HYDRO-ABRASIVE EROSION OF PELTON BUCKETS AND SUSPENDED SEDIMENT MONITORING

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ABSTRACT

Wear of turbine parts due to abrasive particles in the water of hydroelectric power plants (HPP) is of special importance for Pelton turbines where extreme redirection and deceleration of the flow occurs. In an on-going research project at HPP Fieschertal, Switzerland, wear on coated runner buckets is measured with a 3D optical scanner and a thickness gauge, turbine efficiency is periodically evaluated by “sliding needle” index tests and suspended sediment is monitored using various devices.

3D digitizations (measurements) of selected Pelton buckets allow quantifying material losses of the main splitter or of the cut-out section due to turbine operation during a sediment season. In the sediment season 2012 the splitter height decreased in the range of 3 to 5 mm, i.e. approximately 0.5 to 0.8 percent of the inner bucket width of 650 mm. The erosion on the splitter is influenced by the initial geometric condition of the splitter, the particle load and the operating hours.

The history of the index efficiency permits to identify relevant efficiency variations due to hydro-abrasive erosion or due to mechanical works on the turbine runner (e.g. grinding of the splitters). Measurements before and after mechanical works and during the sediment season (with no mechanical works) allow to separate both effects. For one runner the efficiency decrease was 0.9 percent for more than the half sediment season 2012.

Turbidimeters, an acoustic method and a laser diffractometer (LISST) were site-specifically calibrated based on automatically taken water samples. The measurements confirm that suspended sediment concentration (SSC) and particle size distribution (PSD) in turbine water may vary strongly in time. The LISST provides not only SSC but also PSD which is important in the context of hydro-abrasive erosion. All devices yielded similar SSC at low to moderate levels while the LISST measured SSC more accurately during periods of increased SSC with transport of coarser particles. Accepting a temporary bias, turbidimeters and the acoustic method can be used as pragmatic contributions to a real-time decision making system for the operation and maintenance of HPPs.
1. INTRODUCTION

The complications associated with wear due to abrasive particles in the water of hydropower plants (HPPs), so called hydro-abrasive wear or hydro-abrasive erosion, are not new, but the issue is increasingly emphasized because of the worldwide growing energy demand. Hydro-abrasive erosion has a detrimental effect on efficiency, leads to significant maintenance costs and may cause downtime of turbines with corresponding production losses.

To take adequate measures in design, operation and maintenance of HPPs, the knowledge on turbine wear needs to be improved and relevant parameters have to be quantified. The relevant parameters for hydro-abrasive erosion, such as suspended sediment concentration, size, hardness and shape of particles as well as relative velocity between the flow and turbine parts, turbine geometry and turbine material, have been identified (e.g. Gummer 2009, Winkler et al. 2011). But it is still not fully understood to which extent these parameters contribute to the dominant damages. Monitoring suspended sediment concentrations (SSC) and size distributions (PSD) throughout the year is still not common and the effect of hydro-abrasive erosion on efficiency is only qualitatively known.

In an interdisciplinary project initiated by VAW of ETH Zurich and Hochschule Luzern, the problem of hydro-abrasive erosion is investigated mainly by means of a case study at the existing HPP Fieschertal. The goal of the project is to contribute to a better understanding of interactions between suspended sediment load, turbine wear and efficiency as a basis for economic and environmental optimization (Fig. 1):

![Diagram showing the relationship between suspended sediment, turbine wear, and turbine efficiency.](image)

