DEVELOPING A TEST RIG TO MEASURE HYDRO-ABRASIVE EROSION IN PELTON TURBINE

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ABSTRACT

The problem of hydro-abrasive erosion due to sediment is becoming more severe for hydropower plants owing to recent increase in energy demand especially in geologically young mountains, such as the Andes and the Himalaya and extreme flood caused due to climate change. In high head Pelton turbines, even small sediment particles cause critical hydro-abrasion. The effect of different parameters involved in hydro-abrasive erosion is not fully understood as the abrasion tests provide widely varying results. Though it is more appropriate to conduct an abrasion test that resembles the prototype plant conditions, but, no abrasion test rig is reported till now to provide reliable results. The paper presents recent hydro-abrasive studies in Pelton turbine followed with detailed discussion on approaches and findings. Based on the conclusions; a new test rig is proposed to simulate hydro-abrasive conditions in laboratory similar to Pelton turbine actually installed. The proposed study takes into consideration influencing factors like erosion velocity, sediment concentration and sediment size. The paper describes the test rig and erosion measurement methodology. The initial erosion measurement test using proposed methodology shows improved result in comparison to the other previously reported applied measurement techniques for hydro-abrasive erosion. The erosion methodology provides an added advantage of measuring depth and volume of erosion over an area of cross-section, which was not considered in case of weight loss method. This new test rig will facilitate the prediction of hydro-abrasive erosion in Pelton turbines.

Keywords: hydro-abrasive, erosion, turbine, sediment, measurement

1. INTRODUCTION

The rivers in geologically young mountains like the Andes and the Himalaya contain very high sediment concentration during the rainy season. According to Chakrapani and Saini (2009), 70–90% of annual sediment load is transported during 14–24 days of the monsoon season in the Himalayan region. The mountains offer majority potential sites for hydropower generation. The presence of high sediment concentration with hard mineralogical contents erodes the hydropower components. The development and operation of hydropower in fragile mountainous regions encounter the problem of hydro-abrasive erosion of turbine parts and hydraulic structures due to high sediment loads. The hydro-abrasive erosion becomes more prominent with increase in head because higher operating velocities are permitted for economic reasons in penstocks and turbines of high head hydropower plants. The erosive
effect is prominent in case of run-of-river hydropower plants as there is no or very less storage available to allow the settling of suspended sediment. High head Pelton and Francis turbines are most affected by hydro-abrasive erosion. Sometimes, the damage of turbine is extensive even after running one monsoon season. Mann (2000) classified the hydropower plants in India in three categories A, B and C based on their vulnerability to hydro-abrasive erosion and number of monsoon seasons required between repairs. Design of hydraulic structures and mechanical components as well as selection of materials requires the consideration of hydro-abrasive erosion.

The hydro-abrasive erosion is a complex process depending on many factors. The hydro-abrasive erosion of the surfaces due to sediment laden water depends on many factors such as (1) sediment characteristics (concentration, size, mineral composition, shape); (2) flow characteristics (flow velocity, angle of impingement, time of operation, effect of media, temperature etc.) and (3) properties of substrate materials (hardness, surface morphology, properties of the coating) (Thapa, 2004). Though the relevant parameters for hydro-abrasive erosion have been identified (Gummer, 2009; Winkler et al., 2011), but it is still not fully understood to which extent these parameters contribute to the hydro-abrasive erosion. While researchers (Boes, 2009; Abgottspon et al., 2013a) examined influences of some factors recently in prototype Pelton turbines, a general relation for the influences of each factor is still not available. The different types of abrasion tests like rotary disk type, slurry pot tester etc. provides highly varying results depending on the test conditions (IEC 62364, 2013). IEC 62364 (2013) recommend to select an abrasive test with test conditions similar to actual hydropower conditions. This paper presents a detailed review of recent erosion studies in Pelton turbine. The approaches adopted for measuring different factors such as sediment properties, hydro-abrasion of Pelton turbine, material aspects etc. and findings are also discussed. Based on the findings, a set-up is proposed which simulates similar erosion conditions as found in Pelton turbine buckets. Further, measurement of different parameters involved and expected outcome from this study, based on erosion models in literature, are also presented. Initial results from an optical scanning camera are provided to show its potential to measure erosion of small Pelton turbine bucket.

