Hydro-abrasive erosion of hydraulic turbines caused by sediment – a century of research and development

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Abstract. Hydro-abrasive erosion of hydraulic turbines is an economically important issue due to maintenance costs and production losses, in particular at high- and medium-head run-of-river hydropower plants (HPPs) on sediment laden rivers. In this paper, research and development in this field over the last century are reviewed. Facilities for sediment exclusion, typically sand traps, as well as turbine design and materials have been improved considerably. Since the 1980s, hard-coatings have been applied on Francis and Pelton turbine parts of erosion-prone HPPs and became state-of-the-art. These measures have led to increased times between overhauls and smaller efficiency reductions. Analytical, laboratory and field investigations have contributed to a better processes understanding and quantification of sediment-related effects on turbines. More recently, progress has been made in numerical modelling of turbine erosion. To calibrate, validate and further develop prediction models, more measurements from both physical model tests in laboratories and real-scale data from HPPs are required. Significant improvements to mitigate hydro-abrasive erosion have been achieved so far and development is ongoing. A good collaboration between turbine manufacturers, HPP operators, measuring equipment suppliers, engineering consultants, and research institutes is required. This contributes to the energy- and cost-efficient use of the worldwide hydropower potential.

1. Introduction

Since the inventions of Francis, Pelton and Kaplan turbines in the years 1848, 1880 and 1913, respectively, erosion of hydraulic machines due to cavitation and/or due to solid particles has been challenging engineers involved in the design, construction, operation and maintenance of hydropower plants (HPPs). Turbine erosion due to solid particles is also termed ‘sand erosion’, ‘silt erosion’, or ‘hydro-abrasive wear’. In this paper, the term ‘hydro-abrasive erosion’ [1] is adopted.

While improvements in turbine design have contributed to reduce erosion due to cavitation, hydro-abrasive erosion has remained an economically important aspect, particularly for medium and high-head run-of-river HPPs on sediment-laden rivers. High suspended sediment concentrations (SSC) and hard mineral particles causing significant hydro-abrasive erosion are typically found in rivers in the Himalayas, the European Alps, the Andes and the Pacific Coast ranges [2].

In the present paper, the problem of hydro-abrasive erosion in Francis and mainly Pelton turbines, related research, and countermeasures having been developed for about 100 years are reviewed based on selected literature in English, German, French and Italian language.

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2. Turbine erosion and its consequences

2.1. Erosion damages

For the two types of turbines used in medium- and high-head HPPs, the following parts are mainly affected by hydro-abrasive erosion [1] [2] [3] [4] [5]:

- Francis: guide vanes, facing plates and labyrinths of head covers and bottom rings, runners;
- Pelton: needle tips (cones), seat rings and heads of injectors (nozzles); runner buckets, jet deflector, protection roof of injectors; casing, grating below runner.

Early examples of pictures from eroded turbine parts are shown in figure 1. Material losses lead to increased roughness and changes in hydraulic profiles, and may affect the mechanical stability and integrity of turbine parts, the HPPs' availability, electricity generation, and eventually safety [4].

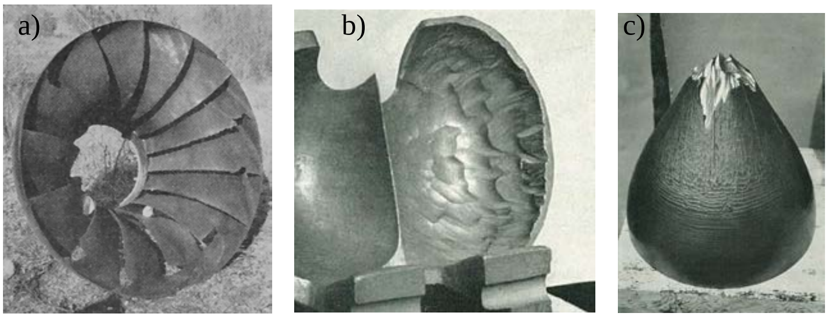

Figure 1. Examples of eroded turbine parts: **a)** Francis runner (with jammed stones) [6], **b)** Pelton bucket (left half of bucket reconstructed by welding) [7] and **c)** needle tip of a Pelton injector [7].