**Fig. 1:** Knowledge on turbine wear as a basis for optimization of HPPs

The HPP Fieschertal (Fig. 2) is a 509 m net head run-of-river type scheme located in the Canton of Valais in the Swiss Alps. Since the HPP was brought into service in 1976 severe hydro-abrasive erosion at needles, nozzles and runners of the two 32 MW Pelton units has been observed. Although coating of turbines and other hydraulics parts reduced the extent of the damages, sediment handling as well as optimized operation and maintenance of the HPP remain an important economic issue.
This paper presents results from the on-going research project on turbine wear, efficiency and suspended sediment monitoring. Turbine inspections giving indications on turbine wear are documented with photographs, surface mapping using a 3D optical scanner and coating thickness measurements inside selected runner buckets before and after the sediment season. The evolution of turbine efficiency over time is measured by periodical efficiency index tests. Suspended sediment in the turbine water is monitored using various optical and acoustic devices, such as turbidimeters, a laser diffractometer and a method based on acoustic discharge measurement installation (see Felix et al. 2012). In the following sections, the measurement devices, the experimental procedure and the results are presented and discussed.

2. TURBINE WEAR MEASUREMENTS

2.1. 3D digitization

The geometries of selected buckets of Pelton runners were measured with a 3D optical scanning camera (Steinbichler Comet L3D) directly inside the turbine casing (Fig. 3). The working principle of the scanner is based on triangulation. It has a resolution of five megapixels in a measurement volume of 480 x 400 x 250 mm. The 3D point distance is 190 µm and the accuracy of the system is within 25 µm.

Since the surfaces of the buckets (stainless steel) are light reflecting a whitening spray has to be applied prior to the scanning. Furthermore, reference markers are used to improve the matching of point clouds and the measuring accuracy. One full day with a two-men team is required to digitize two buckets including calibration of the sensor before the digitizing.
Fig. 3: 3D optical scanning camera used to digitize two selected buckets with reference points.

With regard to wear and efficiency of Pelton turbines the splitters and cut-outs of the buckets are of special importance. Brekke et al. (2002) formulated as a rule of thumb: When the thickness of the splitter has increased to 1 percent of the bucket width, the efficiency drops by 1 percent at full load. The maximum splitter width is practical to measure at turbine inspections. Boes (2009) related the evolution of splitter width with cumulated suspended sediment load.

In Figures 4 to 6, geometrical changes due to hydro-abrasive erosion at splitters and cut-outs, obtained from comparisons of digital geometric models taken before and after the sediment season, are shown.

At the beginning of the sediment season 2012 the runner installed in machine group 1 was fully reconditioned (welding, grinding and complete coating; with geometry close to planned geometry) whereas the runner in machine group 2 has been in use for several seasons after the last factory overhaul and was repaired on site (grinding and local re-coating).

The hydro-abrasive erosion at the splitter (analysed here as height differences along the splitter’s longitudinal profile) for the bucket no. 1 of the runners of the machine group 1 and 2 is displayed in Fig. 4. During the sediment season 2012 the splitter height was reduced by about 3 mm after 3426 operating hours at machine group 1 and by 5 mm after 1430 operating hours at machine group 2. In summer 2012 a major flood event with SSC ranging up to approx. 50 g/l occurred when both turbines were running.

The erosion rates indicate that hydro-abrasive erosion does not mainly depend on operating hours but rather on suspended sediment transport events, e.g. during floods, and on the geometry of the splitters at the beginning of the sediment season (Fig. 5).
Fig. 4: Side view of the digitized main splitter: Comparison (black) between the splitter geometries of buckets no. 1 of the machine groups 1 and 2 before (red) and after (green) the sediment season.

Fig. 5: 3D views of the digitized main splitters (red ellipse): Comparison between the splitter geometries before (transparent) and after the sediment season (grey) of buckets no. 1 of machine groups 1 and 2. The mass reduction is calculated with a density of 7.7 g/cm³ for the base material.

Further damages occur at the cut-out section of the bucket. The digitized edges of the cut-outs of bucket no. 1 of machine group 1 before and after the sediment season are shown in the lower part of Fig. 6 (top view). The differences in geometry of the cut-outs before and after the sediment season are plotted in the upper part of Fig. 6 for both machine groups. The cut-outs were abraded by up to 9 mm towards the turbine axis at machine group 1 and by up to 6 mm at machine
group 2. Interestingly, the erosion measured at the cut-outs exhibits an opposite behaviour compared to the erosion at the splitters.