2. RECENT EROSION STUDIES IN PELTON TURBINE

Mainly three different approaches are adopted for erosion studies, viz. case study, experimental study and CFD study. In case studies approach, the erosion and its adverse effects like material loss, efficiency reduction etc. are studied in actual prototype plant. The case study represents actual extent of erosion in the most realistic way but do not include parameter variations. Moreover, the time involved to observe the erosion is high and erosion measurement is difficult. Though IEC 62364 (2013) proposed a theoretical model for estimating sediment erosion in prototype plants recently, few terms used in the standard, like the flow coefficient ($K_f$) and exponent of RS ($p$), are not provided for Pelton turbine erosion and other terms like $K_m$ for coating, $K_{shape}$ etc. are qualitative. The experimental study tries to replicates the erosion phenomenon in controlled laboratory set-ups. The parameters can be varied according to requirement and time involved is less. The erosion phenomenon is highly
dependent on type of erosion set-up so care must be taken to design the set-up as close as possible with actual erosion environment (IEC 62364, 2013). In CFD study, an erosion model is applied in numerical approach to predict the erosion. Two models, Finnie model and Tabakoff model, are widely used to simulate erosion in CFD software. Though flow in Pelton turbine is studied extensively using CFD (Perrig, 2007; Rygg, 2013), there is very little literature related to erosion studies in Pelton turbine using CFD. Different design and parameters variation can be incorporated in CFD studies but validation is required along with high computational computers and software.

Bajracharya et al. (2008) studied Pelton turbine erosion due to suspended sediment from the field survey of 22 MW Chilime hydropower plant in Nepal. The study found relationships between the erosion rate and the particle size at different quartz content levels as well as the erosion rate and the reduction in efficiency as follows:

\[ \text{Erosion rate (mm/year)} \propto a \times \text{size}^b \]  
\[ \text{For quartz content: } 38\% (a = 351.35, b = 1.4976), 60\% (a = 1199.8, b = 1.8025) \text{ and } 80\% (a = 1482.1, b = 1.8125) \]

The relation between the erosion rate and the reduction efficiency was given by:

\[ \text{Efficiency reduction } \propto 0.1522 \times \text{(Erosion rate)}^{1.6946} \]  

The major erosion parameters found were hard minerals (quartz, feldspar) content and increased sediment load during rainy season. The study revealed that the partial opening of needle resulted in more erosive wear. The methodology adopted to measure different parameters considered during the study is provided in Table 1. In another case study, Boes (2009) studied the sediment erosion problems in Pelton turbine of Dorferbach hydropower project by quantifying sediment parameters (SSC, PSD, sediment load, shape, mineral composition and hardness) with an optical backscatter turbidimeter and a laser diffractometer along with manual pumped sampling. For quantifying turbine erosion, regular turbine erosion rate measurement was performed with frequency once in a week or once bi-weekly. A relation was developed for erosion quantification at the Dorferbach HPP as follows:

\[ W [\mu m/h] = 7.56 \times 10^{-8} \times u^3 \times \text{SSC} \]  
\[ \text{for SSC } \leq 45 \text{ mg/l} \]

\[ W [\mu m/h] = 1.82 \times 10^{-8} \times u^3 \times \text{SSC}^{1.375} \]  
\[ \text{for SSC } > 45 \text{ mg/l} \]

where \( u \) is the relative jet velocity and SSC is the suspended sediment concentration.

Abottspoonet al. (2013) tried to quantify the erosion of Pelton turbine buckets by 3D-digitization of buckets of high head 2×32 MW HPP Fieschertal. The change in geometric profile of two selected buckets was obtained by optical scanner. The first measurement through the set-up showed the abrasion depth of approximately 8 mm due to a single storm in
August 2012. Various devices to measure SSC continuously were investigated in laboratory and installed at site. Erosion depth and volume of Pelton turbine buckets along with efficiency reduction were measured.

