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CAVITATION EROSION OF THE BLADES IN BANKI-MICHEL TURBINE. OBSERVATIONS AND SOME ASPECTS OF THE PROCESS SIMULATION

KAWITACYJNE NISZCZENIE ŁOPATEK W TURBINIE BANKI-MICHELA. OBSERWACJE I WYBRANE ASPEKTY SYMULACJI PROCESU*

Prediction of cavitation erosion performance of the Banki-Michel turbine blades is a domain of the paper. Method based on the phenomenological simulation model has been tested. Experimental research were conducted in hydro power plant in Jeziorany (Poland). Methodology employed consists in determining the cumulative erosion curves for the blades and computing the corresponding theoretical curves. Compatibility of the experimental and theoretical dependences has been accomplished by calibrating the computational parameter values. Analysis of the correlations derived was carried out. As it was found, dependence of the computational parameters on the loading is weak, thus the loading can be accounted in the cavitation erosion prediction procedure as a factor.

Keywords: *Banki-Michel turbine, cavitation erosion, wear prediction.*

Praca dotyczy przewidywania kawitacyjnego niszczenia łopatek turbiny Banki-Michela w oparciu o fenomenologiczny symulacyjny model erozji. Badania eksperymentalne prowadzono w elektrowni wodnej w Jezioranach (Polska). Metodyka badań polegała na wyznaczeniu krzywych erozyjnych zużycia łopatek turbiny, wyznaczeniu odpowiadających im krzywych modelowych poprzez odpowiedni dobór parametrów obliczeniowych oraz dokonaniu analizy uzyskanych korelacji. Ustalono, że zależność parametrów równań modelowych od obciążenia jest niewielka, wobec czego w procedurze przewidywania obciążenie może być uwzględniane jako mnożnik.

Słowa kluczowe: *turbina Banki-Michela, erozja kawitacyjna, prognozowanie zużycia.*

1. Introduction

1.1. Motivation for the work

One of the major conditions of the correct maintenance of the small hydro power plants is regular and effective monitoring of the risk arising from cavitation or abrasion occurrence within the flow parts of the machines [2]. Evaluating the rate of the erosion of such subassemblies as blades, guide vanes, shafts and others during exploitation terms is completed by damage detection. Monitoring the degradation or failure hazard during the operating mode of the machine may be done by registration and analysis of the acoustic emission signal. Frequently met in engineering practice need to predict an effectiveness of the mass loss processes face the lack of the relevant tool for that purpose. Accessible phenomenological models of the erosion and their implementations in most cases do not fulfil the needs of specified applications. It is also the case of many complex and verified models of cavitation erosion (e.g. [5, 6, 9, 16, 18, 21, 23, 27, 31]) or prognostic methods based on scaling procedures [22, 30]. Development of the system for prediction of the random loss processes entails the limitations of its applicability are to be defined, especially in relation to real operating conditions of the hydro-turbine. The attempts to work out such a tool with respect to Francis turbine are presented in the works [4, 7].

In present work the preliminary investigations to verify correctness of the prognostic system for simulation of the cavitation erosion of the Banki-Michel turbine blades are presented – the system based on the model presented in [11, 12] and its numerical implementation [13]. An objective of the system in spe is prediction of cavitation or solid particle erosion as well as obtaining and analysis of various designs of the turbine by selection of the materials and loading conditions. Main capacities of the simulator as the computational element of the system comprise determination and modification of the erosion characteristics, determination of the erosion regimes and probability functions of the component sub-processes. The system needs average loadings are input. Values of the loadings are gained from the measurements. Evaluation of the loadings as a result of calculations of the two-phase flow of defined geometry is a task complicated so much that it has not been realized yet.

Potential benefits of the system implementation include reduction of the costs of designing, prototyping as well as the costs of maintenance and repairs of the turbines.

