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Hydraulic machines – Guide for dealing with hydro-abrasive erosion in Kaplan, Francis, and Pelton turbines

Machines hydrauliques – Guide relatif au traitement de l'érosion hydro-abrasive des turbines Kaplan, Francis et Pelton

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IEC Central Office
3, rue de Varembé
CH-1211 Geneva 20
Switzerland

Tel.: +41 22 919 02 11
Fax: +41 22 919 03 00
info@iec.ch
www.iec.ch

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The text of this standard is based on the following documents:

FDIS	Report on voting
4/279/FDIS	4/283/RVD

Full information on the voting for the approval of this standard can be found in the report on voting indicated in the above table.

This publication has been drafted in accordance with the ISO/IEC Directives, Part 2.

The committee has decided that the contents of this publication will remain unchanged until the stability date indicated on the IEC web site under "http://webstore.iec.ch" in the data related to the specific publication. At this date, the publication will be

- reconfirmed,
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- replaced by a revised edition, or
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INTRODUCTION

Many owners of hydroelectric plants contend with the sometimes very aggressive deterioration of their machines due to particle abrasion. Such owners must find the means to communicate to potential suppliers of machines for their sites, their desire to have the particular attention of the designers at the turbine design phase, directed to the minimization of the severity and effects of particle abrasion.

Limited consensus and very little quantitative data exists on the steps which the designer could and should take to extend the useful life before major overhaul of the turbine components when they are operated under severe particle abrasion service. This has led some owners to write into their specifications, conditions which cannot be met with known methods and materials.

HYDRAULIC MACHINES –
GUIDE FOR DEALING WITH HYDRO-ABRASIVE EROSION IN KAPLAN, FRANCIS, AND PELTON TURBINES

1 Scope

This Guide serves to:

a) present data on particle abrasion rates on several combinations of water quality, operating conditions, component materials, and component properties collected from a variety of hydro sites;

b) develop guidelines for the methods of minimizing particle abrasion by modifications to hydraulic design for clean water. These guidelines do not include details such as hydraulic profile shapes which should be determined by the hydraulic design experts for a given site;

c) develop guidelines based on "experience data" concerning the relative resistance of materials faced with particle abrasion problems;

d) develop guidelines concerning the maintainability of abrasion resistant materials and hard facing coatings;

e) develop guidelines on a recommended approach, which owners could and should take to ensure that specifications communicate the need for particular attention to this aspect of hydraulic design at their sites without establishing criteria which cannot be satisfied because the means are beyond the control of the manufacturers;

f) develop guidelines concerning operation mode of the hydro turbines in water with particle materials to increase the operation life;

It is assumed in this Guide that the water is not chemically aggressive. Since chemical aggressiveness is dependent upon so many possible chemical compositions, and the materials of the machine, it is beyond the scope of this Guide to address these issues.

It is assumed in this Guide that cavitation is not present in the turbine. Cavitation and abrasion may reinforce each other so that the resulting erosion is larger than the sum of cavitation erosion plus abrasion erosion. The quantitative relationship of the resulting abrasion is not known and it is beyond the scope of this guide to assess it, except to recommend that special efforts be made in the turbine design phase to minimize cavitation.

Large solids (e.g. stones, wood, ice, metal objects, etc.) traveling with the water may impact turbine components and produce damage. This damage may in turn increase the flow turbulence thereby accelerating wear by both cavitation and abrasion. Abrasion resistant coatings can also be damaged locally by impact of large solids. It is beyond the scope of this Guide to address these issues.

This guide focuses mainly on hydroelectric powerplant equipment. Certain portions may also be applicable to other hydraulic machines.

2 Terms, definitions and symbols

2.1 Units

The International System of Units (S.I.) is adopted throughout this guide but other systems are allowed.

2.2 Terms, definitions and symbols

For the purposes of this document, the following terms, definitions and symbols apply.

NOTE They are also based, where relevant, on IEC/TR 61364.