Fig. 6: Top view of the digitized cut-out (with the splitter tip in the centre): Comparison (black) of buckets no. 1 of machine groups 1 and 2 between the cut-out geometries before (red) and after (green) the sediment season.

2.2. Coating thickness measurements

To analyse turbine wear mechanisms and local damages in coated Pelton buckets as installed in the HPP Fieschertal, it is essential to quantify coating thicknesses. Since the coating material (approximate Mohs hardness 7.5) is much harder than the base material (approximate Mohs hardness 4.5) of the Pelton bucket, the erosion potential raises significantly when the coating material is removed locally. Reduced coating thicknesses can result from continuous silt and sand abrasion or from single grain or stone impacts, which may crack the coating surface.

In this on-going project the coating thickness distributions inside selected Pelton buckets before and after the sediment season are measured using a thickness gauge (Helmut Fischer Deltascope FMP30 with dual-tip probe) based on magnetic induction. First spatially distributed thickness measurements using a template that defines the measurement locations within the buckets were completed. An example of such a coating thickness distribution inside a bucket of the runner which has been fully reconditioned before the sediment season is shown in Fig. 7. The distribution was obtained from an interpolation between 153 measurement locations (black points in Fig. 7). At each location, ten repeated measurements were done to achieve a mean
value with an expanded measurement uncertainty (at a confidence level of 95 percent) less than 3 percent (average over all measurement locations). As it can be seen from the colour bar, the coating thicknesses vary mainly between 200 and 400 µm with an approximate mean value of 300 µm.

![Coating thickness distribution](image)

Fig. 7: Coating thickness distribution inside the left half of bucket no. 2 of machine group 1 after the sediment season.

3. EFFICIENCY MONITORING

Turbine wear leads to efficiency reduction. Only a few published data are available (e.g. Dahlhaug et al. 2010 or Bajracharya et al. 2008), describing quantitatively the efficiency decay in defined time intervals, correlated to different turbine damages. One main reason for this lack of published data is the effort associated with efficiency measurements with respect to direct costs and cost of eventual power losses during efficiency measurements.

With index efficiency measurements the efficiency changes between two tests can be determined, absolute efficiency data are not required. A periodical evaluation of the index efficiency allows thus to quantify the evolution in turbine efficiency. Classical index efficiency measurements encompass a series of measuring points (part load to full load) with constant operating conditions. Accordingly, such measurements are time-consuming. Almquist et al. (1995) introduced the so called "sliding gate method". In this method the guide vanes of a Kaplan turbine were continuously opened and closed while acquiring data for efficiency evaluation. This method can also be adapted to Pelton and Francis turbines, as discussed by Abgottspon and Staubli (2008). Necessary condition for good measurements is that they are performed under quasi-steady conditions. The closing and opening ramps must accordingly be slow enough to fulfil this condition. An example of such a "sliding needle" procedure in the HPP Fieschertal is shown in Fig. 8. The main advantages of this kind of index efficiency method are:
- feasible for Kaplan, Francis and Pelton turbines,
- reduced time required to perform efficiency tests, and
- continuous efficiency curves over the entire operating range, instead of discrete points.

A further advantage of such index tests is that in most cases the instrumentation of the HPP can be used or data can be extracted from the control system. To do so, an adequate data acquisition algorithm has to be implemented in the control system. At HPP Fieschertal three principal possibilities to calculate the index efficiency are available:

- acoustic discharge measurements at the upper and lower end of the pressure shaft,
- pressure difference measurements in a Venturi pipe section upstream of each machine group, and
- needle stroke measurements.

Redundantly performed measurements and evaluation allow cross-checks and contribute to an increase of the reliability of the evaluated differences in efficiency.