2.2. Efficiency reductions

An early study showing the reduction of turbine efficiency due to hydro-abrasive erosion was conducted by Dufour at HPP Klösterli, Switzerland [8] (figure 2). This HPP on a tributary of the upper Rhone

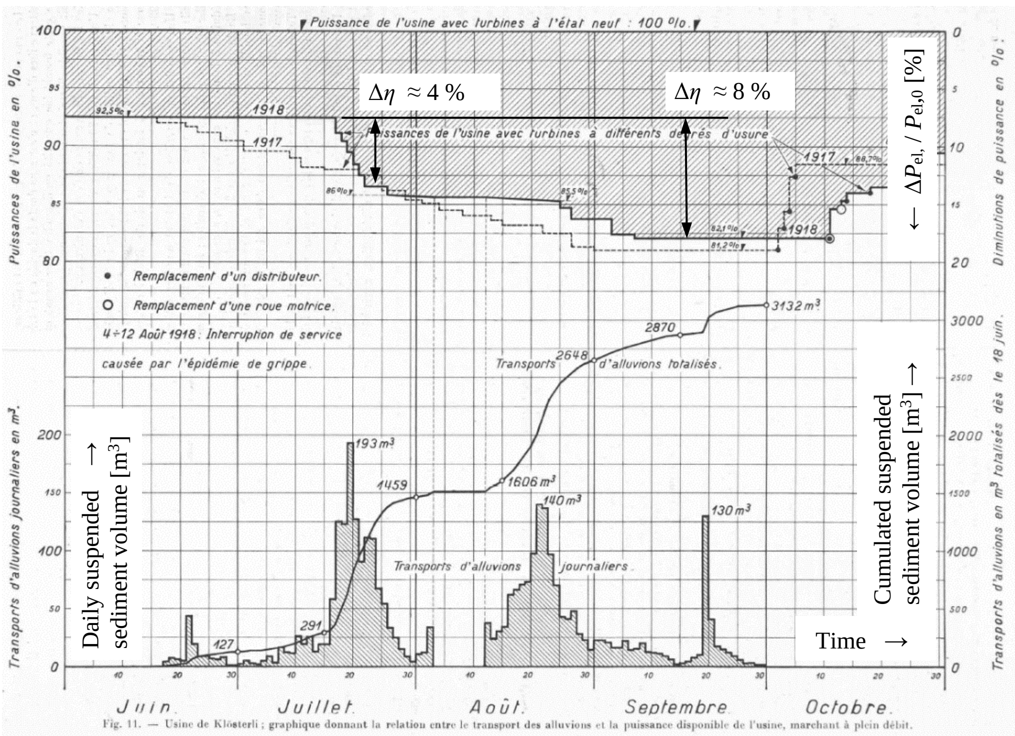

Figure 2. Time series of sediment load in the turbine water and relative changes in electric output (ΔP_{el} at design discharge compared to the output with new runners $P_{el,0}$) measured at HPP Klösterli, Switzerland, from June to October 1918 [8].

river with a design discharge of Q_d = 3 m^3/s and a head of H = 218 m, had one 2.6 MW-Pelton turbine and seven 0.4 MW-Girard turbines. Within one sediment season, the HPP's electric output at design discharge dropped by about 10 %, corresponding to an absolute efficiency reduction of about $\Delta\eta \approx 8$ % (figure 2). In particular, the efficiency dropped by about 4 % during only six days with increased sediment load. The SSC in the turbine water was on average 0.2 g/l during the observation period of 105 days and 1.3 g/l during the day with the maximum sediment transport (193 m^3 of unconsolidated sediment). Such SSC is not outstanding compared to other sediment-laden rivers, but from a today's perspective this efficiency decrease is quick and high.

3. Progress in reducing the sediment load

3.1. Improving trapping efficiency and flushing systems

One of the measures to mitigate turbine erosion is to reduce the sediment load in the power waterway. To this end, facilities for partial sediment exclusion are built in the intake area at medium- and high-head HPPs with no or only small headwater storage, i.e. run-of-river HPPs.

Pioneering work in the design and improvement of sand traps was performed by Dufour [8]. He investigated the problem of turbine erosion and sediment handling at the HPP Florida-Alta (6 x 3 MW reaction turbines, H = 98 m, Q_d = 20 m^3/s) in Chile in 1911. The HPP was equipped with two upstream settling basins and manually operated flushing gates. The cross-section of the 85 m long basins increased in flow direction. Without sediment deposits, the theoretical average flow velocity in the cross section at the end of the basin was ≤ 0.08 m/s, which should allow for a reasonable settling performance. The measured SSC upstream of the basins were in the range of some g/l in the wet season, corresponding to several 1000 m^3 of sediment per day. Dufour found that the sediment evacuation from the basins was by far not sufficient and that the settling efficiency was reduced due to important sediment deposits. He proposed a new sand trap design with continuous automatic sediment evacuation and higher settling efficiency. With the new sand trap, the turbines needed revision every 8000 operating hours, whereas before they needed to be completely replaced after 2000 operating hours. Dufour's flushing system consists of a series of inclined slats between the bottom of a sand trap basin and a pressurized flushing channel below with an outlet valve.