Liu et al. (2012) designed a rotating and jet experiment system with high flow velocity to study the anti-erosion performance of materials of three Pelton turbine components: nozzle tip, needle shaft and runner bucket. 8 different resultant velocities (V) in range 61.12 – 106.47 m/s were selected with sediment concentrations (C) varying between 720 - 12,590 ppm. The sediment size parameters used were $d_{50} = 33.111 \mu m$, $d_{\text{mean}} = 44.56 \mu m$ and range = 2.599 – 101.46 \mu m. The hydro-abrasive erosion (E) in Pelton turbine components found were as follows:

1. **Nozzle tip (ZG230-450):**
   
   \[ E (g/h) = 5.45 \times 10^{-9} \times V^{3.16} \times C^{0.98} \]  \hfill (5)

2. **Needle shaft (42CrMo):**
   
   \[ E (g/h) = 1.47 \times 10^{-9} \times V^{3.41} \times C^{1.02} \]  \hfill (6)

3. **Runner bucket (X3CrNiMo13-4):**
   
   \[ E (g/h) = 8.82 \times 10^{-10} \times V^{3.51} \times C^{1.01} \]  \hfill (7)

Padhy and Saini (2009, 2011, 2012) studied the effect of silt size (S), silt concentration (C), water jet velocity (V) and operating hours (t) on wear rate of small scale Pelton turbine made of brass along with impact on efficiency. Mechanisms of erosion were also discussed. The obtained relations for normalized erosive wear rate (loss of weight/original weight) (W) and percentage efficiency loss of rated efficiency ($\eta_p\%$) are as follows:

1. **Normalized erosive wear rate:**
   
   \[ W = 4.02 \times 10^{-12} \times S^{0.0567} \times C^{1.2267} \times V^{3.79} \times t \]  \text{(Error within ±6.7\%)} \hfill (8)

2. **Percentage efficiency loss:**
   
   \[ \eta_p\% = 2.43 \times 10^{-10} \times S^{0.099} \times C^{0.93} \times V^{3.40} \times t^{0.75} \]  \text{(Error within ±10\%)} \hfill (9)

Table 1 summarizes the details of parameters, measurement methodology and approach of hydro-abrasive erosion study in Pelton turbines.

**Table 1: Detailed summary of approach to hydro-abrasive erosion study in Pelton turbines: please hyphenate words correctly**