Fig. 8: Active power (dark green, lowest curve), needle stroke (green, highest curve) and discharge (blue, curve in the middle) variation during a sliding needle index efficiency measurement.

Fig. 9 shows the efficiency history of machine group 1, calculated twice (independently) based on the two available acoustic discharge measurements. The differences between the instruments indicate reproducibility within 0.2 percent.
Between the reference measurements of July 4, 2012 and the second measurements of Sept. 27, 2012 more than half of the sediment season passed. An index efficiency decrease of 0.9 percent is obtained. This decrease is attributed to hydro-abrasive erosion. On Nov. 5, 2012 none or only a minor rise in the index efficiency level is found compared to the previous measurement, i.e. the index efficiency level remained constant. This agrees with the suspended sediment load which is measured to be low during this period. In the period until the next measurement of March 8, 2013 very low suspended sediment concentrations were measured. The observed index efficiency level rise of up to 0.5 percent can be explained with maintenance works carried out at the main splitters of the Pelton buckets during winter.

In order to distinguish the effects of hydro-abrasive erosion or of maintenance works at relevant turbine parts on turbine efficiency, index tests are required as close as possible before and after such works.

Fig. 9: History of the index efficiency for machine group 1: Absolute differences from weighted index efficiency levels with two different acoustic discharge measurement devices (blue: Rittmeyer crossed 4-path inside mount, green: Endress + Hauser 1-path clamp-on outside mount)

4. SUSPENDED SEDIMENT MONITORING

Among the available techniques for suspended sediment monitoring (SSM) turbidimeters are most popular, despite the fact that their calibration is strongly particle-size dependant and the calibration needs generally to be established by the user (Wren et al. 2000). Various kinds of
turbidimeters (measuring optical transmission or scattering) have been used in the present study. An acoustic method for SSM based on installations for acoustic discharge measurement (ADM) is also applied (single frequency attenuation, see also Costa et al. 2012). Furthermore, a portable laser diffractometer (LISST) is used (Agrawal and Pottsmith 2000). The latter yields not only estimates of SSC, but also of PSD. Particle size is an important parameter in the context of turbine wear.

The devices for SSM used in this study are summarized in Table 1. In a first phase of the project, these devices were tested in the mixing tank in the hydraulic laboratory at Hochschule Luzern, Competence Centre for Fluid Mechanics and Hydro Machines. In summer 2012 they were installed at the study HPP (locations see Tab. 1 and Fig. 2). Most devices are installed in the valve chamber, at the inlet to the penstock. Further information on these devices, the laboratory tests as well as the installation at the study HPP and previous results are described by Felix et al. (2012) and Abgottspon (2011).

In addition to the devices for continuous real-time SSM, an automatic water sampler was installed in the valve chamber and the obtained samples are analysed in the laboratory as a reference for the other devices. Reference SSCs are determined by weighing of the solid residues (primary method). The sampler is programmed to take one sample every 2 days and is additionally triggered by the signal of a turbidimeter to increase the sampling rate during relatively high SSC.

<table>
<thead>
<tr>
<th>Device type</th>
<th>Device model and manufacturer</th>
<th>Device output and measuring principle</th>
<th>Derived parameters</th>
<th>Installed in HPP Fieschertal at</th>
</tr>
</thead>
<tbody>
<tr>
<td>Turbidimeter, submerged</td>
<td><em>Turbimax WCUS41</em> Endress-Hauser</td>
<td>Turbidity [FNU] from backscatter</td>
<td>SSC</td>
<td>Intake (starting 2013)</td>
</tr>
<tr>
<td></td>
<td><em>Solitax ts-line sc</em> Hach-Lange</td>
<td>Turbidity [FNU] from backscatter</td>
<td>SSC</td>
<td>Tailrace channels of each unit</td>
</tr>
<tr>
<td>Turbidimeter, in-line</td>
<td><em>TurbisC</em> (90°, 25°) Sigrist Photometer</td>
<td>Turbidity [FNU] from backscatter</td>
<td>SSC</td>
<td>Valve chamber, at the inlet to the penstock</td>
</tr>
<tr>
<td></td>
<td><em>TF16-N with F20</em> Optek Danulat</td>
<td>Turbidity [CU] from transmission</td>
<td>SSC</td>
<td></td>
</tr>
<tr>
<td>Acoustic method</td>
<td><em>Risonic Modular</em> Rittmeyer</td>
<td>Received amplitude [V] forward scattering</td>
<td>SSC</td>
<td></td>
</tr>
<tr>
<td>Portable laser diffractometer</td>
<td><em>LISST-100X, Type C</em> Sequoia Scientific</td>
<td>Volume concentrations in 32 size classes [ppm]</td>
<td>SSC and PSD</td>
<td></td>
</tr>
</tbody>
</table>