Sub-clause	Term	Definition	Symbol	Unit
2.2.1	specific hydraulic energy of a machine	specific energy of water available between the high and low pressure reference sections 1 and 2 of the machine Note 1 to entry: For full information, see IEC 60193.	E	J/kg
2.2.2	acceleration due to gravity	local value of gravitational acceleration at the place of testing Note 1 to entry: For full information, see IEC 60193.	g	m/s^2
2.2.3	turbine head pump head	available head at hydraulic machine terminal $H = E/g$	H	m
2.2.4	reference diameter	reference diameter of the hydraulic machine Note 1 to entry: For Pelton turbines this is the pitch diameter, for Kaplan turbines this is the runner chamber diameter and for Francis and Francis type pump turbines this is the blade low pressure section diameter at the band Note 2 to entry: See IEC 60193 for further information.	D	m
2.2.5	abrasion depth	depth of metal layer that has been removed from a component due to particle abrasion	S	mm
2.2.6	characteristic velocity	characteristic velocity defined for each machine component and used to quantify particle abrasion damage Note 1 to entry: See also 2.2.20 to 2.2.24.	W	m/s
2.2.7	particle concentration	the mass of all solid particles per m^3 of water solution Note 1 to entry: In case the particle concentration is expressed in ppm it is recommended to use the mass of particles per mass of water, so that 1 000 ppm approximately corresponds to 1 kg/m^3.	C	kg/m^3
2.2.8	particle load	the particle concentration integrated over the time, T, that is under consideration $PL = \int_0^T C(t) \times K_{\text{size}}(t) \times K_{\text{shape}}(t) \times K_{\text{hardness}}(t)\,dt$ $\left(\approx \sum_{n=1}^{N} C_n \times K_{\text{size},n} \times K_{\text{shape},n} \times K_{\text{hardness},n} \times T_{s,n} \right)$ $C(t)$ = 0 if no water is flowing through the turbine. If the unit is at standstill with pressurized spiral case then $C(t)$=0 when calculating PL for runner and labyrinth seals, but $C(t) \neq 0$ when calculating PL for guide vanes and facing plates.	PL	kg × h/m^3
2.2.9	size factor	factor that characterizes how the abrasion relates to the size of the abrasive particles	K_{size}	
2.2.10	shape factor	factor that characterizes how the abrasion relates to the shape of the abrasive particles	K_{shape}	
2.2.11	hardness factor	factor that characterizes how the abrasion relates to the hardness of the abrasive particles	K_{hardness}	

Sub-clause	Term	Definition	Symbol	Unit
2.2.12	material factor	factor that characterizes how the abrasion relates to the material properties of the base material	K_m	
2.2.13	flow coefficient	coefficient that characterizes how the abrasion relates to the water flow around each component	K_f	$\frac{mm \times s^{3,4}}{kg \times h \times m^{\alpha}}$
2.2.14	sampling interval	the time interval between two water samples taken to determine the concentration of abrasive particles in the water	T_s	h
2.2.15	yearly particle load	the total *PL* for 1 year of operation, i.e. *PL* for *T* = 8 760 h calculated in accordance with 2.2.8	PL_{year}	kg × h/m³
2.2.16	maximum concentration	the maximum concentration of abrasive particles over a specified time interval	C_{max}	kg/m³
2.2.17	particle median diameter	the median diameter of abrasive particles in a sample, i.e. such diameter that the particles with size smaller than the value under consideration represent 50 % of the total mass of particles in the sample	dP_{50}	mm
2.2.18	wear resistance index	abrasion depth or volume of a reference material (generally some version stainless steel) divided by the abrasion depth or volume of the material in question, tested under the same conditions	*WRI*	-
2.2.19	impingement angle	the angle between the particle trajectory and the surface of the substrate		°
2.2.20	characteristic velocity in Francis guide vanes characteristic velocity in Kaplan guide vanes	flow through unit divided by the minimum flow area at the guide vane apparatus estimated at best efficiency point $W_{gv} = \frac{Q}{a \times Z_0 \times B_0}$	W_{gv}	m/s
2.2.21	characteristic velocity in guide vanes of Kaplan, Francis or tubular turbines	speed of the water flow at guide vane location $W_{gv} = 0{,}5 \times \sqrt{2 \times E}$	W_{gv}	m/s
2.2.22	characteristic velocity in Pelton injector	speed of the water flow at injector location $W_{inj} = \sqrt{2 \times E}$	W_{inj}	m/s
2.2.23	characteristic velocity in Kaplan or Francis tubular turbine runner	the relative velocity between the water and the runner blade estimated with below formulas at best efficiency point $W_{run} = \sqrt{{u_2}^2 + {c_2}^2}$ $u_2 = n \times \pi \times D$ $c_2 = \frac{Q \times 4}{\pi \times D^2}$ Note 1 to entry: In calculation of c_2 for Kaplan turbines, the hub diameter has been neglected in the interest of simplicity.	W_{run}	m/s
2.2.24	characteristic velocity in Pelton runner	speed of the water flow at a Pelton runner $W_{run} = 0{,}5 \times \sqrt{2 \times E}$	W_{run}	m/s
2.2.25	discharge (volume flow rate)	volume of water per unit time passing through any section in the system	*Q*	m³/s
2.2.26	guide vane opening	average shortest distance between adjacent guide vanes (at a specified section if necessary)	*A*	m

