Erosion of Pelton buckets and changes in turbine efficiency measured in the HPP Fieschertal

A Abgottspon[1], T Staubli[1], D Felix[2]

[1] Competence Center for Fluid Mechanics and Hydro Machines (CC FMHM), Hochschule Luzern (HSLU), Technikumstrasse 21, CH-6048 Horw, Switzerland

[2] Laboratory of Hydraulics, Hydrology and Glaciology (VAW), ETH Zurich, Hönggerbergring 26, CH-8093 Zurich, Switzerland

andre.abgottspon@hslu.ch

Abstract. Geometrical changes and material loss of Pelton turbine runners as well as changes in turbine efficiency were measured at HPP Fieschertal in Valais, Switzerland. The HPP is equipped with two horizontal axis Pelton units, with each 32 MW nominal power, 7.5 m^3/s design discharge, 515 m head and two injectors. The injectors and the buckets are hard-coated.
Hydro-abrasive erosion was quantified based on repeated measurements on two runner buckets using (i) 3d-scanning and (ii) a coating thickness gauge. Changes in efficiency were measured by applying the sliding needle procedure. In addition to these periodically performed measurements, efficiency was also continuously monitored.
The highest erosion rate was measured during the first half of the sediment season 2012 including a major sediment transport event. Because the runner was not fully reconditioned at the beginning of this season, progressive damages occurred. After the event, a splitter width of 10 mm was measured, corresponding to 1.5 % of the inner bucket width. The cut-outs were eroded by up to 9 mm towards the axis. The efficiency reductions ranged from 1 % in the year with the major sediment transport event to insignificant differences in 2014, when the sediment load was small and only little hydro-abrasive erosion occurred.

1. Introduction

Hydro-abrasive erosion increases the maintenance costs, affects the turbine efficiency and leads to production losses. As basis for adequate countermeasures in design, operation and maintenance of HPPs, the knowledge on hydro-abrasive erosion needs to be improved. Relevant parameters such as particle load, dimensions and velocities, as described in IEC 62364, have to be quantified.
In an interdisciplinary project initiated by VAW of ETH Zurich and Hochschule Luzern, the problem of hydro-abrasive erosion was investigated by a case study at the existing HPP Fieschertal. The goal of the project was to contribute to a better understanding of the relations between suspended sediment load, turbine wear and efficiency losses as a basis for economic and environmental optimization. A schematic overview of the HPP Fieschertal with the investigation program is shown in [1] and [2].
This paper presents results of on-going turbine wear and efficiency measurements. Regular inspections are carried out and turbine wear is documented in detail. During inspections before and after sediment seasons, photographs are taken, the actual bucket geometry is recorded using a 3D optical scanner and the coating thickness in selected buckets is measured. The changes in turbine efficiency over time (efficiency history) are measured periodically with the sliding needle procedure and continuously by efficiency monitoring.

2. Aspects of hydro-abrasive erosion

The amount of hydro-abrasive erosion in Pelton turbines is typically determined using a set of metallic 2D templates. With such templates the difference between the actual and the original design-geometry is visualized. This method is suitable to check the shape of the inner bucket contour. The actual splitter width and the cut-out depth can be measured e.g. with a ruler. With these simple methods it is not possible to determine the mass reduction or the areal variations at the cut-out and splitter profiles.

The total mass reduction of a runner can be determined by weighing. Such measurements are reported e.g. by [3] of an uncoated Francis turbine (75 MW, mass reduction of 1500 kg in a revision cycle), or by [4] of an uncoated Pelton runner (10 MW, mass reduction of 100 kg), or by [5] and [6] of model Pelton runners with removable buckets (mass reductions of some g per bucket). The weighing method is suitable for laboratory investigations and for HPPs where runners need to be replaced. For local wear measurements, some turbine manufacturers use 3D handheld laser scanner (e.g. ExoScan) or portable coordinate measuring devices (e.g. FaroArm).

With progressive hydro-abrasive erosion the actual geometries differ increasingly from the original. Reported changes of the geometry of Pelton buckets refer to either local changes at splitters and cut-outs or to global changes in uncoated buckets in form of rough, wavy or scaled surfaces. This leads to a deterioration of the flow conditions and to efficiency reductions ([7] and [8]). On an uncoated Pelton turbine, the efficiency reduction over a sediment season can reach several percent (e.g. [9]). On an uncoated Francis turbine with hydro-abrasive erosion on guide vanes, runner blades, sealing rings and facing plates, an efficiency reduction of 4 % at the best efficiency point and of 8 % at part load was reported by [10].