1.2. Object of investigation

Efficiency of Banki-Michel transverse flow turbines accounts for 0.70 up to 0.80 at the mass flow rate varying between 30–100 per cent of the maximum flow. The turbines work effectively regardless of the water head level (1–200 m) [10]. Water flow energy is transferred to the blades located at the upper or down position in different phases of the flow. The flow is formed according to geometry of the device, especially the shape and position of the guide vanes and control bed as well as the water velocity and mass flow at the outlet. Parameters and operating conditions of the turbines belonging to the type serie presented in [24] lie in the ranges: height 7–30 m, volume flow 0,07–1,5 m^3/s, power 5–200 kW, dynamic specific speed n_{sn}=114. During the

(*) Tekst artykułu w polskiej wersji językowej dostępny w elektronicznym wydaniu kwartalnika na stronie ***www.ein.org.pl*** annual duty cycle an appearance of cavitation is expected: (1) generation of the cavitation clouds within the diffusion zone over the surface of the blades and (2) generation of the jets containing the cavitation bubbles developed in the vortex cores. Conditions favouring the development of cavitation loadings were discerned [20, 24]:

(a) in a turbine interior and within the inter-blades region covering the rotation zone 270°–360° with respect to horizontal axis of the flow strong lowering of the pressure occurs resulting in development of the vortexes. The latter are moved into the zone of increased pressure in the vicinity of the guide vanes and execute the erosion of the blades.

(b) some of the vortexes move along the flow and reach the counter stockade of the blades, where collapse of the cavitating structures is either possible. Among others, the bubbles may vanish over the circulation line of the blade edges. The process depends on the flow characteristics and corresponding rotation velocity of the rotor.

(c) origination of the jets may be linked to failures of the guide vanes, especially a constrictions nearby the outlet zone. Erosion is developed at the convex surfaces and at the leading edge of the blades.

In particular cases the possibility of cavitation occurrence can be evaluated by calculation of the cavitation number for various operating points of the turbine. Prevalent damages of the blade induced by cavitation loadings are chiefly jags of irregular surface and irregular in-depth distributions as a result of chipping and spallation. Jags and depressions created due to cavitating jets action may be locally noticeably deep – up to 2–3 mm. At the developed stage of the erosion such failures may impend on the integrity of the subjected element.

Material destruction under cavitation loading encompass some discernible stages: the incubation stage characterized by the change of microstructure accompanied by micro-cracks generation and coalescence, the stage of accelerated erosion and the stage of quasi regular erosion. In the latter stage participation of the suppressing phenomena, as micro-cracks closure is significant.

1.3. The aim of the work

The aim of the present work is verification of some aspects of cavitation damage prediction of the Banki-Michel turbine blades with simulation model presented in [11]. The results contribute to development of the computational tool for evaluation of the cavitation erosion efficiency for application purposes. Particular aim is to support the thesis that quantification method based on deterministic model with parameters referred to properties of the material and with the loadings come in as scaling parameter is reasonably effective in the operating conditions.

1.4. Methodology

Methodology consisted in: (1) determination of the erosion curves in operating conditions of the machine for two different materials of the blades, (2) determination of the corresponding theoretical curves by selecting values of the model equations parameters and (3) establishing the appropriate correlations.

1.5. Range of the work

The range of the works involved: (1) preparation of the samples, (2) measurements of the volume loss of selected areas of the blades during maintenance controls – the filling method has been applied to map the morphology of the eroded blade, (3) adjustment of the experimental characteristics with theoretical ones by selection of the values of the model equations parameters, (5) assessment of the errors and uncertainties.

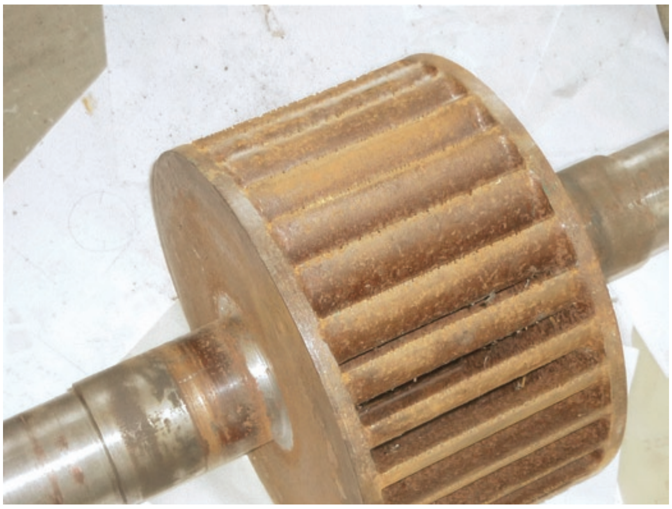


Fig. 1. Banki-Michel turbine employed for investigations. Maximum prospective power of the turbine was 13 kW

