Analysis of hydro-abrasive erosion and efficiency changes measured on the coated Pelton turbines of HPP Fieschertal

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Abstract. Geometrical changes and material loss of Pelton turbine runners as well as changes in turbine efficiency have been measured at HPP Fieschertal in Valais, Switzerland since 2012. The HPP is equipped with two horizontal axis Pelton units, with each 32 MW nominal power, 7.5 m³/s design discharge, 515 m head and two injectors. The nozzles and the buckets are hard-coated. Due to the relatively high hydro-abrasive erosion during the summer (sediment transport season), the splitters and cut-outs of the runner buckets are grinded and re-coated on-site usually every winter.

Turbine erosion was quantified based on repeated measurements on two runner buckets using 3D-scanning and a coating thickness meter. The detailed geometrical models showed amongst others that the splitter width distributions are similar for buckets of one runner, but differ considerably between runners. Changes in turbine efficiency were measured by the sliding needle procedure continuously monitored based on operating data. From the efficiency monitoring over eight years of both turbines, efficiency differences were evaluated for each sediment season and for various refurbishment or replacement actions. The mean efficiency reduction was 0.4 % per sediment season. The on-site refurbishment works partly compensate the efficiency reductions due to erosion, leading to an efficiency drop of e.g. 2 % over six years, after which the runners are usually overhauled in the factory.

1 Introduction

Wear of turbine parts due to abrasive particles is a major challenge in the planning and operation of medium- to high-head hydropower plants (HPP) [1]. Run-of-river schemes and storage HPPs with intermediate intakes along the power waterways in the Alps, the Andes and the Himalaya are particularly affected by hydro-abrasive erosion [2] [3] [4] [5].

The progressive material loss on the turbine parts exposed to the particle-laden flow causes a degradation of the hydraulic contours and the flow fields [6]. This leads to higher losses and hence lower turbine efficiency. Efficiency reductions have been related to the increase of splitter width as well as to the radial erosion on the cut-outs and the splitter tip [7] [8] [9], but there are no generally valid guidelines available to estimate efficiency reductions. Because efficiency reductions are economically relevant, it is important to monitor turbine efficiency, particularly in HPPs at sediment-rich rivers or in HPPs with cavitation problems. To better understand the causes of efficiency reductions, there is a need for further data on the actual changes in the geometry of the affected turbine parts and of the progression of the erosion damages.
Therefore, a research project at HPP Fieschertal, Switzerland, was initiated in 2012. This high-head 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 nozzles [3]. The nozzles and the buckets of the Pelton runners are hard-coated. The runners with an outer diameter of 2790 mm have 20 buckets with an inner bucket width of 650 mm. Wear on runner buckets and changes in turbine efficiency have been measured and monitored since 2012. In parallel, the suspended sediment concentration and particle sizes in the turbine water have been measured over the years (see companion paper [10] and [11]).

In the present paper, the runner management and the turbine investigation program in HPP Fieschertal are described firstly. Secondly, the erosion measurements on the runner buckets and the data evaluation are treated with a focus on the splitter width. Thirdly, the methods for efficiency measurements are described, the efficiency histories of both turbines over eight years are presented, and efficiency differences are evaluated over the sediment seasons and for various refurbishment and/or replacement actions.

2 Turbine runner management and investigation program

In the HPP Fieschertal, five runners are or were in service since 2012 (Fig. 1). In machine group (MG) 1, the Runner 1 was in operation for six years. Usually every winter, the splitters and cut-outs were rounded by grinding if required, and the zones where the base material was visible due to the complete local loss of the coating were re-coated (with thermal spray process) inside the turbine housings. After the six years, Runner 1 was overhauled in the factory. In MG 2 more frequent runner changes were required for the following reasons: Runner 2 was heavily eroded during the flood event of 2012, Runner 3 had a mechanical problem at the root of a bucket and Runner 4 was not in as-new condition when it was installed. The erosion and efficiency measurements will be treated in the next two main sections.

![Figure 1. Timeline of the runners in operation, the refurbishment works as well as the erosion and efficiency measurements for both machine groups (MG) of HPP Fieschertal (extended from [3] [14]).](image-url)
3 Measurements and evaluation of erosion on the runner buckets

3.1 Overview
Hydro-abrasive erosion is measured on the turbine runners at HPP Fieschertal inside the turbine housings with (i) an optical 3d-measurement system (section 3.2) and (ii) a thickness meter (section 3.3). The 3d-surveys as well as the thickness measurements of the coating are usually performed before and after each sediment season (Fig. 1). In some years, when 3d-surveys were not included in the investigation program, geometrical quantities such as splitter widths and cut-out depths were measured with a ruler and templates. In addition, the current erosion status and local damages on the buckets and on the needles of the nozzles are documented with photographs.