Since the degradation of splitters and cut-outs is important for Pelton turbines, attempts were made to relate these geometrical changes to efficiency reductions. According to [4] and [11] the efficiency reduction can reach several percent if the splitter width increases to a few percent of the inner bucket width. For practical purposes the splitter width was used e.g. by [12] as an indicator for turbine wear. However, other investigators [13] noticed that the splitter width is not always clearly defined. They decided to measure the radial erosion of the splitter tip and demonstrated its relationship with the efficiency reduction. The efficiency decrease at uncoated Pelton turbines is more pronounced with increasing erosion: according to [14] e.g. 1.2 % in the first year and 4 % after two years without intermediate maintenance works.

Hard coating greatly contributed to reduce hydro-abrasive erosion. Coated runners have generally a slightly lower efficiency than uncoated ones but longer time intervals between overhauls (e.g. [15] and [16]).

3. Hydro-abrasive erosion measured in the HPP Fieschertal

Hydro-abrasive erosion was measured on the mounted turbine runners inside the turbine housings with the instruments listed in table 1 and described in the sections 3.1. and 3.2.

Table 1. Instruments and parameters for turbine wear measurements at HPP Fieschertal.

No.	Measuring technique	Model	Manufacturer	Derived parameters		
1	Thickness gauge based on magnetic induction	*Deltascope FMP 30*	Helmut Fischer	Coating thickness		
2	3D-digitization with optical scanning camera	*Comet L3D 5M*	Steinbichler	Splitter height Δh	Splitter width s	Cut-out depth Δd

3.1. Coating thickness

The local thickness of the coating was measured using a handheld gauge based on electromagnetic induction. The use of this technique was possible since the base material, a martensitic chrome nickel steel, is magnetic while the coating is essentially non-magnetic. 3D templates were used for the positioning of the probe at 152 measuring points in each bucket half.

Figure 1 shows a map of the coating thickness in bucket no. 1 of each machine group (MG). The iso-color surfaces were interpolated from the measurements at the black dots. These measurements were taken in April 2013 on runners which have been in operation for at least one season since the last coating in the factory. The coating thickness varied between 200 and 500 µm for MG 1. At MG 2 local damages have been repaired by on-site re-coating, which explains local thicknesses of up to 800 µm. But also without re-coating the thickness may vary considerably, as e.g. in the bucket of MG 1, where the thickness changes by up to 200 µm within a distance of 40 mm close the left contour of the bucket. This emphasizes the importance of a good reproducibility of the measuring points. Measurements in a second bucket of both MGs showed similar patterns as in the first buckets.

From the successive measurements, an area-averaged reduction of the coating thickness was evaluated. This reduction amounted to 10 µm for the sediment season of 2013 with a sediment load of 29 000 tons and to 4 µm for 2014 with a sediment load of 22 000 tons (MG 1). The reproducibility of these coating thickness difference measurements was estimated to be ±5 µm. Thus the thickness reduction of 2013 is significant while the one of 2014 lies within the band of uncertainty.

It was concluded that in absence of a major sediment transport event as in 2012, the coating in the buckets lasts for several years. In the runner which had to be replaced after the sediment event in 2012, coating thicknesses of only 50 to 100 µm were measured in the bottom region of the bucket and in the neighborhood of areas where the coating was completely removed.

Most relevant for efficiency loss is the local erosion or the splintering due to stones at the cut-outs and the splitters of the bucket. Such local erosion occurred also in years without major sediment transport events. The complete removal of the coating in these zones leads to scouring of the less resistant base material. Since the magnetic induction method is not suited for coating thickness measurements at cut-outs or splitters, an optical method was applied to quantify the erosion in these zones.

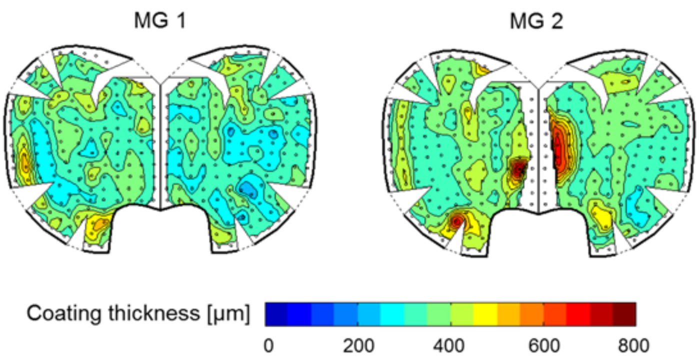

Figure 1. Maps of coating thickness in buckets no. 1 of MG 1 (left) and MG 2 (right).