2. Experimental investigations

2.1. Measurement procedures

Investigations have been carried out in hydro-power plant in Jeziorany (Poland), ul. Kościuszki 24, 11-320 Jeziorany, located at the Symsarna river bed. Object belonged to Energetic Enterprise S.A. in Olsztyn. Height of the water upper level was 9 m. Fluctuating mass flow of the water depended on the hydro-meteorological conditions within the catchment area. Its average value during the period 2005-2009 years equalled 0.2 m^3/s. Object of investigation was Banki-Michel turbine installed to operate with horizontal in-flow configuration. The rotor of the turbine is presented in Fig. 1. Water flows twice through the stockade of the blades. An adjustment to various flow intensities was done due to proper division of the rotor and guide vanes. The length of the blades and the rotor diameter equalled 15 cm and 25 cm appropriately. The water flowed out of the turbine through the suction orifice. Some aeration valves were mounted in the region.

Six blades counter to the axis have been chosen for investigations. In order to trace the erosion since the beginning the chosen blades have been restored by the method of electrode cladding. Convex surfaces of the three blades and areas adjoin to the leading edge have been covered with welding wire material SP-1 (the trade name). Convex surfaces and areas adjoin to the leading edge of the remain blades have been covered with welding electrode material EB-150 (the trade name). The excessive material was abraded and original shapes of the blades were approximately restored. However, the significant roughness of the surfaces remained due to the lack of the polishing processing. Annealing processing has not been performed too, which influenced the process of cavitation erosion considerably. Three areas of 2 cm^2 each on the convex surface of each blade were chosen for quantification analysis. Total time of turbine operation stand for 10512 hours.

2.2. Determination of the cumulative erosion characteristics

The volume loss of the blade material detected over 164, 284 and 438 days of the turbine operation was the base of experimental reference of theoretical erosion curves. The following diagnostic methods were applied to estimation of the blade wear:

- the filling method for determination of the volume loss and mapping the surface profile and leading edge of the blade and
- the photo-recording of the damaged surface of the blades.

Surface morphology was mapped with low consistency light bodied paste KDD-KONDISIL V-3. It was low adhesive formula usable at peeling off the mould. The paste was featured by short time of the bonding, resistant to environmental agents and it did not yield to autodestruction.

Local volume loss were determined twofold: (1) by using the space scanner 3D VI-9i (Konica-Minolta) with objective of f=25 mm focal length and specialised software "RapidForm Veryfier", (2) by measuring the plaster cast volume. The measurement error was assessed as very substantial. It was the result of (1) inaccurate imaging of surface morphology, (2) insufficient precision in filling the pits and depressions and (3) difficulties in the choice of the proper reference plane for scanning due to rounding of the blade surface.

2.3. Results of the investigations

Some results of the experimental investigations as well as the results of corresponding model simulations are presented in Figures 2–5. Cumulative volume loss of the blade materials after some periods of the turbine operation can be found in Figs 2 and 4. The measurement errors are depicted in the diagrams. Exemplary pictures of the damaged segments of the blades and their geometrical imaging are presented in Figs 3 and 5.