3.2 Erosion measured by optical 3d-survey
The geometries of the eroded and refurbished runner buckets were measured repeatedly with a structured light digitizing system Comet L3D 5M from Steinbichler (now Carl Zeiss Optotechnik). The system is based on spatial triangulation and has a resolution of five million points. With a measurement volume of 480 mm width · 400 mm height · 250 mm depth, the average distance between the points is 190 µm. A whitening spray was applied to reduce glare. Circular stickers served as references for the matching of overlapping shots. For geometrical reasons (line of sight obstructions) and due to the relatively large buckets, about 75 shots from adequate angles were required to acquire the geometry of one bucket (inner and outer sides). After preparation of the runner and calibrating the system to the prevailing temperature, the survey of two buckets of a runner takes one full working day of a two men team [3].

Figure 2 shows the degree of detail of the optical survey. The erosion features on the splitter flank in the picture (Fig. 2a) are also well visible on the rendered geometrical model (Fig. 2b).

Figure 3b to 3d show distributions of splitter widths along the splitters, evaluated with the described definition. The splitter width distributions were similar in buckets 1 (black lines) and 2 (orange lines) of the same runner, but varied among the runners (Figs. 3b vs. 3c) depending on the wear and the refurbishment works. In the first example of a runner, which had been in operation during three years...
since the last factory overhaul, the splitters were widest in the central third of the splitter length. In the other two examples however, the splitters were widest at the splitter tip. Over two years, the splitter width increased mainly in the central and outer third of the splitter length (Figs. 3c vs. 3d). Further results of the geometry measurements are reported in [13].

**Figure 3.** a) Determination of the splitter width $s$ based on a threshold value of slope on both sides in a cross section (modified from [12]), b) to d) examples of splitter width distributions evaluated from optical 3d-surveys of the Pelton runners in the HPP Fieschertal (modified from [3] and [12]).

3.3 Erosion on coating measured by inductive thickness meter
The local thickness of the coating was measured with a handheld thickness meter (gauge) *Deltascope FMP 30* from Helmut Fischer. Its operating principle is based on electromagnetic induction. The base material (martensitic chrome nickel steel) is sufficiently more magnetizable than the coating (tungsten carbide particles in cobalt-chrome). To define the positions of the measurement points in the periodic measurements over the years, 3d-templates were made of glued paper. The approximately 150 points per bucket half have a grid spacing of maximum 40 mm. Reference measurements were made on uncoated surfaces with certified foils to calibrate the thickness meter. Due to placing the probe several ten-thousand times on the hard coating over the years, the probe tip has been visibly eroded. Therefore, the probe tip was replaced after three years and the gradual probe tip erosion is compensated in the data evaluation [3].
4 Measurements and evaluation of turbine efficiency changes

4.1 Sliding needle efficiency measurements (SNM)
Changes in efficiency of the Pelton units were determined by periodically performed Sliding Needle Measurements (SNM). In a SNM, the turbine discharge and thus the power are gradually increased from 40 to 100 percent (%) and then decreased back to 40 % during about one hour while the operating data are recorded. The procedure is similar to the Sliding Gate method for Francis turbines [15] [16].

The SNM in HPP Fieschertal were performed in single-unit operation, i.e. one unit was running while the spherical valve of the other was closed. This has the advantage that the acoustic flow meters at the upper and lower end of the penstock can be directly used for the quantification of the turbine discharge. The drawback is that no SNM are performed during the full load operation period in summer to avoid production losses due to the part load operation during SNM and other restrictions of HPP availability. The reproducibility of SNM is in the order of ±0.2 %.

Every year, four to six SNM per MG were usually performed (Fig. 1). The SNM are planned over the year and can be shifted by a few weeks depending on the available MG, the inflow and the production requirements. The SNM need to be announced to the dispatch center a few days ahead. The SNM procedure was implemented in the HPP’s control system. The automated procedure can be activated by a staff member of the operator after flushing the pressure sensors.