3.2. 3D-digitization

Eroded or damaged splitters and cut-outs of Pelton buckets are not only relevant for efficiency, but also for secondary damages induced by local cavitation or droplet erosion. Cavitation damages are typically observed at the splitter sides or underneath the cut-out. High energy droplets arise when the jet impinges on a bluff splitter and also when the jet is interacting with an abraded cut-out. In the first case droplets hit the half buckets in their central part and in the second case droplets hit the precedent bucket [17].

The geometries of selected buckets were measured with a 3D optical scanning camera [18]. Its working principle is based on structured light projection and spatial triangulation. In order to compare the geometries of the successive measurements, a consistent and reproducible geometrical reference had to be used for the positioning of the digital geometric models (3D point clouds) of the buckets. Further information on this procedure and on the data treatment is given in [19]. Figure 2 shows an overlay of the measured geometries of two digitized buckets before and after the sediment season 2012 in topview in the zone of the cut-outs. Erosion occurred mainly in the centre part of the cut-outs and on the tips of the splitters. On the outer sides of the cut-outs the geometry is not altered with time.

The perfect overlay in the zones without erosion indicates a good reproducibility of the geometrical measurements with this method. The reproducibility was estimated to be better than ±0.2 mm in the zones of the splitters and the cut-outs.

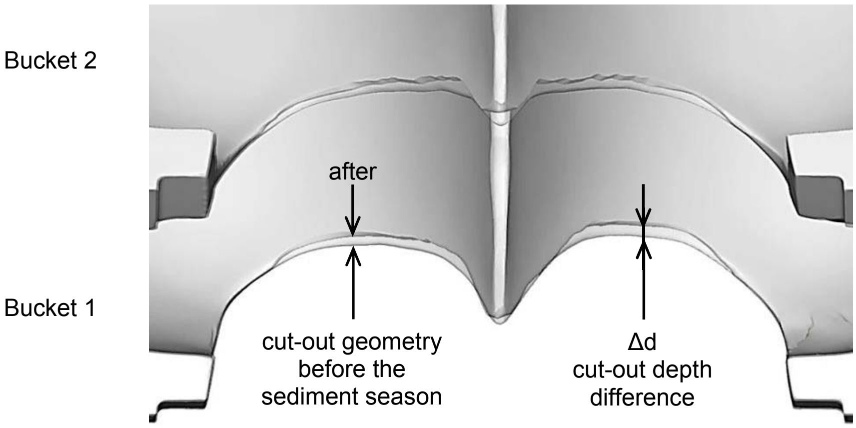

Figure 2. Overlay of the topview geometries of the cut-outs and splitter tips before and after the sediment season 2012 for MG 2.

In the lower part of figure 3 the measured contours for the cut-outs of buckets no. 1 of MG 1 are shown also in topview. In addition, the differences in cut-out depths are shown in the upper part of the figure for each sediment season. The results for the bucket no. 2 were similar.