Another early example of better sediment exclusion has been reported from the high-head HPP Ackersand (4 x 4.5 MW Pelton turbines, H = 700 m) in Switzerland [8]. With two parallel sand trap basins which were flushed intermittently, the efficiency of the turbines at design discharge dropped by 13 % during the sediment-rich year 1918. In winter, the sand trap was improved by implementing a continuous flushing system and tranquilizer racks at the inlets of the basins. After the modification of the sand trap, the efficiency drop of the turbines at design discharge was reduced to 6 % in 1919, the costs for turbine maintenance and spare parts were 70 % lower, and downtimes of the HPP were reduced by 95 %. With the improved sand trap, the turbine water contained only particles smaller than 0.5 mm (figure 3b) and the SSC in the turbine water was reduced accordingly. Before, particles up to 12 mm diameter (highlighted in figure 3a) passed the turbines, especially when the sand trap was temporarily operated at overload due to flushing of one basin with complete water level drawdown.

Further systems to evacuate sediment deposits from sand traps without water level drawdown have been developed since then, e.g. 'Bieri', '4S' (Serpent Sediment Sluicing System), 'SediCon Sluicer' and 'HSR (Hochschule Rapperswil)' [9] [10] [11]. The oldest sand trap flushing system, i.e. flushing with supercritical flow, is also still in use today. This simple system may have advantages when the water contains large quantities of fine driftwood, leaves or grass which might block advanced flushing systems. In rivers with high transport of coarse sediment, separate gravel traps upstream of sand traps may be advantageous. The following points remain important for sand trap design:

- Achieve a high trap efficiency by favorable hydraulic conditions at the inlet (geometry of the expansion, tranquilizer racks), flow guidance and avoiding of resuspension;
- Maintain a high trap efficiency by suitable flushing systems, i.e. preferably without interruption of operation, requiring only small volumes of flushing water and low maintenance.

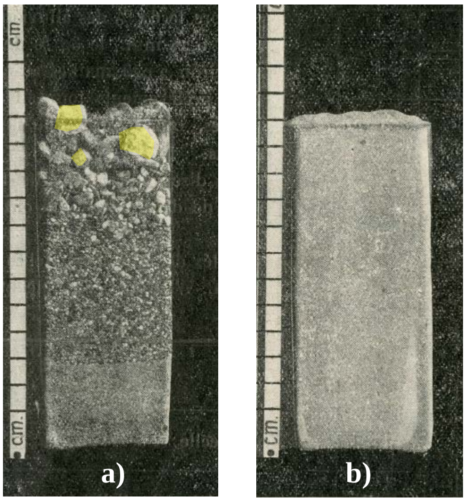

Figure 3.
Sediment sampled in the turbine water at the high-head Pelton HPP Ackersand, Switzerland in 1918/1919 [8]
a) before and
b) after improvement of the sand trap

3.2. Closing of intakes and turbine switch-offs

High sediment loads in the turbine water can be reduced not only by sediment exclusion facilities, but also with operational measures such as closing of intakes and pausing of turbine operation (switch-off) during floods or other events with high SSC and transport of larger particles. In the last decades, instruments for continuous real-time measurements of sediment levels, SSC and particle sizes have become available and have been installed in some HPPs [12] [13]. Such instruments allow for remote real-time monitoring with less effort. Decisions for HPP operation can be taken based on such sediment data, together with real-time (or forecast) weather and discharge data.

4. Progress in improving the turbine design and increasing the erosion resistance

4.1. General

In addition to reducing the sediment load, improved turbine design and increased resistance of turbine parts have contributed to mitigate turbine erosion. With well-designed geometries, cavitation is avoided for new turbine parts. Like this, not only damages due to cavitation, but also due to the synergy-effect of cavitation and hydro-abrasive erosion are avoided. However, cavitation may still occur on turbine parts with degraded hydraulic profiles.

The possibilities of increasing the erosion resistance of turbine parts are limited, because materials need to have not only high hardness, but also high toughness, resistance to fatigue and good machinability. Early turbine runners were made of cast iron. The advantages of using stainless steel were recognized and field-tested already in 1934 [4]. A martensitic stainless steel with 13 % chrome and 4 % nickel has become the standard material for hydraulic turbine parts [1]. Such steel has a Mohs hardness of 4.5 to 5. In many mountain ridges, igneous rocks are present which typically contain high percentages of harder minerals such as quartz and feldspar (Mohs hardness 7 and 6, respectively). Various surface treatments and e.g. chrome coatings were developed and tested over decades, but the progress was relatively small because the surface hardness of the turbine parts was not higher than the hardness of such mineral particles.

A significant step in the reduction of turbine erosion was the use of hard-coatings made of tungsten carbide, cobalt and chrome (WC-CoCr) [14]. This type of coating is particularly resistant to particles impinging at low angles or sliding on turbine parts [5]. Hard-coatings are applied by high velocity oxy fuel (HVOF). The quality of coatings may differ among suppliers because of the properties of the coating powder, the preparations and the spraying process. Hard-coatings have been increasingly used on Francis and Pelton turbine parts since the 1980s [15] [16] [17], and have become the state-of-the-art for Francis and Pelton turbine parts [2].

