Optimization of Hydropower Plants Regarding Hydro-abrasive Erosion

Article in International Journal of Fluid Machinery and Systems - June 2019
DOI: 10.5293/IJFMS.2019.12.2.119

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Optimization of Hydropower Plants Regarding Hydro-abrasive Erosion

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Abstract

The hydro-abrasive erosion poses challenges for smooth and efficient operation of existing hydropower plants (HPPs) as well as planning for new HPPs. The loss in revenue is caused due to reduced generation on account of reduced efficiency, down time for repair and maintenance for restoring the machinery and other components. In this study, various optimization considerations required with respect to hydro-abrasive erosion at both the planning and the operation stage of a HPP are presented. The factors involved in each steps like unit sizing, selection and design of turbines, capacity of desanders, cut-off limits of sediment concentration for turbine switch-offs, preventive measures such as coatings etc. were discussed. Further, a case study of an operational HPP located in Indian Himalayas is presented where suspended sediments, hydro-abrasive erosion and reduction in efficiency were measured simultaneously. Available models were used with measured values to obtain various losses due to hydro-abrasive erosion. The cost of coating, a preventive measure, is compared with the losses in operating the uncoated turbine. A decision making criterion is also introduced.

Keywords: Hydraulic Turbine; hydro-abrasive Erosion; Suspended sediment; Efficiency; Optimization; Hydropower

1. Introduction

In geologically young mountains like the Andes and the Himalaya, high sediment content during high flow season causes hydro-abrasive erosion of hydraulic turbine and other components of a hydropower plant (HPP) coming in contact with the flow [1-4]. It leads to gradual reduction in efficiency of the turbine due to a change in profile of the turbine blades and other components such as guide vanes, nozzle rings, nozzles etc. The loss in revenue is caused due to reduced generation on account of reduced efficiency, replacement of HPP components, down time for repair and maintenance to restore the machinery and efficiency. It is challenging to assess the amount of erosion in a specific duration of turbine operation and respective efficiency reduction. Researchers attempted to quantify the loss of efficiency due to erosion through development of erosion models [5-7]; however, verification and broad acceptance of the developed models still remain in progress as the models were developed for specific laboratory or field conditions.

The reduction in efficiency of the turbine due to hydro-abrasive erosion is widely reported in literature. Through thermodynamic efficiency tests of a Francis turbine in Jhimruk HPP (3×4 MW), Pradhan et al. [8] observed reduction of 4% in efficiency at the best efficiency point (BEP) within a duration of 11 weeks. Out of the reduced efficiency, 50% and 25% were contributed from the leakage at labyrinth seals and erosion in guide vanes respectively. From analysis of erosion and suspended sediments inflows in a Pelton turbine of Chilime HPP (2x11 MW), Bajracharya et al. [5] predicted a reduction of 1.21% in turbine efficiency during the first year of operation whereas projected the reduction of 4% for the consecutive year. In an extensive erosion study, Felix et al. [1] and Abgottspen et al. [9] measured the change in Pelton turbine efficiency caused by erosion and restoration of bucket profiles with grinding work at Fieschertal HPP (2×32 MW) from the year 2012 to 2016. Due to a major sediment event of 20 g/l SSC in 2012, the splitter height was found to reduce by 3 to 5 mm [1].

The decision of repair, maintenance and replacement of various components is a challenging task for plant operators of HPPs operating in erosive conditions. Thapa [10] discussed the economic aspects of HPPs due to erosion and recommended a long term monitoring approach to find the optimal operating regime for a HPP. Repair of eroded turbines is a labor-intensive work; hence cost of maintenance varies in different parts of the world depending upon wages [10]. In the Himalayan region, the hydropower companies usually prefer to repair the turbine rather than to replace them because of low labour cost which is in the range of 10% to 15% of the

Received January 30 2019; accepted for publication April 1 2019: Review conducted by Yoshinobu Tsujimoto. (Paper number O19034S)
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* Part of this paper was presented at the 29th IAHR Symposium on Hydraulic Machinery and Systems, held at Kyoto, Sept. 16-21st, 2018.
replacement cost. Regular inspections are recommended to find out the repair cycle [10-11]. The operation and maintenance cost for HPPs increases over the period of time and the rate of increment is high in case of erosion. The restoration of the output can be achieved with rehabilitation to initial rated output and can even be increased by redesign in some cases [12-13].