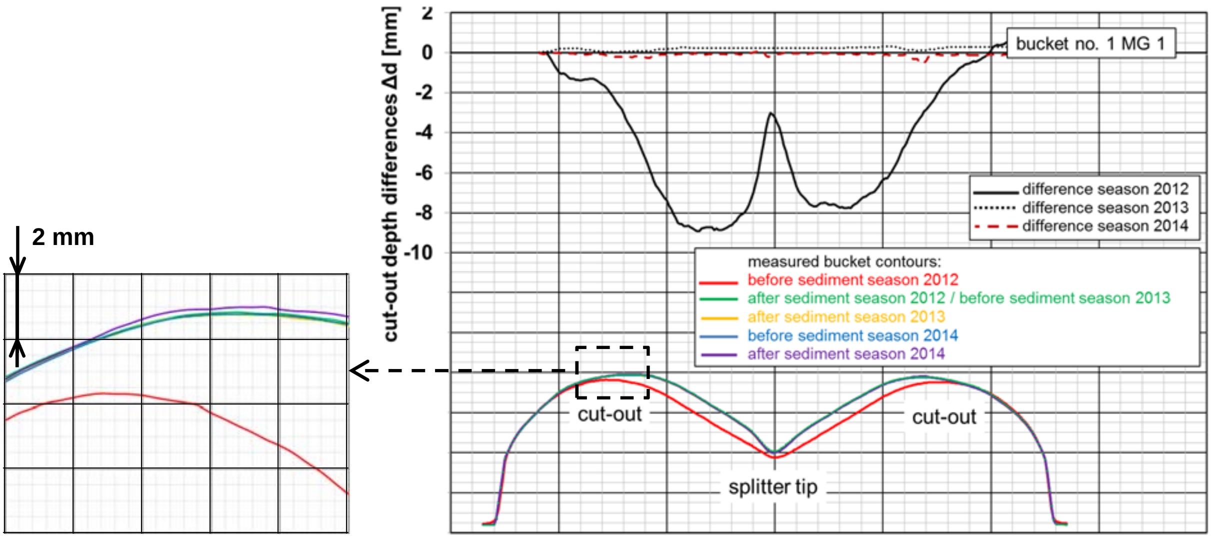

Figure 3. Topview of the cut-outs digitized at various times (with a zoom on the left) and differences (on the top) for each sediment season for bucket no. 1 of MG 1.

During the sediment season 2012 the cut-out depth increased for the bucket shown in figure 3 by up to 9 mm towards the turbine axis. This corresponds to 1.4 % of the inner bucket width (B=650 mm). Contrarily, no or very small hydro-abrasive erosion occurred in the other seasons (no detectable difference of the green, yellow, blue and purple lines). These findings are confirmed in figure 4 where for the same bucket the measured longitudinal profiles of the splitter are depicted. The resulting differences of the splitter heights for each sediment season are quantified. During the sediment season 2012 the splitter height was reduced by up to 6 mm in the middle part of the splitter. This corresponds to 0.9 % of the inner bucket width. The overlay of the lines in the zoomed details of figures 3 and 4 demonstrates the high resolution and the high degree of details of the measurement method used.

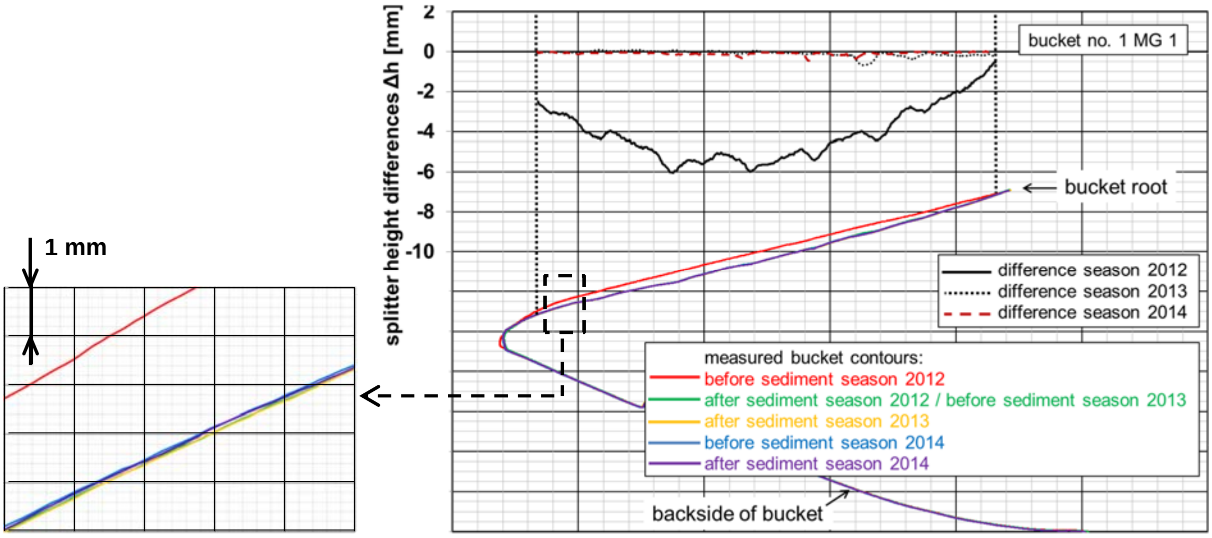

Figure 4. Side view of the splitters digitized at various times (with a zoom on the left) and differences (on the top) for each sediment season for bucket no. 1 of MG 1