<table>
<thead>
<tr>
<th>S. No.</th>
<th>Researchers</th>
<th>Parameters considered in study</th>
<th>Measurement of parameters considered</th>
<th>Data analysis and presentation of results</th>
<th>Remarks</th>
</tr>
</thead>
</table>
| 1.    | Liu et al., 2012 | 1) Sediment concentration  
2) Erosion velocity and operating time | 1) Measured amount of sediment is mixed with known amount of water  
2) Weight loss  
3) Calculated during tests | Weight loss of 3 different materials are calculated per hour and related with concentration of sediment and velocity of erosion | Recirculation of sediment during experiments may have altered the sediment shape, mechanism of wear is predicted |
<table>
<thead>
<tr>
<th>S. No.</th>
<th>Researchers</th>
<th>Parameters considered in study</th>
<th>Measurement of parameters considered</th>
<th>Data analysis and presentation of results</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.</td>
<td>Padhy and Saini, 2009, 2011 &amp; 2012</td>
<td>1) Sediment characteristics (PSD, SSC, Mineral content and Shape) 2) Erosion 3) Head and discharge</td>
<td>1) Measured amount of sediment is mixed with known amount of water, other properties of sediment measured in laboratory before mixing 2) Weighing the buckets before and after erosion 3) Head: Pressure transducer before nozzle, discharge: v - notch</td>
<td>Weight loss of bucket is related to parameter variation such as SSC, sediment size and velocity during experiments. The efficiency loss of the turbine model is also related with parameter variations</td>
<td>Sediment is recirculated; the material of bucket was brass whereas in actual case it is steel in prototype plants, mechanism of wear is predicted</td>
</tr>
<tr>
<td>3.</td>
<td>Bajracharya et al., 2008</td>
<td>1) Sediment characteristics (PSD, SSC, Mineral content and Shape) 2) Erosion (wear depth and surface texture) 3) Analysis of flow of water through surface of needle</td>
<td>1) From samples collected and analysed in laboratory (PSD - Sieve analysis and visual accumulation tube, other properties – no details) 2) Using stylus probe, only 2 observations – after 1st and 2nd maintenance 3) Drawing flow net diagrams (full and half opening)</td>
<td>Sediment load calculated, sediment deposition volume in the reservoir is estimated, profile of erosion surface of spur needle for both units developed, relation of erosion in mm/year and respective efficiency loss established for the Chilime HPP</td>
<td>Manual sediment sample collection lead to erroneous sediment load in case frequency of water sample collection is not high, erosion measurement technique is cumbersome and time consuming, no erosion measurement of splitter and turbine bucket</td>
</tr>
<tr>
<td>4.</td>
<td>Boes, 2009</td>
<td>1) Sediment characteristics (PSD, SSC, Mineral content and Shape)</td>
<td>1) Continuous monitoring of SSC and PSD with optical backscatter turbidimeter and laser diffraction</td>
<td>Total sediment load derived, erosion velocity computed via net head, specific rate of sediment transport is</td>
<td>Splitter width is established as controlling measure for erosion, continuous monitoring of</td>
</tr>
<tr>
<td>S. No.</td>
<td>Researchers</td>
<td>Parameters considered in study</td>
<td>Measurement of parameters considered</td>
<td>Data analysis and presentation of results</td>
<td>Remarks</td>
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<tr>
<td>2)</td>
<td>Erosion (wear depth)</td>
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<td>3)</td>
<td>Flow and head</td>
<td></td>
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<tr>
<td></td>
<td>sensor along with regular conventional pumped sample (PSD – evaporation method and laser diffractometer, other properties – no details)</td>
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<tr>
<td>2)</td>
<td>Runner bucket geometry and splitter (weekly or bi-weekly), 17 erosion measurements of bucket performed</td>
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<td>3)</td>
<td>Flow: Ultrasonic flow meter and head: pressure measurement data</td>
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<td></td>
<td>shown by gradient of cumulative suspended load line, relation between mean sediment diameter and SSC established, an erosion relation for Dorferbach HPP is derived</td>
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<td>5.</td>
<td>Felix et al., 2012</td>
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<td>&amp;Abgottspon et al., 2013a,b</td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>1)</td>
<td>Sediment characteristics (PSD, SSC, Mineral content and Shape)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2)</td>
<td>Erosion (wear depth and surface erosion)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3)</td>
<td>Efficiency of turbine</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1)</td>
<td>5 different types of turbidimeters, acoustic method and a laser diffractometer to measure sediment properties</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2)</td>
<td>Optical scanning camera (3D digitization of two Pelton buckets) and a thickness gauge for coating index efficiency measurement</td>
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<td></td>
<td>Different possibilities of geometric changes due to erosion like reduction of splitter height, increase of splitter width, volume difference etc. are presented along with efficiency decrease, sediment load and operating time</td>
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<tr>
<td></td>
<td>Different possibilities with use of optical scanner for erosion measurement is presented along with suggestion that splitter width can provide easy way to relate erosion with other parameters practically</td>
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</table>

3. **EXPERIMENTAL SET-UP**

Actual erosion of the hydro turbine is a slow process. It takes at least one monsoon season to observe the effect of sediment erosion. Moreover, monitoring suspended sediment properties like concentrations, size distributions, shape etc. along with erosion of turbine is still not common practice (IEC 62364, 2013). Thus, it is very difficult to obtain any quantitative
relation between parameters involved and erosion of turbine from prototype plant erosion. Most expressions for the hydro-abrasive erosion found in literature are based on experimental experience. Experience shows that the abrasion tests give widely varying results depending on different test rigs, erosion velocity, impact angle, composition, concentration and size of particles, etc. (IEC 62354, 2013; Thapa, 2004). Additionally, the existing data from experiments is difficult to transfer to the prototype due as most previous and existing test rigs do not simulate the conditions in the prototype. Hence, a test method resembling the conditions in a prototype plant as closely as possible is required for analyzing the impact of sediment erosion in Pelton turbines.