Each SNM yields an index efficiency curve from 40 % part load to full load. From each SNM, a weighted index efficiency was evaluated with equal weights over the 40 to 100 % load range.

In Figure 4, the filled markers show the efficiency history of MG 1 (top chart) and MG 2 (bottom chart) obtained from the SNM over eight years. The efficiency differences $\Delta \eta$ were evaluated with respect to the first SNM of the respective MG.

4.2 Continuous efficiency monitoring (CEM)
In addition to the SNM, the MGs’ index efficiencies were continuously monitored based on operating data from the HPP’s control system. To do so, a steady-state detector and routines for filtering and elimination of outliers had to be developed.

In single-unit operation, the turbine discharge is taken from an acoustic flow meter at the penstock. If both units are running, as usually during the summer, the turbine discharges are calculated from the needle positions. The relations between needle positions and turbine discharge are evaluated from data recorded during periodically performed SNM. These relations are regularly updated to compensate effects of erosion on the needles, replacement of nozzle parts and modifications on their controls.

In Figure 4, the empty markers show the efficiency history of MG 1 and MG 2 obtained from the continuous efficiency monitoring (CEM). The $\Delta \eta$ were also evaluated with respect to the first SNM at the respective MG. The CEM data give valuable information on the efficiency history between SNM data points, e.g. in summer 2016 for the MG 1, or for the history until the very end of the year, e.g. in winter 2018 for the MG 2. The scatter of the CEM data points is larger than that of the SNM.

4.3 Efficiency differences over the sediment seasons
$\Delta \eta$ over each sediment season were evaluated from the SNM results before and after the sediment seasons. In general two SNM results were averaged to obtain the index efficiencies before or after a sediment season. Furthermore, the values of the CEM are used to quantify the efficiency differences for the sediment seasons 2018 and 2019 for the MG 2. These absolute $\Delta \eta$ over each sediment season are listed in Table 1 together with the respective operating hours.

$\Delta \eta$ smaller than ±0.2 %, which were determined for about half of the cases, are within the range of reproducibility of the measuring method (e.g. −0.13 % and +0.14 % in the year 2014). In such cases, the suspended sediment load was rather low and/or the runners were in good condition before the sediment season, there was no major erosion of base material on the runners and hence no significant changes in the splitter and cut-out geometries [3]. In the other cases, however, the suspended sediment load was higher [10] and/or the geometry of the runners before the season differed more from the planned one, resulting in significant erosion on the splitters and cut-outs. $\Delta \eta$ of around 1.0 % were determined for
MG 1 in a year including a major flood with a high suspended sediment load (2012) and in the two last years before the Runner 1 was taken out of service for the factory overhaul, i.e. when the runner was rather “worn down”. For MG 2, no $\Delta \eta$ can be evaluated in 2012 due to a lack of data and an unexpected runner change after the major flood. The highest efficiency reduction evaluated for MG 2 so far was in the year 2016, i.e. in the last year before the Runner 4 was taken out of service for the factory overhaul. The mean efficiency reduction over the observation period is lower for MG 2 than for MG 1 because there is no data for MG 2 in 2012 with the major flood and there were more runner changes in MG 2 resulting in more years with runners having no pronounced erosion.

Overall, the efficiency changed on average by $-0.40\%$ per sediment season while the turbines were operated about 3000 hours. The standard deviation of all available $\Delta \eta$ is 0.43 %. At 95 % confidence level, the uncertainty in the average efficiency reduction is estimated as $\pm 0.24\%$ (expanded standard deviation of the mean, with Student’s t-distribution factor 2.15 for 15 values). No clear correlation between the $\Delta \eta$ and the operating hours was found, because the turbine erosion does not only depend on the operating hours, but also on the particle load [1], the resistance of the coating and the condition of the runners before an exposure period [13].

4.4 Efficiency differences due to on-site refurbishment and replacement of turbine parts

$\Delta \eta$ due to on-site refurbishment works (grinding and re-coating) and/or replacement of turbine parts (runners and nozzles) were evaluated from the SNM results before and after the respective actions. For each type of action, the $\Delta \eta$ of those cases were averaged. These averaged absolute $\Delta \eta$ as a consequence of the actions are listed in Table 2 together with the number of cases per MG. The abbreviations for the actions correspond to those defined in the legends of Figures 1 and 4. Moreover, the uncertainty of the average efficiency differences per type of action is indicated at the 95 % confidence level (expanded standard deviation of the mean with Student’s t-distribution factor) when at least three values are available. Due to operational and organizational constraints, sometimes multiple actions were taken between two SNM. Therefore it was not always possible to distinguish the effects of a single action.