In present study, various factors required to be considered from hydro-abrasive erosion aspect in the planning, design and operation of a HPP are presented and discussed. The preventive measures like hard coatings to be applied to reduce the gradual reduction in efficiency and its consequences like a minor loss of efficiency are also discussed. As the methods to implement and figure out optimal steps for a HPP require a multi-disciplinary approach, a systematic approach at every level may lead to selecting suitable preventive and curative measures to mitigate financial losses. Further, a case study of optimization of an operational HPP located in Indian Himalayas and severely affected by hydro-abrasive erosion is provided. Various losses were calculated from experience of the HPP, available models and simultaneous measurements of suspended sediments, hydro-abrasive erosion and reduction in efficiency. A decision making criterion is suggested for operational plants to handle erosion issue effectively.

2. Optimization considerations

The financial considerations for erosion in a HPP can be carried out at both planning as well as operation stage. At planning stage, the extent of erosion at a proposed site for development can be obtained with measurement of suspended sediment inflow over a period of time and using various erosion models available in literature [4-6, 11]. At operation stage, the experience of erosion in various components along with available models can allow an accurate estimation of erosion in future. Further, economically limiting value of SSC for stopping the turbine to avoid severe erosion can be estimated precisely based on the erosion estimates. The optimization considerations to be taken into account at both the planning and the operation stage of a HPP are shown in Fig. 1 along with the factors, which guide the selection of each step.

![Fig. 1 Optimization considerations for erosion issues in HPP](image)

2.1 Planning stage of HPP

The information about extent of erosion at the planning stage of a HPP will be helpful in proper layout of the plant, selection of turbine type, design of turbine components as well as hydraulic structures such as desilting and water intake arrangements. These decisions affect the financial health of the plant during the entire life of the plant. It is well known that the turbine efficiency reduces considerably at part load, especially for Francis turbines. Due to synergic effect of cavitation and abrasive erosion, the susceptibility to erosion increases at part load [5, 14, 15]. To increase the availability of turbine units to operate at full load, the number of units can be increased and selectively repaired to minimize the maintenance time [14]. However, this strategy of increasing number of units will result in smaller units in a plant which may be prone to relatively higher erosion due to smaller radius of curvature [15]. Hence, an optimization study should be performed for each individual plant to obtain a better solution already at the planning stage of power plants at erosion prone sites.

2.2 Operation stage – repair, maintenance and replacement

Various problems arise in the operation of a hydropower plant due to hydro-abrasive erosion such as excessive vibration and noise, drop in efficiency/power generation and malfunctioning of instruments installed for monitoring discharge, pressure etc. in the plant. It is necessary to monitor the extent of erosion in turbine components at regular intervals (dependent on the site condition and past
experiences) to limit the erosion to such an extent that the repair of the eroded part is feasible [10-11]. Delaying the repair may increase risk of unplanned outage, increased overhaul cost and even make the component irreparable due to excessive damage (Fig. 2).

Fig. 2 Severely eroded uncoated runner after 1 high flow season – (a) Toss HPP and (b) Malana HPP [12]

The maintenance cost includes the cost of material, manpower and downtime. The type of maintenance decisions required for eroded part can be classified in three major classes [11].

- Overhaul: Restoration of entire part of the eroded turbine/components to the original geometry
- Replacement: Installing a new turbine/components in place of the eroded one
  - Installing new turbine/components with same geometry as the original one
  - Uprating the power plant to get higher power output and efficiency
- Repair: Local treatment of turbine/components at eroded areas to the following extent:
  - Repair A: Improve hydraulic shape just by grinding
  - Repair B: Restore hydraulic shape by welding and grinding
  - Repair C: Re-apply coating on prepared surface, after possible repair A or B

The restoration of the output can be achieved with repair to initial rated output and can even be increased by redesign in some cases as shown in Fig. 3 [12, 13, 15].

Fig. 3 Increase in power output of Alfalfal HPP, Chile due to uprating with enhanced coatings [12]

The optimization of repair and maintenance with the decision of replacement, if any, requires the cost of the repair technology, downtime during repair, amount of investment for material and labour. The eroded turbine is repaired by welding with suitable electrodes and grinded to obtain the initial profile of blade or bucket. Further, the repaired runner goes through the process of heat treatment to relieve stresses during welding and grinding processes. The challenge for the repair of eroded turbines is to select and use the proper type of welding and coating material to get the best performance from the turbine.