Researchers tried to address hydro-abrasive erosion issue using slurry pot tester (Desale et al., 2009; Amarendra et al., 2012 etc.) and jet type erosion tester (Thapa et al., 2012, Winkler et al., 2011 etc.). The slurry pot testers do not simulate erosion condition of Pelton turbines 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, Coriolis force etc., which are only present in the rotating frame. Moreover, factors like Coanda effect on backside of buckets (Perrig, 2007) and secondary erosion (cavitation) do not exist in these set-ups, but are encountered in prototype plants. To include the effects of dynamic conditions, some researchers (Khurana et al., 2013; Padhy and Saini, 2009 etc.) used model impulse turbines as test rig for hydro-abrasive erosion. However, these studies involved high sediment concentration and soft material brass specimens during experiments to get reasonable amount of erosion in less time. These conditions differ considerably from prototype plant operation where the plant is shutdown at concentrations higher than 3000 ppm to reduce hydro-abrasive erosion (Dahl, 2014). Moreover, a hard material like martensitic steel is used for turbine blades. Brekke in Duan and Karelin (2002) explained that different materials in similar flow conditions exhibit different erosion behavior (also mentioned in IEC 62364, 2013). Hence, erosion results from brass sample cannot be applied to estimate hydro turbine steel erosion in actual condition. Moreover, the studies have not made any attempt to correlate the erosion of brass and turbine steel in the experimental set-up to make the outcome applicable. To obtain results applicable for prototype plants, the test set-up proposes to use turbine materials like 13Cr4Ni, 16Cr5Ni martensitic steel etc. for testing purpose.

The hydro-abrasive erosion in the proposed experimental set-up is similar to erosion in Pelton turbines with respect to parameters like sediment properties (concentration, size, shape and mineral composition), material of bucket, and flow conditions. The jet velocity in erosion test is designed to be in the range 60 – 70 m/s. The estimated time required for erosion of martensitic steel buckets is high of the order of 12 to 48 hrs. to get measurable amount of erosion. The proposed set-up consists of a Pelton turbine designed in accordance with IEC 60193 (1999) as shown in Fig. 1. The minimum values for model size and test parameters are kept as per IEC 60193 (1999) as given below for Pelton turbine:

- Minimum bucket width required = 0.08 m
- Minimum Reynolds number, Re = 2·10^6
- Specific hydraulic energy (per stage), E = 500 J/kg
Fig. 1: Schematic of the experimental set-up

The Fig. 1 shows the schematic of the proposed experimental set-up. A calculated amount of sediment will be stirred continuously with a motor (8) in a water in tank (7) of known volume to obtain a suspended sediment mixture of known properties. This suspended sediment mixture will be delivered to the turbine (1) under designed head and discharge created with the pump (9) and controlled with the valves (10). Two control valves will allow precise control of flow and head. The discharge and head to the turbine will be measured with ultrasonic flowmeter (11) and pressure gauge (4), respectively. The control panel (6) will dissipate the generated electricity from generator (5). The water will be recirculated in the closed loop system.

There is no method mentioned in literature which can exactly predict hydro-abrasive erosion expected in the proposed set-up. The expected erosion depth from the proposed set-up is calculated using IEC 62364 with reasonable assumption of unknown parameters like the flow coefficient ($K_f$) and RS exponent ($\alpha$). The assumed values of different constants are shown in Table 2. The expected erosion depth of Pelton bucket in proposed set-up predicted from IEC 62364 is given in Table 3 for different test trials assumed. Table 3 also presents the expected weight loss of the Pelton buckets as per modified model of Liu et al. (2012) in mg. The model of Liu et al. (2012) is modified in the calculation because sediment of different size properties are expected to be used.