Grinding (G) improved the efficiency by 0.43 % as an average of three cases. This result is significant because it is well above the reproducibility of the $\Delta \eta$. The expanded standard deviation of the mean of the $\Delta \eta$ due to grinding is quite high because only three samples are available so far and because the extent of the grinding – and thus its beneficial effect – varies according to the amount of hydro-abrasive erosion in the sediment season before the grinding.

After on-site re-coating of the splitter crests and the cut-out edges (C) slightly higher ($+0.13\%$) efficiencies were evaluated as an average of four cases. Possible reasons for this are real physical effects or rather the reproducibility of the SNM.

Due to a runner replacement (R) efficiency increased by 0.67 % as an average of two cases with $+1.56\%$ (MG 1) and $-0.22\%$ (MG 2). In the first case, the runner which had been in service for six years was replaced by a runner coming back from factory overhaul. In the second case, however, the partly worn Runner 3 was replaced by Runner 4 which had already been in service for some years. This replacement was done because a mechanical problem was detected at Runner 3, i.e. was an exceptional case.

So far, it was not possible to quantify the effect of new needles (N) on the turbine efficiency because the nozzle parts are preferably replaced in combination with other refurbishment works to reduce the effort for dismantling and reassembling.

After grinding and re-coating (G + C), or grinding and new nozzles (G + N), only very slight efficiency increases ($+0.14$ and $+0.02\%$) were evaluated as an average of six cases or one case, respectively. This is in contrast to the result for only grinding ($+0.43\%$) evaluated as an average of three other cases. It is assumed that the extent of grinding was larger in the (G) cases than in the (G + C) and (G + N) cases. Finally, an efficiency increase of $+1.52\%$ was evaluated for a runner and nozzle replacement (R + N) in one case. This is similar to the first runner replacement case (R, MG 1, $+1.56\%$).

The expanded standard deviations of the mean of the $\Delta \eta$ in Table 2 are of the same magnitude as the mean values, i.e. the $\Delta \eta$ are indicative (not yet significant). With additional data in the course of time, the uncertainty in the $\Delta \eta$ is expected to decrease.
Figure 4. Time series of efficiency differences $\Delta \eta$ obtained from SNM and CEM (both based on needle positions) between 2012 and 2019, top chart for MG 1 and bottom chart for MG 2 (extended from [13] and [14]).
Table 1. Absolute, weighted index efficiency differences $\Delta \eta$ over the sediment seasons and corresponding operating hours for each MG between 2012 and 2019 (extended from [14]).

| Sediment season | Operating hours [h] | Efficiency difference $\Delta \eta$ [%] | Operating hours [h] | Efficiency difference $\Delta \eta$ [%] |
|-----------------|---------------------|--------------------------------------|---------------------|--------------------------------------|
| 2012            | 1902                | - 1.05                               | -                   | -                                    |
| 2013            | 2096                | - 0.05                               | 2979                | - 0.49                               |
| 2014            | 3076                | - 0.13                               | 3113                | + 0.14                               |
| 2015            | 2515                | - 0.03                               | 3737                | - 0.43                               |
| 2016            | 2484                | - 1.01                               | 3265                | - 0.57                               |
| 2017            | 3143                | - 1.26                               | 2859                | - 0.07                               |
| 2018            | 3151                | - 0.18                               | 3767                | - 0.55                               |
| 2019            | 3326                | + 0.08                               | 2761                | - 0.40                               |
| **Mean per MG** | **2712**            | **- 0.45 ± 0.46 %**                  | **3212**            | **- 0.34 ± 0.25 %**                  |
| (8 values)      | (7 values)          |                                      |                      |                                      |

Overall Mean

| 2945 h with - 0.40 % ± 0.24 %* per sediment season (15 values) |

* Expanded standard deviation of the mean for a 95 % confidence interval

Table 2. Absolute, weighted index efficiency differences $\Delta \eta$ for various on-site refurbishment and/or replacement works between 2012 and 2019.