2.3 Design stage - Numerical/CFD analysis to improve blade/bucket

Recently, researchers used computational fluid dynamics (CFD) to optimize the profile of the turbine blade to reduce erosion as well as obtaining the highest possible efficiency [17-18]. The design of turbine is often modified, even with minor loss of initial efficiency, to cope with hydro- abrasive erosion and to maintain the profile for longer duration in erosive conditions. Researchers attempted to develop hydro-abrasive erosion resistive turbines, especially Francis turbine, to mitigate erosion [17-18]. The philosophy behind such attempts is to modify the profile of turbine in such a way that velocity component of suspended particles towards blade surface is reduced to the minimum value. Khanal et al. [17] provided a methodology to improve the erosion susceptibility of Francis turbines and showed numerically that the modified blade has 31.5 times less erosion rate than the original profile with 0.25% change (reduced) in efficiency. Similarly, Mangla [18] found 50% improvement in erosion rate co-efficient with a modified profile of a Francis runner.
Model tests confirmed only a minor loss of 0.3% efficiency at peak efficiency. The effect of such modified surfaces on erosion in actual HPP is not reported.

2.4 Preventive measure - hard coatings

Hard coatings are applied as a preventive measure to reduce the gradual decrease in the output of HPPs due to erosion. When a coating is applied on turbine surfaces, a minor amount of efficiency is also lost due to higher roughness of coated surface; however, the loss of efficiency of uncoated turbine due to erosion decreases faster over the period of operation (Fig. 4). Thus it is economical to apply coating on turbine components susceptible to erosion. The efficiency of coated turbines also decreases over the period of time after a first period of efficiency increase due to smoothing of the surfaces, but the rate of decrease of a coated turbine is much less compared to an uncoated turbine. The nature of rate of decrease depends on several factors such as coating properties, particle properties and operating conditions. The relative gain in efficiency increases generation benefits and repair interval.

Fig. 4 Efficiency loss due to erosion in uncoated and coated turbines of Pradella HPP, Switzerland [14]

The repair of coated turbine is a tedious task as it requires the removal of remaining coating after the erosion [4]. The removal of remaining coating requires highly skilled personnel. High velocity water jet is used to remove the remaining coating. About 5 mm of base material is also needed to be removed from the turbine surface for recoating, which increases the cost of the process. For uncoated turbine, the repair work can be directly done on the surface of runner which saves cost and time.

3. Case study

3.1 Site description

The study HPP, Toss HPP (2×5 MW), is located in the Himalayan hills of Kullu district in Himachal Pradesh, India, at the river Tosh, a tributary of Parbati River. The plant has two vertical 4-jet Pelton turbine units installed with a design head of 174 m and a unit discharge of 3.5 m³/s. In Unit-1, the buckets of the Pelton turbine were uncoated whereas buckets were coated in Unit-2. The combined desilting tank and forebay of the HPP are designed to remove sediments with particle size greater than 200 µm.

3.2 Methodology

Simultaneous measurements of suspended sediment, hydro-abrasive erosion and efficiency reduction were performed in study HPP [2-4]. The obtained values were used to calculate various losses due to hydro-abrasive erosion detailed as follows:

1. Gradual efficiency drop loss - Reduction in electricity production due to reduced turbine efficiency
2. Downtime loss - No electricity production during shutdowns on account of dismantling, replacements and reinstallations
3. Repair loss - Repair cost to restore the turbine, especially welding and grinding
4. Heat treatment, balancing and transportation loss - Cost of heat treatment and balancing including cost of transportation, as required
5. Replacement loss – Cost of new runner and other components in case of replacement
6. Non-compliance loss - Penalty on account of non-compliance with generation plan

In addition to these components, the optimization consideration with respect to erosion requires the calculation of preventive measures like coating of turbine and its components, increasing the storage capacity of the desilting arrangement to remove finer particles efficiently and catchment area treatment to reduce soil erosion [13, 15]. These preventive measures are also discussed.

