that the erosion had no significant effect on the variation of roughness of the samples. The roughness parameters were found to increase and decrease randomly slightly after tests for BG1 to BG4. This type of observation was also noticed in literature [25]. In case of coated buckets BG5 and BG6, the surface roughness decreased progressively at locations where the coating started getting removed. This surface smoothening of the removed coating kept going till it reached a steady state value similar to the uncoated bucket roughness values. The roughness of coated buckets was higher compared to uncoated buckets as commonly known. Among both coatings, BG5 had a higher roughness than BG6. In this study, it was observed that the progressing erosion had no significant effect on the variation of roughness of the uncoated samples as shown in Fig. 9, where the roughness parameter Ra is plotted with respect to particle load (PL) and particle size respectively.

4. Uncertainty analysis

The uncertainty in this research work is analysed using formulae given by Klein and McClintok [26], which estimates the uncertainty as per eqn. (8) to eqn. (10).

\[ Y = f(X_1, X_2, X_3, \ldots, X_n) \]  

\[ \delta Y = \sqrt{\left( \frac{\partial Y}{\partial X_1} \cdot \delta X_1 \right)^2 + \left( \frac{\partial Y}{\partial X_2} \cdot \delta X_2 \right)^2 + \left( \frac{\partial Y}{\partial X_3} \cdot \delta X_3 \right)^2 + \ldots + \left( \frac{\partial Y}{\partial X_n} \cdot \delta X_n \right)^2} \]  

\[ \% \text{ uncertainty (relative uncertainty)} = \frac{\delta Y}{Y} \cdot 100 \]  

where.

\( X_1, X_2, X_3, \ldots, X_n = n \) number of basic independent variables,

\( \delta Y \) = absolute uncertainty in measurement of \( Y \), which is a function of basic independent variables.
Fig. 4. Erosion versus particle size ($d_{50}$) for different SSC at fixed $V = 32.11$ m/s and $t = 3$ h.

(a) For SSC = 750 ppm

(b) For SSC = 1500 ppm

(c) For SSC = 3000 ppm

(d) Variation of erosion with particle size [22]

Fig. 5. Erosion versus time of operation at SSC = 1500 ppm, PSD = (90–180) μm and $V = 32.11$ m/s.

Fig. 6. Erosion versus velocity for SSC = 1500 ppm, PSD = (90–180) μm and $t = 3$ h.
\[\Delta X_1, \Delta X_2, \Delta X_3, \ldots, \Delta X_n = \text{possible error in measurement (absolute uncertainty) of basic independent variables}\]

### 4.1. Uncertainty in erosion measurement

The uncertainties in erosion measurement of model Pelton buckets in the laboratory using weighing method are as shown in Table 4.

With decrease in absolute value \(Y\), relative uncertainty increases as per eqn. (A3). That is why relative uncertainty of the minimum erosion of BG6 has a high value. The uncertainty in erosion measurement of Pelton buckets in the Toss HPP was in average less than 1% because the 3D-scanner used for measurement had high accuracy (below 8 \(\mu\)m) after calibration and overall accuracy of less than 20 \(\mu\)m.

### 4.2. Uncertainty in sediment parameter measurement

During gravimetric analysis of manual samples from Toss HPP, the calculated uncertainty in total suspended solids measurement (drying and filtering methods) was 1.77% due to use of a high precision weighing balance. The uncertainties due to sub-sampling, error in sample collection and flow variation, sample handling and storage were neglected.

### 5. Conclusions

In this study, the hydro-abrasive erosion in Pelton buckets has been analysed using an experimental approach. The experiments were performed on 1:8 scaled down model of Pelton buckets of an erosion affected prototype plant located in Indian Himalayas. Six
**Fig. 8.**

a: Progressive erosion and coating removal in BG5

b: Progressive erosion and coating removal in BG6

**Fig. 9.** Variation of roughness with particle load and sediment size for uncoated buckets.

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### Table 4

Uncertainty in measurement of erosion in buckets.

<table>
<thead>
<tr>
<th>Bucket group</th>
<th>BG1</th>
<th>BG2</th>
<th>BG3</th>
<th>BG4</th>
<th>BG5</th>
<th>BG6</th>
</tr>
</thead>
<tbody>
<tr>
<td>max (g)</td>
<td>1.0791</td>
<td>0.5232</td>
<td>0.5055</td>
<td>0.5067</td>
<td>0.3201</td>
<td>0.0511</td>
</tr>
<tr>
<td>min (g)</td>
<td>0.0736</td>
<td>0.0332</td>
<td>0.0326</td>
<td>0.0322</td>
<td>0.0213</td>
<td>0.0035</td>
</tr>
<tr>
<td>avg (g)</td>
<td>0.3557</td>
<td>0.1719</td>
<td>0.1652</td>
<td>0.1657</td>
<td>0.1112</td>
<td>0.0209</td>
</tr>
<tr>
<td>% uncertainty</td>
<td>max</td>
<td>0.01</td>
<td>0.03</td>
<td>0.03</td>
<td>0.03</td>
<td>0.04</td>
</tr>
<tr>
<td></td>
<td>min</td>
<td>0.19</td>
<td>0.43</td>
<td>0.43</td>
<td>0.44</td>
<td>0.67</td>
</tr>
<tr>
<td></td>
<td>avg</td>
<td>0.04</td>
<td>0.08</td>
<td>0.09</td>
<td>0.09</td>
<td>0.13</td>
</tr>
</tbody>
</table>
types of materials were tested in similar hydraulic conditions and it is found that the WC-Co-Cr coating applied through HVOF process performed best against hydro-abrasive erosion. The erosion model developed from this study showed good correlation with the experimental values and actual erosion obtained from field study. Use of such models by turbine operators will benefit in planning the erosion scheduling and turbine manufacturers may use it for prediction of erosion already at manufacturing stage.

In future, the developed models can be used for validation of CFD codes complemented with erosion models simulating hydro-abrasive erosion of Pelton turbine buckets. This in turn, will allow in a successive step of estimation of efficiency losses with time. The study of progressive erosion on reduction of efficiency of Pelton turbine and scheduling the repair works is also required. The developed models can further be applied to different case studies operating around world under wide range of operating conditions. As erosion is multi-parameter process, effect of one parameter on the other parameters need to be evaluated. Additionally, systematic experiments are required to study hydro-abrasive erosion on different parts such as the splitter, curved zones and the cut-out separately.

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Appendix A. Supplementary data

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