4.2. Coating of Francis turbines

In Francis turbines, coating can be applied on selected or all parts in contact with the water. An early example of a partly hard-coated Francis runner was in HPP Pradella (4 x 72 MW, H = 484 m) in Switzerland. Full coating was not possible on this medium-size high-head Francis runner, due to limited accessibility with the spray gun. Although the coating had been applied only partly, the efficiency drop was slowed down considerably.

Fully coated Francis turbines have been in operation for example at HPP Karcham Wangtoo (4 x 25 MW, H = 298 m) in India since 2011. After three monsoon seasons with SSC up to 8 g/l, the coating was removed from only about 5 % of the area [2]. Although the coating does not fully prevent erosion of the base material, the times between overhauls were extended. For relatively small coated Francis runners, whose blade surfaces are not fully accessible with the spray gun, a bolted construction is an option [18]. With this approach, the pieces of the runner are assembled after coating.

4.3. Coating of Pelton turbines

In Pelton turbines at sites with high erosion potential, hard-coating is typically applied in the buckets of runners as well as on cones and seat rings of injectors, if the injector parts are not made of other material with high resistance to erosion (e.g. steel-cobalt-alloys such as 'stellite').

Hard-coating contributed to reduce turbine erosion for example in HPP Fieschertal, Switzerland (2 x 32 MW, H = 520 m): In contrast to the earlier pronounced full-surface erosion with a scaly pattern inside uncoated buckets (similar to figure 4a), the coating inside the buckets prevented erosion of the base material (figure 4b). During a sediment season, the coating was only removed from the splitter crests and the entrance lips of the cut-outs [19]. The coating was repaired every winter directly in the turbine casing with a hand-held HVOF-spray gun, after rounding of bluntly eroded splitters and cut-out edges by grinding. Coatings sprayed on-site may have inferior quality compared to factory coatings, but runners do not need to be changed and transported. With on-site re-coating, frequent coating repairs are feasible, which contributes to limit the erosion propagation. With this maintenance strategy, measured reductions in turbine efficiencies were $\leq$ 1 % per sediment season in the years 2012-2014 [19].

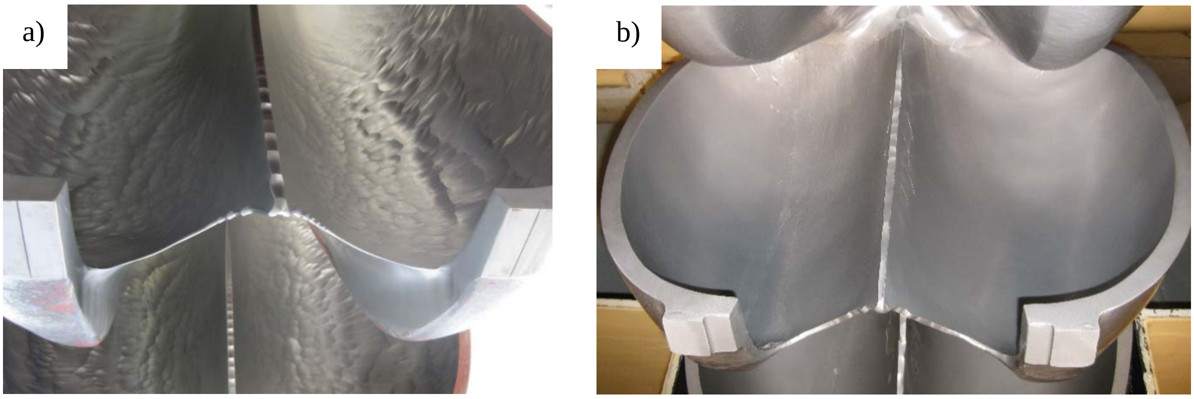

Figure 4. Pelton buckets with typical erosion: **a)** uncoated (HPP Emosson, Switzerland, runner out of service) and **b)** coated (HPP Fieschertal, Switzerland, 2012) (pictures: VAW, ETH Zürich).

In another example, at HPP Alfalfal, Chile (2 x 89 MW, H = 690 m), hard-coating also protected most of the bucket area from erosion and the coating was eroded from splitters and cut-outs. With an erosion potential higher than at HPP Fieschertal, the base material in these zones was considerably eroded and the turbine efficiency dropped by some percent during three months [2]. Although turbine erosion cannot fully be prevented in such severe conditions, hard-coating has led to tripling of the times between overhauls and the eroded steel mass has been reduced to one quarter [2].

5. Progress in research and modelling of hydro-abrasive erosion

5.1. Erosion mechanisms and analytical approaches

Bergeron (1950) [20] analytically studied hydro-abrasive erosion in centrifugal pumps and distinguished two modes of erosion by solid particles: (i) particle impact, and (ii) particle sliding along a curved wall. For (i) he postulated that the eroded mass is proportional to the difference in kinetic energy of a particle before and after the impact. For a single particle, the erosion is thus approximately proportional to the square of its relative velocity w before the impact. The number of impacts per unit time increases with w [21]. Thus, the eroded mass per unit time is approximately proportional to w^3.