Table 1: Devices used for continuous suspended sediment monitoring.

The time series of SSC in the turbine water obtained from the devices installed in the valve chamber are shown in Fig. 10 for the period from July 2012 to the end of the sediment transport season. The conversion (calibration) from original units of the devices (e.g. FNU) to SSC is based on the reference SSCs collected so far at the study site.
The time series of the in-line turbidimeter (optical backscatter and optical transmission) models used here show considerable drift. Their signals are increasingly biased by particles that accumulated on the optics in the flow-through cells and by bio-fouling. Flushing of the flow cells by increasing the discharge of the sampling line for some minutes was not sufficient to clean the optics. Only manual cleaning (at day 303) brought the signals back to the low level expected for the relatively clear water in late autumn. In the sediment season 2013 another turbidimeter model, measuring the turbidity at a free falling jet (AquaScat from Sigrist Photometer), will be installed at the sampling line in order to avoid signal drift and frequent manual cleaning. At the two turbidimeters installed at the tailrace channels no problem of signal drift occurred since those submerged turbidimeters are equipped with a wiper that keeps their optics clean.

![Graph](image)

**Fig. 10:** Time series of daily averaged SSC in the turbine water, obtained from various devices installed in the valve chamber, from July, 19 (day 200) to December, 6 (day 340) in year 2012.

Figure 11 shows a close caption of Figure 10 as an example of suspended sediment transport during three summer days. In addition, three of the reference SSCs from laboratory analysis of bottled samples and the time series of the median size of the particles in the turbine water (d_{50}, i.e. the median diameter by mass) obtained from the LISST (right axis) are also shown in Fig. 11. Data were recorded every second for turbidimeters and the acoustic method and every minute for the LISST. The time series were smoothed by moving average over 20 minutes and implausible data were discarded. Trends and offsets visible in Fig. 10 were removed from the turbidimeter data.

During summer days SSC was approx. 0.5 g/l and the time series from all devices (turbidimeters, laser diffractometer and acoustics) show similar behaviour, except for a sediment transport peak in the early morning hours of day 239. During this event the LISST yields a higher SSC compared to the other continuous measuring methods. The LISST measurement is supported by
the reference measurement taken during the rising limb of the SSC peak. From Figure 11 it can be seen that the median size of the particles in the turbine water is approximately 15 microns, except for the phase of increased sediment transport. During this phase, about three times coarser particles (d$_{50}$ approximately 45 microns for some hours) were transported. The maximum of d$_{50}$ occurred approximately one hour after the maximum in SSC.

Fig. 11: Time series of SSC in the turbine water, from devices as in Figure 10, reference SSCs from bottled samples, and time series of d$_{50}$ obtained from LISST; example of three summer days (August 25 to 27, 2012).