3.2.1 Calculation of gradual efficiency drop loss

The losses in electricity generation due to gradual decrease in efficiency were assessed with four efficiency reduction models. The models were calibrated with respect to the study HPP by obtaining reduction in efficiency of the Unit-I from measurement of the unit efficiency two times – (a) before the start of the operation on 5th May 2015 and (b) before a major overhaul and replacement of eroded components on 24th July 2015. These plant specific calibrated models were used for obtaining the gradual loss of efficiency and electricity in the study HPP [19].
3.2.2 Calculation of downtime loss

Downtime of the plant machinery may be due to several reasons like fault in power evacuation, scheduled outage, forced outage due to failure of a component and operational measures like stopping the plant at limiting value of SSC in inflows. In the financial analysis, only the downtime due to erosion problems has been considered. During lean season when the available water can be entirely used for generation using other operating units and no surplus water is wasted. This is the ideal time for repair and maintenance as it amounts to no loss of electricity generation.

3.2.3 Calculation of repair loss

The repair of eroded turbines consists of mainly two processes (a) welding - to fill the material removed by erosion and (b) grinding - to restore the original profile from the deposited weld material. For obtaining the rate of various repairs, the turbine manufacturers in India were contacted. With increased erosion duration, the amount of material removed and the cost of welding increase. The cost of welding depends on the instances of repair whereas the cost of grinding remains constant as the surface area of the turbine parts to be ground generally remains constant even when the entire surface encounters erosion.

3.2.4 Calculation of heat treatment, balancing and transportation losses

After welding a heat treatment, which usually cannot be done on site, is needed. The costs involved remains constant for (a) heat treatment and balancing of the entire runner and (b) for transportation of the turbine from the HPP to the runner balancing site. These costs, dependent on the location of the HPP and its accessibility, were obtained from the history of the study HPP.

3.2.5 Calculation of replacement loss

The turbine runner is preferred to be repaired in Himalayan region because of lesser labour cost [10]; however, other components such as nozzle, nozzle rings, guide vanes, labyrinth rings etc. are replaced with new ones. In excessive damage of turbines, the old eroded runner also requires to be discarded and replaced by the new runner. For the study plant, the cost of various components and its replacement frequency was obtained from the history of the plant.

3.2.6 Calculation of non-compliance loss and preventive measures cost

There may be a penalty for non-compliance with the generation plan i.e., disability to generate electricity as projected by the regulating agency due to erosion or failure of a component. The practice of shutting down a plant above a limiting value of SSC for avoiding erosion may also induce non-compliance losses.

In view of availability of 3 months data, the coating option has been explored as a preventive measure in the study plant. The cost of per unit area for coating using high velocity oxy fuel (HVOF) process is obtained from turbine manufacturers and is used with the surface area calculated from 3D-scanned images of Toss HPP buckets to obtain the cost of coating the turbine.

3.3 Results and discussions

For the study plant, the results of financial analysis are presented here for each cost component.

3.3.1 Efficiency of the turbine unit

For the turbine unit with uncoated buckets, the relative efficiency scaled with highest efficiency before erosion is shown in Fig. 5. The uneroded turbine in Fig. 5 refers to the turbine installed in the unit on 5th May 2015 and the eroded turbine refers to the turbine eroded till 24th July 2015. The efficiency drop of the unit was in the order of 6% at the range of 60% to 80% load and the efficiency drop increased rapidly for higher loads due to excessive leakage of water. The discharge required for power produced increases rapidly above 82% power. Due to vibration and safety concerns, the efficiency testing was limited to maximum load of 91% at 4 nozzle opening for the eroded turbine. Similar drop in efficiency of 4% of the turbine unit in Jhimruk HPP was observed between 1st September and 11th November 2003 [8].

3.3.2 Loss due to gradual efficiency reduction

The gradual loss of efficiency during the measurement period, obtained from four different models, is presented in Fig. 6. The rate of efficiency loss due to erosion was initially less and increased to the maximum at the final part of the study as shown with gradients of straight lines in Fig. 6. This variation was caused by the higher SSC values in the inflows.
The loss of electricity generation due to this gradual reduction in efficiency of the turbine unit was calculated assuming the plant to be operational at full load during the 12 week study duration. The loss of energy units (kWh) was calculated as per four models chosen for gradual efficiency reduction calculation and is shown in Fig. 7.

The shut-downs of the plant due to power line maintenance or some forced reasons were taken into account. The valleys in Fig. 7 were formed due to the intermediate shutdowns due to reasons other than erosion. As these shut-downs were not caused by erosion, these were excluded in financial analysis of erosion in the plant. The electricity generation lost due to gradual efficiency decrease is given in Table 1.