For (ii), i.e. erosion due to sliding particles, Bergeron – and Bovet (1958) [7] – derived that the erosion rate is proportional to the friction power. The friction power is inversely proportional to the radius of curvature and again proportional to the third power of the relative velocity w^3.

Finnie (1960) and Bitter (1963) contributed to the theoretical understanding of these two types of erosion, which are also called erosion due to ‘deformation’ and due to ‘cutting’, respectively. Preece and Macmillan [22] reviewed the literature on erosion until 1977. An overview on erosion models has been given by Meng and Ludema (1995) [23]. Literature on erosion in hydraulic turbines has been reviewed by Truscott (1971) [24], as well as by Padhy and Saini (2008) [25].

5.2. Laboratory investigations

Several laboratory tests for the investigation of the erosion resistance of materials are described in [1]. Such tests yield the relative erosion resistance compared to a reference material. The erosion resistances obtained from various test methods may differ considerably among each other and from those in real-scale turbines. The type of erosion (angle of attack, etc.) depends also on the locations within Francis or Pelton turbines. Hence specific test setups are required to realistically investigate a certain type of turbine erosion in the laboratory. Several series of erosion tests have been conducted over decades (table 1). Such laboratory tests gave valuable insight into the effects of single parameters, e.g. SSC, relative velocity w, or angle of attack on the erosion rate. For example, velocity exponents were found to range between 2 and 4 [1] with a majority around 3 [24], which are similar to the analytical considerations mentioned above.

Table 1. Selected experimental laboratory investigations on hydro-abrasive erosion

Investigators and references	Type of test rig, velocity range	Remarks
Ilgaz 1952 [26]	Jet-type, 26 - 44 m/s	Tests on metal plates with varying angle; one of the first jet-type test rigs with sand in water found in the literature
Grein and Krause 1994 [27]	Rotating shaft, up to 80 m/s	Highly turbulent flow in gap between rotating shaft and specimens fixed on its housing; laboratory results were compared to field data (erosion depths on uncoated Pelton buckets)
Thapa 2004 [28]	Jet-type, up to 80 m/s	Tests on plates with varying angle and on specimens with a splitter and curvature, also with soft- and hard-coatings
Winkler et al. 2011 [29]	Jet-type, 40 - 85 m/s	Tests on plates and real-scale splitter specimens (with reduced jet diameter), also with hard-coatings
Grewal et al. 2013 [30]	Jet-type, 4 and 16 m/s	Tests on plates with varying angle; references given to ten other laboratory studies of erosion on 13Cr4Ni-steel

5.3. Empirical relations based on laboratory and field investigations

Nozaki (1990) [31] compiled field data on turbine erosion of HPPs in South America. He proposed a 'modified SSC' to consider the effects of particle size, shape (angularity), hardness, and the resistance of the turbine material on the erosion rate. Nozaki established outstanding diagrams from which the times between overhauls of uncoated Francis and Pelton turbine parts can be read as a function of the net head and the time-averaged modified SSC (figure 5a) [9] [32]. However, the application of the diagrams is limited because (i) it is not clear which extent of erosion or efficiency loss had been accepted until turbine overhauls, and (ii) coated turbine parts were not treated at that time.

Nozaki's diagrams have also been used to economically optimize the size of sand traps: In the example of HPP Kukule Ganga, Sri Lanka, the design particle size was varied between 0.2 mm and 0.5 mm, and the corresponding costs of (i) the construction of the sand trap and (ii) the maintenance/ replacement of the Francis turbines were estimated (figure 5b) [33]. With a moderate head of 185 m and a relatively low average SSC = 0.02 g/l, the minimum total cost was found with a design particle size of 0.3 mm, which is a typical value.

In 2013, a semi-empirical equation for prediction of erosion depths has been proposed in IEC 62364 [1] based on a literature review of various erosion models. Model parameters for uncoated Francis turbine parts were determined based on data obtained from seven HPPs mainly in China.

A few field investigations on turbine erosion in some HPPs worldwide are partly published, e.g. [12] [13] [15] [19] [34] [35] [36]. A systematic evaluation of the published data to determine parameters for erosion models is however difficult because (i) measured parameters and conditions are not always comparable, and (ii) not all required information is available.