Figure 5 shows the measured cross sections through the splitters of the buckets no. 1 of each MG. The sections are located at half of the splitter length. Always the same runner was installed in MG 1 in the years from 2012 to 2014. Due to heavy hydro-abrasive erosion in the year 2012 and the maintenance works afterwards, the splitter at MG 1 was widened and rounded. During the following two years it remained practically unchanged. At MG 2 the splitter was already relatively wide at the beginning of the sediment season 2012. The splitter was further widened in part of the year 2012. After the major sediment transport event the runner was taken out of operation in August 2012. Although the reductions of the splitter heights at MG 1 and 2 were similar, more material was eroded at MG 2 because of the wider splitter.

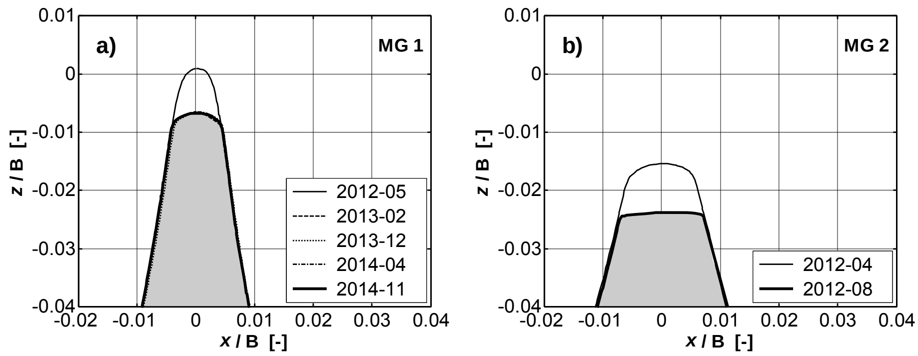

Figure 5. Splitter cross sections of buckets no. 1 at various stages of erosion and maintenance works: a) MG 1 and b) MG 2; coordinates are normalized by the inner bucket width B.

3.3. Correlation of turbine wear with sediment load

Figure 6 shows the variation of height and width of the splitter as well as the increase of the cut-out depth for both MGs as a function of their cumulated sediment loads. Displayed are the averaged values for bucket no. 1 and no. 2. As mentioned before, always the same runner was installed in MG 1 since 2012. In MG 2 three different runners were installed during the same period for which reason the lines are interrupted. A first runner exchange was necessary after the major sediment transport event of 2012. The second runner replacement became necessary due to a crack at the bucket root, unrelatedly to hydro-abrasive erosion.

In the course of the sediment season 2012 the coating in the zones of the splitters and the cut-outs of both MGs was completely removed by hydro-abrasive erosion. The successive erosion led to considerable loss of base material. At MG 1, the splitter was widened by about 3 mm and its height was reduced by 6.5 mm after a sediment load of 60 000 tons. In contrast, only very local removal of the coating was observed during the sediment seasons of 2013 and 2014 and no changes in splitter and cut-out geometries were measured. At MG 2, the initial splitter width was more than twice that of MG 1. This led to serious secondary damages and the runner had to be replaced after the major sediment transport event, in spite of a 30 % lower sediment load compared to MG 1, where no runner exchange was required. This demonstrates that the status of a runner before exposure to high sediment loads is essential for the arising amount of erosion.