Sub-clause	Term	Definition	Symbol	Unit
		Note 1 to entry: For further information, see IEC 60193.		
2.2.27	number of guide vanes	total number of guide vanes in a turbine	z_0	
2.2.28	distributor height	height of the distributor in a turbine	B_0	m
2.2.29	rotational speed	number of revolutions per unit time	n	1/s
2.2.30	specific speed	commonly used specific speed to of an hydraulic machine $n_\mathrm{s} = \frac{60 \times n \times \sqrt{P}}{H^{5/4}}$ P and H are taken in the rated operating point and given in kW and m respectively	n_s	
2.2.31	output	output of the turbine in the rated operating point	P	kW
2.2.32	actual abrasion depth of target unit	the estimated depth of metal that will be removed from a component of the target turbine due to particle abrasion Note 1 to entry: For use with the Reference model.	$S_\mathrm{target,\ actual}$	mm
2.2.33	actual abrasion depth of reference unit	the actual depth of metal that has been removed from a component of the reference turbine due to particle abrasion Note 1 to entry: For use with the Reference model.	$S_\mathrm{ref,\ actual}$	mm
2.2.34	number of nozzles	number of nozzles in a Pelton turbine	z_0	
2.2.35	bucket width	bucket width in a Pelton runner	B_2	mm
2.2.36	number of buckets	number of buckets in a Pelton runner	z_2	
2.2.37	time between overhaul for target unit	time between overhaul for target unit Note 1 to entry: For use with the reference model.	TBO_target	h
2.2.38	time between overhaul for reference unit	time between overhaul for reference unit Note 1 to entry: For use with the reference model.	TBO_ref	h
2.2.39	turbine reference size	the reference size for calculation curvature dependent effects of erosion Note 1 to entry: For Francis turbines, it is the reference diameter, D (see 2.2.4). Note 2 to entry: For Pelton turbines it is the inner bucket width, B. Note 3 to entry: For further information in the inner bucket width, B, see IEC 60609-2.	RS	m
2.2.40	size exponent	exponent that describes the size dependant effects of erosion in evaluating RS	p	
2.2.41	exponent	numerical value of 0,4-p that balances units for K_f	α	

3 Abrasion rate

3.1 Theoretical model

In order to demonstrate how different critical aspects impact the particle abrasion rate in the turbine, the following formula is considered:

$dS/dt = f$(particle velocity, particle concentration, particle physical properties, flow pattern, turbine material properties, other factors)

However, this formula being of little practical use, several simplifications are introduced. The first simplification is to consider the several variables as independent as follows:

$dS/dt = f$(particle velocity) × f(particle concentration) × f(particle physical properties, turbine material properties) × f(particle physical properties) × f(flow pattern) × f(turbine material properties) × f(other factors)

This simplification is not proven. In fact, many examples can be found where this simplification was not strictly valid. Nevertheless, based on literature studies and experience, this simplification is considered to be justified for hydraulic machines.