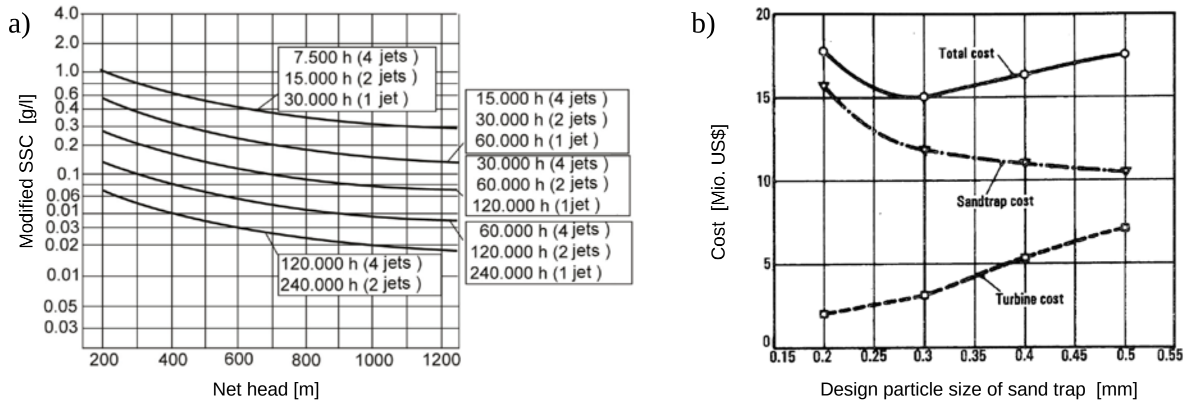

Figure 5. a) Operation hours between overhauls of uncoated Pelton runners according to Nozaki [31] (published in [32]) and **b)** Example of the determination of the limit particle size for a sand trap based on economic optimization [33].

5.4. Numerical simulations

More recently, mechanistic or semi-empirical erosion equations have been implemented in numerical simulation codes. The numerical simulation involves the determination of flow velocities (flow field) and SSC close to turbine parts. Depending on the implemented erosion model, the particle impingement rate and angle of attack, as well as the material removal are determined. This last step depends on the material properties and the behavior of the eroded material which is reflected by constitutive models.

For Francis turbines, spatially distributed relative erosion rates on runner blades have been simulated [37] [38], using the erosion model by Finnie (1960) which is summarized in [23]. In [38] the reduction of coating thickness on guide vanes and blades was also measured, but no quantitative comparison of numerically determined and measured erosion rates was presented. Numerical simulations of relative erosion rates were used to optimize the shapes of Francis runner blades [39].

For Pelton turbines, the simulation of the flow field is a particularly challenging task because of the 3d-free-surface flow (figure 6a). In addition to grid-based methods (e.g. Volume Of Fluid VOF), also mesh-free methods such as Smoothed Particle Hydrodynamics (SPH) or Finite Particle Volume Method (FPVM) have been further developed. They have been used to simulate the flow in Pelton buckets, as well as the particle movements and erosion under less complex conditions, e.g. for an inclined particle-laden jet on a stationary plate [40] [41]. The effect of particle size on the erosion of Pelton splitters was studied in [29]. Simulation showed that particles approaching directly above the splitter impinge on the splitter when they have a diameter of 80 µm (figure 6b), whereas smaller particles (20 µm) rather follow the streamlines around the splitter (figure 6c).

So far, not all processes can be simulated numerically, e.g. erosion on coated parts with local loss of coating and subsequent erosion of base material including secondary damages due to cavitation.

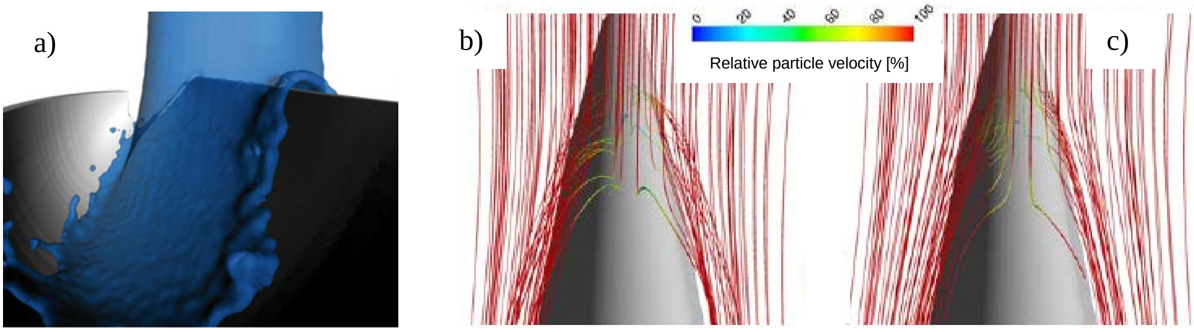

Figure 6. Examples of numerical simulation results at the splitter of a Pelton bucket: **a)** flow [40], and trajectories of particles with diameters of **b)** 80 µm and **c)** 20 µm [29].

6. Conclusions and Outlook

Hydro-abrasive erosion has been mitigated since the early 20th century by reducing the sediment load and improving turbine designs and materials, in particular by applying hard-coatings since the 1980s. Although it is not possible to fully prevent erosion damages, erosion-induced costs and electricity generation losses have been reduced.