<table>
<thead>
<tr>
<th>$K_{size}$</th>
<th>$K_{shape}$</th>
<th>$K_{hardness}$</th>
<th>$K_m$</th>
<th>$K_f$</th>
<th>RS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Abrasive co-efficient</td>
<td>Abrasive co-efficient</td>
<td>Abrasive co-efficient</td>
<td>Material co-efficient</td>
<td>Water flow co-efficient</td>
<td>Reference size</td>
</tr>
<tr>
<td>0.425</td>
<td>1.5</td>
<td>0.73</td>
<td>1</td>
<td>1.0E-06</td>
<td>0.08</td>
</tr>
</tbody>
</table>
Table 3: Different parametric variations and corresponding estimated hydro-abrasive erosion from IEC 62364 and Lie et al. (2012) models (please hyphenate correctly)

<table>
<thead>
<tr>
<th>Trial no.</th>
<th>W</th>
<th>Cn</th>
<th>PL</th>
<th>S (Erosion depth) for different time of erosion (Ts) as per IEC 62364</th>
<th>Erosion weight loss as per modified Liu et al. (2012) model</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Erosion velocity</td>
<td>Sediment concentration</td>
<td>Particle load calculated for 48hrs.</td>
<td>Ts = 48 hrs</td>
<td>Ts = 24 hrs</td>
</tr>
<tr>
<td>test no.</td>
<td>m/s</td>
<td>kg/m³</td>
<td>kg * h/m³</td>
<td>mm</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>30</td>
<td>0.5</td>
<td>11.169</td>
<td>4.2</td>
<td>2.1</td>
</tr>
<tr>
<td>2</td>
<td>30</td>
<td>1.5</td>
<td>33.507</td>
<td>12.47</td>
<td>6.23</td>
</tr>
<tr>
<td>3</td>
<td>30</td>
<td>3</td>
<td>67.014</td>
<td>24.94</td>
<td>12.47</td>
</tr>
<tr>
<td>4</td>
<td>32.5</td>
<td>0.5</td>
<td>11.169</td>
<td>5.46</td>
<td>2.73</td>
</tr>
<tr>
<td>5</td>
<td>32.5</td>
<td>1.5</td>
<td>33.507</td>
<td>16.37</td>
<td>8.18</td>
</tr>
<tr>
<td>6</td>
<td>32.5</td>
<td>3</td>
<td>67.014</td>
<td>32.74</td>
<td>16.37</td>
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<tr>
<td>7</td>
<td>35</td>
<td>0.5</td>
<td>11.169</td>
<td>7.02</td>
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<tr>
<td>8</td>
<td>35</td>
<td>1.5</td>
<td>33.507</td>
<td>21.06</td>
<td>10.53</td>
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<tr>
<td>9</td>
<td>35</td>
<td>3</td>
<td>67.014</td>
<td>42.12</td>
<td>21.06</td>
</tr>
</tbody>
</table>

4. EROSION MEASUREMENT METHODOLOGY

In prototype plants, thickness reduction is generally measured using calipers during the maintenance periods and hydro-abrasive erosion quantity is estimated (Thapa, 2004). In experimental set-ups, the loss in thickness is very little so hydro-abrasive erosion is measured in terms of weight loss (Padhy and Saini, 2009). The process of thickness measurement is tedious and time-consuming. Moreover, higher accuracy of erosion data requires erosion measurement at more points on the profile. IEC 62364 (2013) suggested to measure Pelton bucket erosion by using templates at minimum 5 points per half bucket and at least 3 locations (front, middle and back). Further, photographing the eroded bucket is suggested for records. This paper proposes to measure erosion of Pelton turbine with the help of a line-of-sight optical scanning camera along with weight loss measurement. These two independent methods of erosion measurement will give higher confidence in measured values.

An optical scanning camera Comet L3D (Make: Steinbichler) with a resolution of 1 megapixel in a measurement volume of 92 x 69 x 60 mm³ and 3D point distance of 79 µm is selected for the proposed study. The overall accuracy of the system was within 20 µm and measurement time of 2.5 sec. Abgottspon et al. (2013a, b) used similar optical camera to digitize two Pelton buckets in situ in the hydropower plant of Fieschertalin Switzerland. To check the capability
of aforesaid optical scanning camera for measuring erosion of small Pelton bucket in the experimental set-up, an erosion measurement test on a Pelton bucket was conducted. The bucket with inner width of 46mm was chosen and 3D digitized with the optical scanning camera as shown in Fig. 2a. Further, the bucket was slightly eroded manually with a grinding wheel in the order of 0.5 - 1 mm thickness reduction and again 3D digitized with the optical scanning camera as shown in Fig. 2b. The Pelton bucket is weighed both before and after erosion with a weighing balance (Make: Samson) having least count of 0.01 gm and maximum weighing capacity of 300 gm.