The next simplification consists in assigning values to the functions. In the following equations the numerical values for the parameters, without units, have to be used. The units in which the values should be based are given below:

- f(particle velocity) = (particle velocity)^n. In the literature abrasion is often considered proportional to the velocity raised to an exponent, n. Most references give values of n between 2 and 4. In this guide we suggest to use $n = 3{,}4$. Particle velocity in m/s,
- f(particle concentration) = particle concentration in kg/m^3,
- f(particle physical properties, turbine material properties) = K_{hardness} = function of how hard the particles are in relation to the material at the surface. At the present stage we suggest to use K_{hardness} = fraction of particles harder than the material at the surface,
- f(flow pattern) = $K_{\mathrm{f}}/RS^{\mathrm{p}}$ (K_{f} = constant for each turbine component, RS = turbine reference size in m, p = exponent for each turbine component). K_{f} considers impingement angle and flow turbulence. RS^{p} considers part curvature radius,
- f(particle physical properties) = f(particle size, particle shape, particle hardness) = f(particle size) × f(particle shape) = $K_{\mathrm{size}} \times K_{\mathrm{shape}}$. Note that in this simplification it as assumed that there is no influence from the particle hardness for this function. The particle hardness is considered in the K_{hardness} factor,
- K_{size} = median diameter of particles in mm,
- $K_{\mathrm{shape}} = f$(particle angularity). It is believed that K_{shape} will increase with the degree of irregularity of the particles. Specific data is not available at present but several literature references indicate that K_{shape} varies from 1 to 2 from round to sharp,
- f(turbine material properties) = K_{m}. In this guide we consider $K_{\mathrm{m}} = 1$ for martensitic stainless steel with 13 % Cr and 4 % Ni and $K_{\mathrm{m}} = 2$ for carbon steel. For coated components K_{m} should be smaller than 1,
- f(other factors) = 1.

Again, these functions are engineering approximations in order to obtain useful results for hydraulic machines. We then have the following formula