| Action (see Fig. 4) | Mean efficiency difference $\Delta \eta$ [%] | Expanded std. dev. of mean [%] (95 % confidence interval) | Number of cases |
|---------------------|--------------------------------------|----------------------------------------------------------|----------------|
| G                   | + 0.43                               | ± 0.71                                                   | 2              |
| C                   | + 0.13                               | ± 0.19                                                   | 2              |
| R                   | + 0.67                               | -                                                        | 1              |
| N                   | -                                    | -                                                        | -              |
| G + C               | + 0.14                               | ± 0.15                                                   | 3              |
| G + N               | + 0.02                               | -                                                        | 1              |
| R + N               | + 1.52                               | -                                                        | 1              |

4.5 Combined effects of erosion and refurbishment on turbine efficiency

At MG 1, where the same runner was in operation from 2012 to 2017, an overall efficiency decrease of about $-2.1$ % was evaluated for these six years. The sum of the efficiency decreases during the sediment seasons of these years according to Table 1 is $-3.5$ %. The refurbishment actions in the five maintenance periods in the winters increased thus the efficiency by $3.5 \% - 2.1 \% = +1.4 \%$ in total. As can be seen in the top chart of Figure 4, the effect of the refurbishment (mainly the grinding) on the efficiency was higher when the efficiency reduction during the previous sediment season was high. The same chart shows also that the initial efficiency level cannot be restored by on-site refurbishments and that the efficiencies after the annual refurbishments decline probably progressively (except for MG 1 in 2019). This is attributed to the increasing deviations from the planned original bucket geometry due to the accumulated effects of hydro-abrasive erosion and grinding.
5 Conclusions and recommendations
Hydro-abrasive erosion on the hard-coated Pelton runners of HPP Fieschertal has been quantified inside the turbine housings since 2012 using an optical measurement system and a coating thickness meter. The optical surveys yield detailed 3d-geometrical models of the erosion features in the base material, where the coating was locally eroded before. The evaluation of the measured geometries showed that the distributions of the splitter width along the splitters are similar for buckets of the same runner and differ considerably among runners, depending on the accumulated wear and the refurbishment works. For repeated coating thickness measurements over time, custom-made 3d-templates were used to define the positions of the measurement points.
Changes in turbine efficiency were measured by the sliding needle method (SNM) and continuously monitored based on operating data (CEM). CEM data have higher temporal resolution than SNM data, but show larger scatter. Both methods complement each other and the operating data recorded during SNM provide a basis for the determination of the turbine discharge for CEM if more than one MG is running.
Detailed efficiency histories of two Pelton units over eight years were presented. Such efficiency histories have not been available in the literature so far. The efficiency reductions over the sediment seasons ranged from approximately 1 % in a year with a major flood event to no significant differences, when the sediment load was lower than usual and only little damage occurred on the splitters and cut-outs of the runners. An average efficiency reduction of 0.40 % per sediment season (with approx. 3000 operating hours on average) was found. The analyses of the measurements showed that not only the particle load but also the condition of a runner before a sediment season is essential for the extent of erosion and efficiency reduction during a sediment season.
The effects of on-site refurbishment works (grinding and local re-coating) and of runner and nozzle replacements on the turbine efficiency were analysed. It was confirmed that grinding has a beneficial effect on the efficiency, particularly if the splitter crests and cut-out edges were eroded in the range of millimeters in the previous sediment season. The on-site refurbishment works partly compensate the efficiency losses due to wear, leading to an efficiency reduction of e.g. 2 % over six years, after which the runners are overhauled in the factory.

6 Outlook
In the research project at HPP Fieschertal, the data acquisition and evaluation are continued. In particular the following tasks are planned:
- Further evaluation of the particle loads of the turbines according to IEC 62364 [1] over the years,
- Further evaluation of the 3d-models from the optical surveys of the eroded runner buckets and the data of the coating thickness measurements,
- Further evaluation of the turbine efficiency changes in recent years,
- Investigation of the relations between particles loads, erosion and the efficiency changes,
- Economic analyses of refurbishment works and replacements,
- Recommendations on monitoring strategy and operational improvements.
Further comprehensive studies at other medium- and high-head HPPs at sediment-rich rivers are recommended to extend the data base and reduce the uncertainty in the respective modelling approaches. Moreover, laboratory studies are required to systematically investigate the effects of single parameters. Data from field and laboratory studies are a valuable basis for the further development, calibration and validation of analytical-empirical approaches and numerical models. Such approaches and numerical models serve to estimate the expected turbine erosion and to select suitable mitigation measures.
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