**Table 1** Energy loss in the plant unit with uncoated buckets from 5th May to 24th July 2015

<table>
<thead>
<tr>
<th>S. No.</th>
<th>Model applied</th>
<th>Electricity generation loss (kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Bajracharya et al. [5] model</td>
<td>107,500</td>
</tr>
<tr>
<td>2</td>
<td>Modified Takgi et al. [20] model</td>
<td>135,000</td>
</tr>
<tr>
<td>3</td>
<td>Particle load model from IEC 62364 [11]</td>
<td>152,500</td>
</tr>
<tr>
<td>4</td>
<td>Suspended sediment load model</td>
<td>150,500</td>
</tr>
</tbody>
</table>

### 3.3.3 Loss due to downtime

The operators of the study plant maintained the inventories of spares for each component susceptible to erosion especially spear head, nozzle ring, nozzle shield and turbine runner available for replacement from their past experience. The spares available for replacement reduced the downtime effectively. Moreover, all the components except the runner were replaced since replacement was relatively more economical than the repair. The spear head and nozzle ring were eroded in axial direction with thin eroded lines along its surfaces similar to erosion patterns reported in literature [5, 21]. The time required for changing various turbine components, their major issues and frequency of change for the study plant is obtained from plant experience and is provided in Table 2. As per values from the Table 2, the total downtime for the major overhaul at the end of 23rd July 2015 was 12 hours.
### Table 2 Time to change various eroded components of runner at Toss HPP

<table>
<thead>
<tr>
<th>Sl. No.</th>
<th>Turbine part</th>
<th>Major issues</th>
<th>Time required</th>
<th>Detection criteria</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Runner</td>
<td>Highly eroded after each high flow season</td>
<td>24 hours</td>
<td>Visual inspection</td>
<td>Changed every year</td>
</tr>
<tr>
<td>2</td>
<td>Nozzle ring</td>
<td>No pressure building, sediment erosion</td>
<td>5 hours</td>
<td>Visual inspection and working condition</td>
<td>Frequent change once or twice/year</td>
</tr>
<tr>
<td>3</td>
<td>Nozzle spear head</td>
<td>breakage of internal thread and minor erosion</td>
<td>2 hours</td>
<td>Visual inspection and working condition</td>
<td>Change once per year</td>
</tr>
<tr>
<td>4</td>
<td>Nozzle shield</td>
<td>Excessive vibrations</td>
<td>2 hours</td>
<td>Visual inspection</td>
<td>Changed once in 4 years</td>
</tr>
</tbody>
</table>

#### 3.3.4 Repair cost

Generally, the repair cost of small turbines less than 25 MW capacity depends on labour charges comprising of number of man hours of work and wage rate of person engaged for such work. Sinha [22] reported that the welding cost (including labour cost) was INR 1,000 per kg of turbine material and grinding cost (including labour cost) was INR 40,000 per m2 in 2010 for repairing a small turbine. In the study plant, the loss of weight of the turbine was 5% of the total runner weight after December 2015.

#### 3.3.5 Replacements and obligation costs

The eroded components need to be repaired and brought back to their original profile before being reinstalled. For all eroded components except the turbine runner, it was cost effective to use a new one rather than repairing the eroded one because of comparatively lesser cost of the new components for Toss HPP. The cost of various components affected by erosion in the study plant is obtained from plant history. During the study period, one nozzle spear head and two nozzle rings were replaced amounting to INR 0.35 million.

For various HPPs around the world, the penalty for not generating the committed electricity would add to the losses due to hydroabrasive erosion. For the study plant, being small hydro there was no penalty for electricity generation; hence, there was no loss due to obligations in this case.

#### 3.3.6 Preventive measure

The preventive measure with respect to the turbine such as coatings is discussed here. Coating is particularly well suited to runners with easy blade access, enabling coating material to be sprayed onto all surface areas. The high abrasion and fatigue resistance of the HVOF coating is achieved using tungsten carbide ceramic powder embedded in a metal substance. The cost of HVOF coating is INR 0.2 Million per m2 for a thickness of 0.3 mm [22]. In case of the study HPP, the total surface area of buckets of a Pelton runner is calculated as 6.62 m2. Hence, the cost of coating will be about INR 1 million for coating 75% of the bucket surface.