Modelling and predicting hydro-abrasive erosion are challenging because of the many parameters involved and their complex interactions. Semi-empirical equations and numerical simulation models need calibration and validation based on data which have been and need to be acquired at HPPs and in laboratories. For the planning and design of HPPs with respect to sediment handling and mitigation of turbine erosion, operation experience remains an important source of information.

Proven measuring techniques are available for the real-time monitoring of SSC, particle sizes, turbine erosion and efficiency with high temporal resolution. Such monitoring data serve as a sound basis for decision making in operation and maintenance.

Significant improvements to mitigate hydro-abrasive erosion have been achieved so far. Further analytical, laboratory, field and numerical investigations are recommended to foster future development in this interdisciplinary field. A good collaboration between engineers and scientists working in the design and manufacturing of hydro-mechanical equipment and measuring systems, HPP operators, consultants and research institutes is required. This will contribute to further improve the energy- and cost-efficient use of the worldwide hydropower potential, also at medium- and high-head run-of-river HPPs on watercourses with high SSC and hard mineral particles.

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References

[1] IEC 62364 2013 *Guide for dealing with hydro-abrasive erosion in Kaplan, Francis, and Pelton turbines* Edition 1.0 (Geneva: International Electrotechnical Commission)

[2] Winkler K 2014 Hydro-abrasive erosion: problems and solutions *Proc. 27th IAHR Symposium on Hydraulic Machinery and Systems* Montreal, Canada *IOP Conf. Series* **22** 052022

[3] Neopane H P, Dahlhaug O G and Cervantes M 2011 Sediment Erosion in Hydraulic Turbines *Global J. of researches in Engineering, Mechanical and Mechanics engineering* **11**(6)

[4] Faletti N 1934 L'erosione e la corrosione delle turbine idrauliche (Erosion and corrosion of hydraulic turbines) *L'energia elettrica* **11** 277 (in Italian)

[5] Gummer J H 2009 Combating Silt Erosion in Hydraulic Turbines *Hydro Review Worldwide* **17**(1)

[6] Dufour H 1936 Entkiesungs- und Entsandungsanlage der Kraftwerke Pont-de-Claix und Drac-Inférieur (Gravel and sand traps of HPPs Pont-de-Claix and Drac-Inférieur) *Schweizerische Bauzeitung* **108**(12) 125 (in German)

[7] Bovet T 1958 Contribution à l'étude du phénomène d'érosion par frottement dans le domaine des turbines hydrauliques (Contribution to the study of abrasive erosion in hydraulic turbines) *Bulletin technique de la Suisse romande* **84**(3) 37 (in French)

[8] Dufour H 1921 L'usure des turbines hydrauliques et ses conséquences et les moyens d'y parer (Wear of hydraulic turbines, consequences and countermeasures) (Grenoble: J Rey); also in *La Houille Blanche* **1920**(6) 233, **1921**(1) 18, **1921**(2) 53 and **1921**(3) 97 (in French)

[9] Ortmanns C 2006 Entsander von Wasserkraftanlagen (Sand traps of HPPs) *PhD thesis VAW-Mitteilung* **193** (ed H E Minor), ETH Zurich, Switzerland (in German)

[10] Jacobsen T and Jiménez A 2015 Recent experiences from sediment removal projects *Proc. Hydro Conf.* Bordeaux, France, paper no. 28.08

[11] Truffer B, Küttel M and Meier J 2009 Wasserfassung Titer der GKW – Entsanderabzüge System HSR in grossen Entsanderanlagen (Sand evacuation system HSR in large sand traps) *Wasser Energie Luft* **101**(3) 207 (in German)

[12] Boes R 2009 Real-time monitoring of SSC and PSD in the headwater way of a high-head hydropower plant *Proc. 33rd IAHR Concress* Vancouver, Canada 11026 4037

[13] Felix D, Albayrak I, Abgottspon A and Boes R M 2016 Real-time measurements of suspended sediment concentration and particle size using five techniques *Proc. 28th IAHR Symposium on Hydraulic Machinery and Systems* Grenoble, France *IOP Conf. Series*

[14] Karimi A, Verdon C, Martin J L and Schmid R K 1995 Slurry erosion behaviour of thermally sprayed WC-M coatings *Wear* **186-187** 480

[15] Kalberer A 1988 Erfahrungen mit neuartigen Beschichtungen im Wasserturbinenbau (experiences with new types of coatings for hydraulic turbines) *VAW-Mitteilung* **100** (ed D Vischer) ETH Zürich, Switzerland, p 245 (in German)

[16] Sidhu S S 1999 Experience of coating and successful field tests of coated guide vanes at Baira Siul HEP *Proc. 1st Intl. Conf. on Silting Problems in Hydro Power Plants* New Delhi, India eds C V J Varma *et al* (Rotterdam/Brookfield: Balkema) paper no. 28