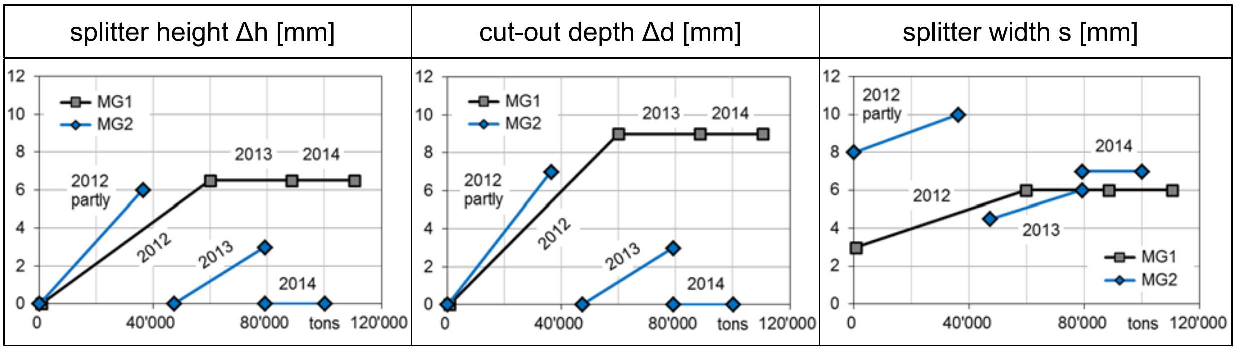

Figure 6. Histories of splitter and cut-out geometries as a function of the cumulated sediment load per MG in the HPP Fieschertal.

4. Monitoring turbine efficiency in the HPP Fieschertal

The quantities listed in table 2 were measured with a data acquisition system independently from the HPP's control system. These quantities were then used to calculate and monitor the turbine efficiency.

Table 2. Quantities and instruments for turbine efficiency measurements in the HPP Fieschertal.

No.	Measured quantities	Model	Manufacturer	Derived parameters
1	Static pressures	*gauge 2088*	Rosemount	Net heads
2	Head water level	*differential 1151*	Rosemount	Checking of pressure measurements
3	Discharge in the penstock	*Prosonic 93 PA2*	Endress+Hauser	Discharge of both MGs
4	Needle strokes	*Kinax WT707*	Camille Bauer	Discharge per MG
5	Generators active power	*Sineax M563*	Camille Bauer	Electric outputs

4.1. Sliding needle efficiency measurements

For comparative measurements of efficiency it is not necessary to know the absolute value of efficiency. Comparisons are possible based on index efficiency tests. The reference - a quantity proportional to the true discharge - must be well reproducible over time. A periodical determination of efficiency curves as a function of flow rate or power allows supervising the changes in efficiency. In the HPP Fieschertal only minor variations of head (less than 1 %) occur what facilitates such efficiency comparisons. In plants with high sediment loads, pressure taps have to be flushed on a regular basis. While this is less critical for head measurements, the measurements of an index flow rate based on pressure difference measurements, e.g. with a Venturi meter, becomes unfeasible in case of high sediment loads. Flow meters such as magnetic inductive meters or acoustic meters based on transit time measurements avoid such problems.

During the employed sliding needle procedure, the needle was opened continuously starting from a small opening – and after reaching full load – it was closed again continuously. The test duration was approximately one hour. The sliding needle procedure of Pelton turbines corresponds to the sliding gate procedure of Kaplan and Francis turbines first described by [20]. In both procedures an actuator increases and decreases the flow rate. Reliable measurements require quasi-steady conditions in the plant. An overview on this type of measurements is given by [21]. The sliding needle procedure can be performed in a much shorter time than a set of classical single point efficiency measurements. From the evaluated efficiency curve of each sliding needle measurement a weighted efficiency was calculated. The temporal evolution – the history – of this weighted efficiency shows the actual status of the runner as given in figure 7.

4.2. Continous efficiency monitoring

For an optimum operation of a plant with more than one MG it is important to monitor efficiency with good temporal resolution. Although the sliding needle procedure interferes during only one hour with the normal operation of the plant, such an operation constraint is undesirable especially during periods with full load operation. For this reason a procedure was developed to enable continuous evaluation of an averaged efficiency during normal operation.

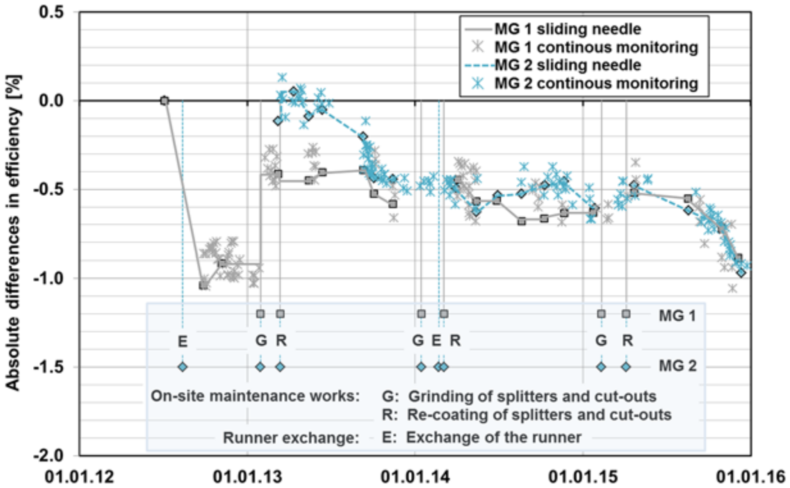

Figure 7. Efficiency history obtained from the sliding needle procedure compared with the continuous efficiency monitoring and remarks on maintenance works and runner exchanges.