The density of Pelton bucket material is calculated by dividing the initial mass with the initial volume obtained from the 3D digitized uneroded bucket. The erosion volume obtained from 3D digitized bucket profiles before and after erosion is multiplied with obtained density to obtain mass loss. This calculated mass loss is compared to the mass loss obtained from the weighing balance. The thickness loss over the profile of the Pelton bucket is measured from software Inspect plus provided with optical scanning camera as shown in Fig. 3. The software has the provision to analyse erosion at any desired cross-section which is shown in Fig. 4.

![Fig. 2: Pelton bucket digitized with the 3D optical scanning camera before and after erosion](image)

![Fig. 3: Thickness loss over the profile of the Pelton bucket](image)
5. RESULTS AND DISCUSSIONS

The pelton turbine shown in Fig. 2a is eroded by 0.7% to obtain the eroded profile shown in Fig 2b. The volume of the digitized 3D scans as shown in Fig. 2 is calculated as below:

\[
\begin{align*}
\text{Volume of the uneroded bucket: } V_1 & = 16.478 \text{ cc} \\
\text{Volume of the eroded bucket: } V_2 & = 16.376 \text{ cc} \\
\text{Hence, the erosion volume: } \Delta V & = V_1 - V_2 = 0.102 \text{ cc}
\end{align*}
\]

The mass measured before and after erosion is as follows:

\[
\begin{align*}
\text{Mass of the uneroded bucket: } M_1 & = 54.77 \text{ gm} \\
\text{Mass of the eroded bucket: } M_2 & = 54.38 \text{ gm}
\end{align*}
\]

Hence, the erosion mass measured by the weighing balance: \( \Delta M_{\text{weighing}} = M_1 - M_2 = 0.39 \text{ gm} \)

The erosion mass loss from 3D digitized scans: \( \Delta M_{\text{3D scan}} = \Delta V \cdot \left( \frac{M_1}{V_1} \right) = 0.34 \text{ gm} \)

The density of material was not known, so it was calculated as \( \frac{M_1}{V_1} \). The difference in measured erosion mass loss values can be attributed to factors like less resolution of weighing balance (10 mg) and unknown value of density. A weighing balance with least count 0.1 mg and material of known density is expected to improve results. The comparison of surface profile at specific points are marked with flyers (what is meant with flyer??) which represent the co-ordinates of the points with respect to a coordinate system XYZ shown in Fig 3. The deviation of the respective coordinates are shown in flyers along with 3D deviation. The erosion depth varies up to 1.2 mm. Fig. 4 shows erosion depth at a specific cross-section having maximum erosion depth.

The measurement of erosion with optical scanning camera allowed to measure volume loss due to erosion along with other measurement possibilities like splitter thickness increase, depth of erosion at any desired point and mass reduction. The fast response time allows to capture images rapidly. Abgottspon et al. (2013a, b) used this system to measure erosion of Pelton buckets with inner width 650 mm whereas this study shows result of a Pelton bucket.
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having width 46 mm. However, the optical scanning camera is line-of-sight type so it is not capable of measuring hidden geometry parts. In case of Pelton buckets, it has potential to quantify erosion even for smaller buckets. A laser diffractometer (LISST-Portable) will be used during experiments to regularly monitor the sediment properties like sediment concentration and size. In case the size of sediment breaks down below the expected limit, the sediment will be replaced.

6. CONCLUSION

The sediment erosion in hydropower plants is a complex phenomenon, which depends upon different parameters such as sediment size, hardness and concentration, velocity of water, and base material properties. Various researchers have conducted experiments to study the effect of these parameters on hydro-abrasive erosion. The developed erosion relations give wide variations in predicting erosion due to the variation of conditions existing in prototype plants. This study identified the important parameters for erosion of Pelton buckets and based on those parameters, an experimental set-up has been proposed to simulate erosion conditions of prototype plant. A method for 3D digitization of Pelton buckets has been proposed and initial results have been presented. This approach has been found to provide small erosion as expected in our experimental set-up. Further research is needed to check the accuracy of this scanner for the future erosion study of Pelton buckets.

REFERENCES