[17] Engelhardt M, Schneider C and Oechsle D 2001 Real scale performance of advanced erosion protection techniques on water turbines *Proc. 2nd Intl. Conf. on Silting Problems in HPPs* Bangkok, Thailand eds S P Kaushish and B S K Naidu, p 168

[18] Dahlhaug O G, Skåre P E, Mossing V and Gutierrez A 2010 Erosion resistant coatings for Francis runners and guidevanes *Intl. J. on Hydropower & Dams* **17**(2) 109

[19] Abgottspon A, Staubli T and Felix D 2016 Erosion of Pelton buckets and changes in turbine efficiency measured in the HPP Fieschertal *Proc. 28th IAHR Symposium on Hydraulic Machinery and Systems* Grenoble, France *IOP Conf. Series*
[20] Bergeron P 1950 Similitude des usures causées par des mixtures liquide-solides (Similitude of wear caused by liquids carrying solids in suspension) *La Houille Blanche* **1950**(B) 716 (in French)
[21] Brekke H, Wu Y L and Cai B Y 2002 Design of Hydraulic Machinery Working in Sand Laden Water *Abrasive Erosion & Corrosion of Hydraulic Machinery* eds C G Duan und V Y Karelin (London: Imperial College Press) pp 155-233
[22] Preece C and Macmillan N H 1977 Erosion *Annual Review of Materials Science* **7** 95
[23] Meng H C and Ludema K C 1995 Wear models and predictive equations: their form and content *Wear* **181-183** 443
[24] Truscott G F 1971 A literature survey on abrasive wear in hydraulic machinery *Wear* **20** 29
[25] Padhy M K and Saini R P 2008 A review on silt erosion in hydro turbines *Renewable and Sustainable Energy Reviews* **12**(7) 1974
[26] Ilgaz C 1952 Etude de l'usure d'une surface plane par un jet d'eau chargé de sable (Study of the wear of a plane surface by a sand laden jet of water) *La Houille Blanche* **1952**(4) 554 (in French)
[27] Grein H and Krause M 1994 Research and Prevention of Hydroabrasive Wear *Proc. 17th IAHR Symposium on Hydraulic Machinery* Beijing, China
[28] Thapa B 2004 Sand Erosion in Hydraulic Machinery *PhD thesis* NTNU Trondheim, Norway
[29] Winkler K, Dekumbis R, Rentschler M, Parkinson E and Garcin H 2011 Understanding hydro-abrasive erosion *Proc*. *Hydro Conf.* Prague, Czech Republic, paper no. 02.05
[30] Grewal H S, Agrawal A and Singh H 2013 Slurry erosion mechanism of hydroturbine steel: Effect of operating parameters *Tribol Lett* **52** 287
[31] Nozaki T 1990 Estimation of repair cycle of turbine due to abrasion caused by suspended sand and determination of desilting basin capacity *Japan Intl. Cooperation Agency*, Tokyo
[32] Ortmanns C 2006 A new design of desilting chambers of hydro power plants *Proc. Hydro Conf.* Porto Carras, Greece
[33] Moric P 1996 Optimizing Desilting Facilities for Hydro Plants *Intl. J. on Hydropower & Dams* **3**(6) 31
[34] Singh M, Banerjee J, Patel P L and Tiwari H 2013 Effect of silt erosion on Francis turbine: a case study of Maneri Bhali Stage-II, Uttarakhand, India *ISH J. of Hydr. Eng.* **19**(1) 1
[35] Bajracharya T R, Acharya B, Joshi C B, Saini R P and Dahlhaug O G 2008 Sand erosion of Pelton turbine nozzles and buckets: A case study of Chilime hydropower plant *Wear* **264** (3-4) 177
[36] Padhy M K and Saini R P 2011 Study of silt erosion on performance of a Pelton turbine *Energy* **36**(1) 141
[37] Neopane H P 2010 Sediment Erosion in Hydro Turbines *PhD thesis* NTNU, Trondheim, Norway
[38] Guangjie P, Zhengwei W, Yexiang X and Yongyao L 2013 Abrasion predictions for Francis turbines based on liquid-solid two-phase fluid simulations *Engineering Failure Analysis* **33** 327
[39] Khanal K, Neopane H P, Rai S, Thapa M, Bhatt S and Shrestha R 2016 A methodology for designing Francis runner blade to find minimum sediment erosion using CFD *Renewable Energy* **87**(1) 307
[40] Vessaz C, Jahanbakhsh E and Avellan F 2015 Flow Simulation of Jet Deviation by Rotating Pelton Buckets Using Finite Volume Particle Method *J. of Fluids Eng.* **137**(7) 074501
[41] Jahanbakhsh E 2014 Simulation of Silt Erosion Using Particle-Based Methods *PhD thesis* no. 6284, Laboratory for Hydraulic Machines, EPFL Lausanne, Switzerland