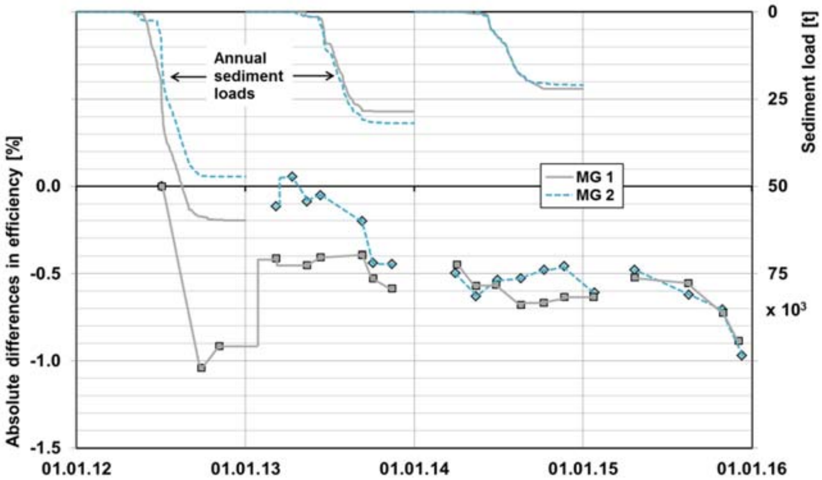

Figure 8. Comparison of the measured efficiency differences (primary axis) with the annual sediment loads (secondary axis) for MG 1 and 2.

For continuous monitoring, data are recorded at 1 Hz, as for the sliding needle measurements. For each set of sampled data efficiency is evaluated. The scatter of these efficiencies is relatively high and a daily averaged difference to a reference curve from a sliding needle measurement is evaluated in steady state conditions. The history of such data is displayed in figure 7 and the larger scatter compared to the sliding needle data is obvious. This scatter was reduced by sophisticated data processing, elimination of outliers and filtering. Further it was necessary to introduce plausibility tests to check the individual measuring quantities, especially the pressure measurements. Pressure data were compared to calculated pressures, evaluated from head water level measurements considering the head losses in the penstock. Figure 7 shows the index efficiency history for both MGs for a period of four years from 2012 to 2015. The points which are connected by lines show the history evaluated from the sliding needle procedure. The crosses indicate the results from the continuous efficiency monitoring. The maintenance works carried out are marked as well.

In the second part of the sediment season 2012 an efficiency loss of 1 % was measured after 1902 operating hours at MG 1. The main cause for this efficiency loss is the major sediment transport event of July 2012. In the winter 2012 / 2013 the splitters and cut-outs were grinded and rounded. This led to a measured increase in efficiency of 0.56 %. In the year 2014 the measured efficiency reduction of MG 1 was only 0.14% after 3048 operating hours. Two further grinding and re-coating actions after the sediment seasons 2013 and 2014 did not lead to significant increases in efficiency. Efficiency benefits of on-site maintenance works depend on the erosion status of the runner.

Figure 8 shows the comparison of the efficiency histories and the sediment loads [22] for the three years from 2012 to 2014. The on-site grinding and re-coating for the MG 1 before the season 2013 led to slowed efficiency losses over the season. Although both MGs were exposed to a similar annual sediment load, MG 2 had a higher efficiency loss (-0.30 %) than MG 1 (-0.12 %). The initial status of a runner at the beginning of a sediment season is essential and this knowledge is most important for an estimated prediction of efficiency losses.

4.3. Correlation of turbine efficiency with sediment load

For each sediment season and each runner the efficiency changes are displayed in figure 9. The shown efficiency differences are taken from the efficiency data of figure 8. The estimated reproducibility is ±0.2 %. In this range the results should not be over-interpreted; especially the small increase of efficiency is questionable.