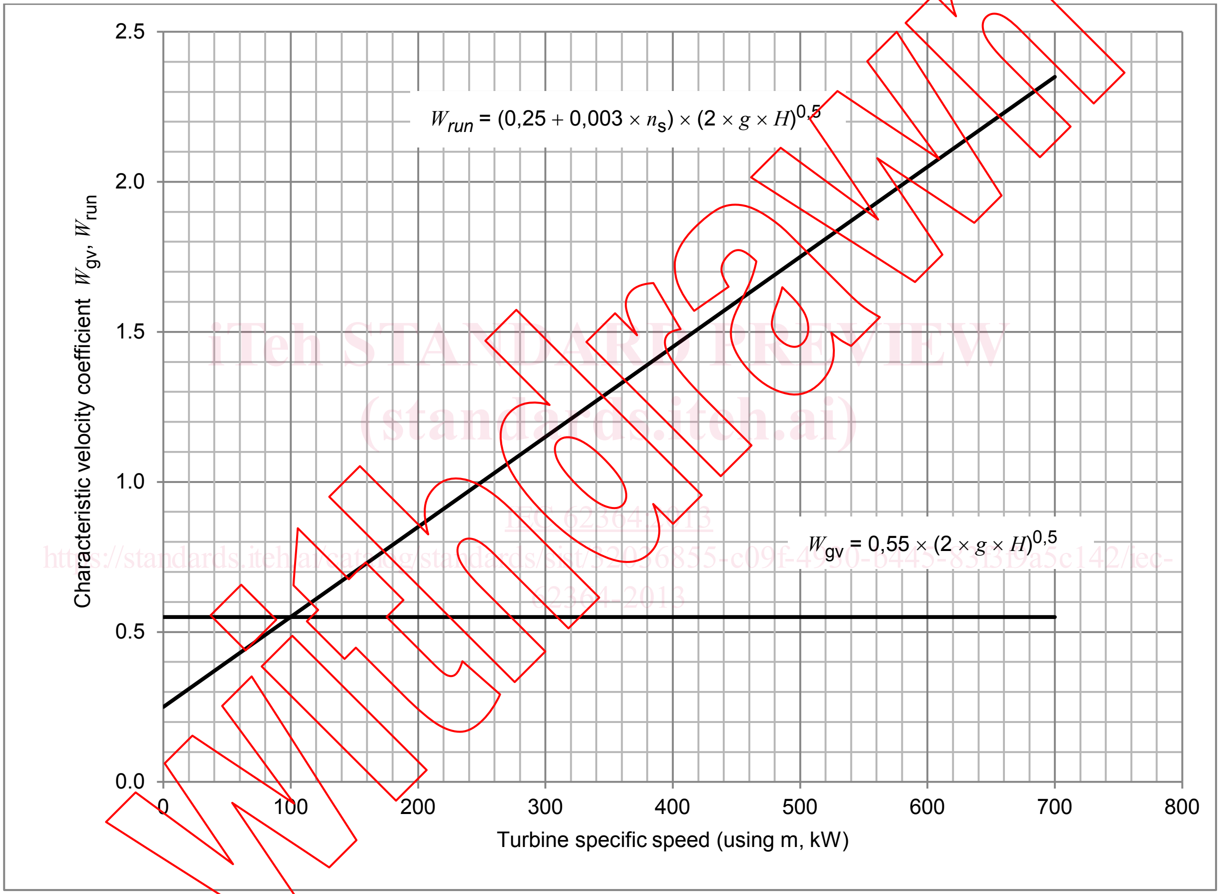
$$dS/dt = (\text{particle velocity})^{3{,}4} \times C \times K_{\mathrm{hardness}} \times K_{\mathrm{size}} \times K_{\mathrm{shape}} \times K_{\mathrm{f}}\,/RS^{\mathrm{p}} \times K_{\mathrm{m}}$$

The final step is to integrate this formula with respect to time. When we do this we find three distinct different types of variables with respect to their variations in time:

1) particle velocity and K_{f}: these variables vary with the water flow relative to the individual component, which in turn may vary with the head and flow;
2) C, K_{hardness}, K_{size} and K_{shape}: these variables vary with the particle properties. Integrated over time these variables become particle load, PL (see 2.2.8 for definition of PL and Annex A for a sample calculation);
3) RS, p and K_{m}: these variables are constant in time.

To find a simple and reasonably accurate estimate of the time integral, the PL variable (see 2.2.8) is introduced. PL integrates C, K_{hardness}, K_{size} and K_{shape} over time. When using PL, the particle velocity and K_{f} can be considered approximately constant over a limited variation of head and flow (see 3.2). Since these variables are considered constant, K_{f} and p were used as calibration factors to obtain good agreement between actual test data and the formula. The particle velocity can be replaced with the characteristic velocity, W, defined in 2.2.20 to 2.2.24.

W may be calculated for a specific turbine based on main data and dimensions. Since the effect of velocity on abrasion is proportional to the velocity raised to a power of 3,4 it is very important to estimate it accurately. For new turbines during design and bid stage, W for different components should be provided by the turbine manufacturer. When this is not possible, W can be estimated approximately from the diagram in Figure 1.



NOTE Values of ns and H in this figure refer to the rated operating point while the characteristic velocities are given for the points noted in 2.2.

Figure 1 – Estimation of the characteristic velocities in guide vanes, W_{gv}, and runner, W_{run}, as a function of turbine specific speed

So the final, time integrated formula becomes:

$$S = W^{3,4} \times PL \times K_{\mathrm{m}} \times K_{\mathrm{f}} / RS^{\mathrm{p}}$$

S is the numerical value of the abrasion depth in mm.

3.2 Introduction to the *PL* variable

In this code the PL variable has been introduced, which has not been widely used before. One common way to integrate abrasion over time has been to consider the total weight of particles