In Figure 12 selected PSDs obtained from the LISST are displayed. The times at which these PSDs were measured are indicated in Fig. 11 with capital letters. The PSDs measured before (B) and after (E) the SSC peak as well as during a minor SSC peak (A) are similar. The PSDs recorded at maximum SSC (C) and at maximum d$_{50}$ (D) are considerably coarser. The underestimation of SSC by the turbidimeters and the acoustic method (single frequency forward scattering) in times with transport of coarser particles is related to their physical operating principle. Coarser particles do not cause as much turbidity or scattering as finer ones (at same SSC). The calibration of those devices depends strongly on particle size, for which in practice a constant time-averaged value has to be adopted. As it can be seen from Figures 10 and 11, the deviation in SSC estimates of those devices with respect to SSC from the LISST and reference SSCs may be significant during phases of increased suspended sediment transport. In the rest of the time, however, those devices provide quite accurate SSC estimates.
5. CONCLUSIONS

First analyses of the hydro-abrasive erosion rates for both machine groups in the HPP Fieschertal, Switzerland, showed that single events such as heavy rains lead to major material loss at Pelton buckets. Therefore, temporary shutdowns of the HPP would help to prevent excessive hydro-abrasive erosion during such events. To do so, a reliable method for continuous real-time measurement of suspended sediment load is needed.

Using several devices for SSM based on different physical principles allows for a cross-comparison of their measuring capabilities under field conditions and leads to higher reliability. The combination of devices for continuous SSM with an automatic water sampler allows calibrating the devices based on the site-specific conditions, e.g. with respect to typically prevailing particle sizes and mineralogical composition (particle shape, optical properties). The calibration of the devices will be improved based on the increasing data set of reference SSC from the study site.

Since frequent manual cleaning of measuring devices is not practical, turbidimeters with an automatic cleaning system (wiper or pressurized air) or turbidimeters with optics not in contact with the sediment-laden flow (free falling jet type) are recommended, even in cold and relatively nutrient-poor water of mountain streams. The acoustic method based on ADM installations existing in many HPPs offers the advantage of monitoring suspended sediment directly in the penstock. Among the devices used here, LISST offers new possibilities for SSM, since it provides not only information on SSC, but also on PSD. In environments with variable particle sizes LISST measures SSC more accurately than devices with a fixed calibration depending on particle size. For a better understanding of hydro-abrasive erosion, measuring PSD is important.
since coarser particles have higher abrasion potential (for a given SSC) and are therefore particularly harmful to turbines. Devices with particle size-dependant calibration may be used as pragmatic contributions to a real-time decision making system for the operation and maintenance of HPPs, especially for smaller schemes.

In summer 2012 SSC of approximately 0.5 g/l with $d_{50}$ of normally 15 microns was observed in the turbine water of HPP Fieschertal. The measurements confirmed that SSC and PSD may vary strongly within short time, e.g. due to precipitation events, to SSC of up to approximately 50 g/l and $d_{50}$ of e.g. 45 microns.

Wear at coated Pelton runner buckets was measured with a 3D optical scanner and a thickness gauge. Digital models of selected Pelton buckets allowed quantifying material losses at the main splitter and at the cut-outs due to turbine operation over a sediment season. The analysis showed that the splitter height decreased 3 to 5 mm during the sediment season 2012, this corresponds to approximately 0.5 to 0.8 percent of the inner bucket width of 650 mm. The hydro-abrasive erosion at the splitter is influenced by the splitter geometry at the beginning of the sediment season, particle load and the operating hours. Local coating thicknesses in the bucket of a Pelton runner were measured with a thickness gauge based on magnetic induction.

Turbine efficiency was periodically evaluated by “sliding needle” index measurements. The history of the index efficiency permits to identify relevant efficiency variations due to hydro-abrasive erosion. For one of the investigated turbines the efficiency decrease was 0.9 percent for half of the sediment season 2012. In order to distinguish the effects of hydro-abrasive erosion and the effects of maintenance works at relevant turbine parts (e.g. grinding of the splitter) on turbine efficiency, index tests should be performed before and after such works. Redundantly performed index measurements and evaluation allows cross-checking and increasing the reliability of the evaluated differences in efficiency.

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