No efficiency difference is available for MG 2 in the year 2012, since the runner had to be replaced unexpectedly after the major sediment transport event. For MG 1 one observes for similar cumulated sediment loads of about 30 000 tons efficiency differences of -1.0 and -0.1 % in a part of the year 2012 and in the year 2014, respectively. This corresponds to a factor of ten, from what can be concluded that the sediment load alone is not suited for explanation and prediction of efficiency losses.

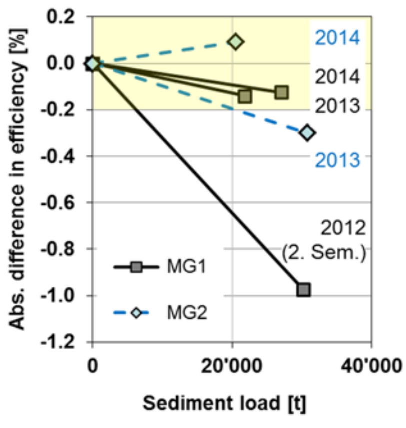

Figure 9. Comparison of the measured efficiency differences with the sediment loads per MG and year at HPP Fieschertal.

4.4. Correlation of turbine efficiency with turbine wear

As mentioned in section 2, the erosion at splitters and cut-outs is a main reason for efficiency reduction in a Pelton turbine. At HPP Fieschertal, with an inner bucket width of B=650 mm, the following values are available from the measurements:

- At MG 1, in part of the sediment season 2012: The splitter width increased from 3 to 6 mm, i.e. 0.5 % to 0.9 % of B, while the efficiency was reduced by 1.0 %.
- At MG 2, in the sediment season 2013: The splitter width increased from 4.5 to 6 mm, i.e. 0.7 % to 0.9 % of B, while the efficiency was reduced by 0.3 %.

The measurements confirm the positive correlation between increase of relative splitter width and turbine efficiency reduction. In contrast to smaller Pelton runners, the changes in relative splitter width and efficiency were relatively small in the present study. No quantitative correlation between splitter width and efficiency decrease can be determined, since the number of observations is yet too small and the splitter width is not the only influencing parameter. Although the measured efficiency reductions were in maximum 1 %, they are economically important. Since turbine wear cannot be monitored continuously and the amounts of related efficiency changes are not well predictable, efficiency monitoring is important for an economically optimized operation of HPPs.

5. Conclusions

Coating thickness reductions, material losses at splitters and cut-outs, as well as the associated efficiency losses were successfully measured in the HPP Fieschertal. From the coating thickness measurements in the buckets it was concluded that in years without a major sediment transport event the reduction of the coating thickness is immaterial. Relevant, however, is the coating removal on the splitters and the cut-outs and the successive scour of base material. In order to quantify this material removal, a 3D optical scanning camera was employed. From the geometrical 3D models dimensional changes and local mass losses were determined with sufficient accuracy.

From the sediment load measurements carried out in parallel it was concluded that the measured erosion correlates only to a minor degree with the sediment load. A higher degree of correlation is to be expected for new and uncoated runners. In the present study the erosion was highly dependent on the initial status of the splitters and cut-outs of each runner before the sediment season.

Efficiency changes were quantified using the sliding needle procedure. The results were confirmed by the continuous efficiency monitoring. The highest observed efficiency loss amounted to 1 % in the first part of the sediment season 2012 with the effects of a major sediment transport event. Besides efficiency reductions due to hydro-abrasive erosion, also effects of maintenance works were quantified. In one case an efficiency increase of 0.6 % due to grinding (rounding) of the splitters and the cut-outs was measured.

As was observed for the erosion, also the measured efficiency losses correlated only to a minor degree with the operating hours or the sediment load. The actual hydraulic contour at the beginning of each sediment season was again identified as the dominant influencing factor. Since no tools are available to estimate efficiency deficits of eroded buckets or the efficiency benefits of turbine maintenance works, periodically performed or continuous measurements of efficiency are needed.

The use of measurement techniques shown in this paper can provide a sound economic basis for HPP operators and turbine manufactures for an optimum planning of turbine maintenance works. The methods might also be useful to improve the formulation of specifications and for checking of guaranteed maximum mass losses due to hydro-abrasive erosion and cavitation. The correlations between sediment load, turbine wear and efficiency losses, however, are site-specific and depend on local conditions (e.g. particle properties), on the design characteristics and on the mode of operation of the turbines.

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