#### 3.3.7 Strategy for optimal operation of plant

The optimization strategy with respect to various losses presented here for the study plant considers the consequences of repair at the end of months May, June and July. The loss due to gradual efficiency reduction calculated from PL model and other three models are provided in Table 3. The losses due to various components at the end of months May, June and July are provided in Table 4. The losses were around 15%, 18% and 23% of the cost of the uncoated turbine when repaired at the end of May, June and July 2015 respectively considering cost of repair, heat treatment, balancing and transportation each time. The cost of coating, calculated from the rates obtained from the manufacturers was about 11% of the cost of the new uncoated turbine. Hence, the loss of revenue in repairing the uncoated turbine was higher than the coating of new uncoated turbine in the study plant for initial 3 months of installation with around 1400 hrs of operation.

### Table 3 Losses due to gradual efficiency reduction calculated from models

<table>
<thead>
<tr>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td>May</td>
<td>13,000</td>
<td>24,000</td>
<td>53,000</td>
<td>45,000</td>
</tr>
<tr>
<td>June</td>
<td>145,000</td>
<td>238,000</td>
<td>285,000</td>
<td>284,000</td>
</tr>
<tr>
<td>July</td>
<td>378,000</td>
<td>414,000</td>
<td>424,000</td>
<td>424,000</td>
</tr>
</tbody>
</table>

### Table 4 Losses involved for repair schedule at the end of May, June and July 2015 (in INR)

<table>
<thead>
<tr>
<th>End of month</th>
<th>Gradual efficiency drop loss using PL model</th>
<th>Downtime cost</th>
<th>Repair cost</th>
<th>Heat treatment balancing, and transport cost</th>
<th>Replacement cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>May</td>
<td>53,000</td>
<td>300,000</td>
<td>265,000</td>
<td>6,000</td>
<td>50,000</td>
</tr>
<tr>
<td>June</td>
<td>285,000</td>
<td>300,000</td>
<td>265,000</td>
<td>17,000</td>
<td>50,000</td>
</tr>
<tr>
<td>July</td>
<td>424,000</td>
<td>300,000</td>
<td>265,000</td>
<td>19,000</td>
<td>50,000</td>
</tr>
</tbody>
</table>
For decision making in case of erosion conditions, researchers derived cut-off limit of SSC value for plant operation [7, 23-24]. For financial analysis and decision making in case of erosion conditions in a HPP, erosion models were used in this research work. Various losses were calculated with the help of these erosion models [19]. The loss components for all the months are shown in Fig. 8 and it allows a better timing for deciding the repair and maintenance for an erosion affected HPP. For the study plant, the loss component due to gradual reduction of efficiency increases rapidly with each passing month. The plants may fix a limiting value on this loss as the criteria for overhaul or replacing the turbine.

4. Conclusions

In this paper, various considerations required for optimization of a HPP both at planning and operation stages with respect to hydro-abrasive erosion have been presented and discussed from general perspective. Further, various losses due to erosion in an operational HPP have been presented as a case study. The costs involved in preventive measures such as coating the turbine blades were also discussed. The models available for calculating gradual loss of efficiency of turbine were applied for calculating loss of efficiency. As the erosion data required for financial analysis was not available for the whole high flow period (April to September), the analysis has been carried out for 3 months duration only. The losses in operating the uncoated turbine for the duration has been found as 15.7% whereas the cost of coating was 11% of the uncoated turbine cost. Thus, the option of the coated turbine has been found more economical for Toss HPP. The gradual efficiency loss was a major portion of the total loss. Furthermore, the cost of preventive measures and a criterion for decision making has been presented. For decision making, the losses for repairing the turbine at the end of three months May, June and July has been assessed. To assess the complete loss due to erosion and optimum measures to minimize the losses, long term data needs to be obtained at a HPP.

Acknowledgements

The authors sincerely acknowledge Mr. R.K. Verma, CEO of Sai Engineering Foundation and owner of Toss plant, Mr. Pankaj Thakur and Mr. Akhilesh, engineers in charge of Toss plant and staff Bidhi Chand for their kind permission and cooperation in allowing as well as arranging the logistical support at site. The financial support in form of a PhD scholarship from the Ministry of Human Development Resource (MHRD), India is also acknowledged.

References


Fig. 8 Various losses and their variations with time in the study plant