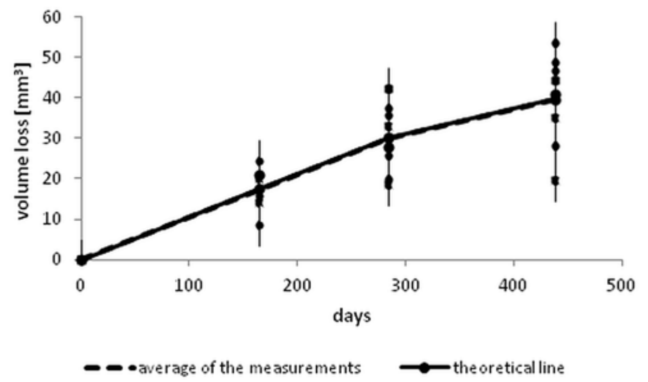
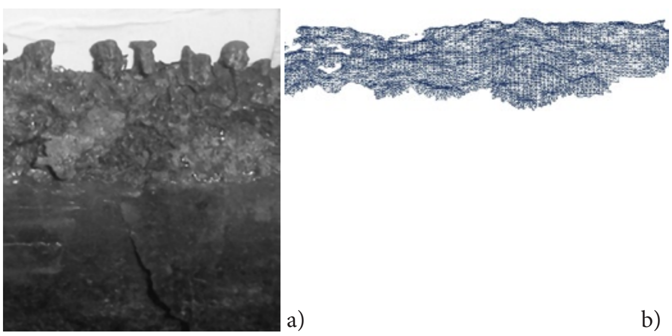


Fig. 2. Volume of the material lost from the surface area of 1 cm² of the blade restored with SP-1. Experimental points recorded during each control maintenance (164, 284 and 438 days of the turbine operation) refer to various blades and localisations. Continuous lines are line segments between the points averaged of the measurements and the corresponding line determined by model calculations



a) b)

Fig. 3. (a) Leading edge and the lateral surface picture taken in the middle zone of the blade No 22 (operating designation), made of the material SP-1 after 464 days of exploitation. (b) Geometrical image of the morphology of the damaged blade recorded with 3D scanner

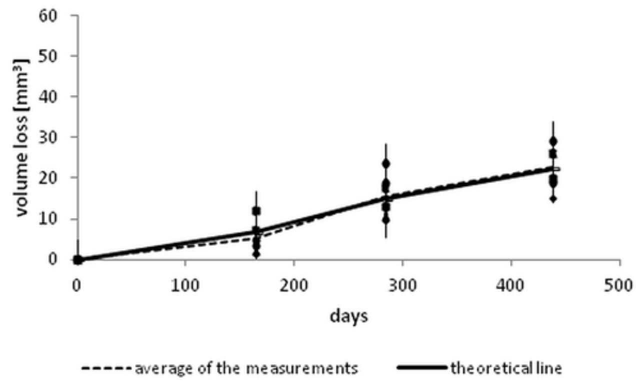
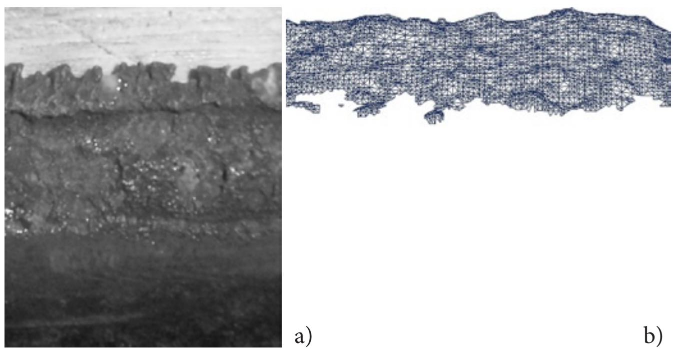


Fig. 4. Volume of the material lost from the surface area of 1 cm2 of the blade restored with EB-150. Experimental points recorded during each control maintenance (164, 284 and 438 days of the turbine operation) refer to various blades and localisations. Continuous lines are line segments between the points averaged of the measurements and the corresponding line determined by model calculations



a) b)

Fig. 5. (a) Leading edge and the lateral surface picture taken in the middle zone of the blade No 23 (operating designation), made of the material SP-1 after 464 days of exploitation. (b) Space image of the morphology of the damaged blade recorded with 3D scanner.

3. Quantification of the process. The prognostic system

3.1. Assumptions and equations of the model.

Mathematical model for assessment of the effectiveness of the mass loss processes proceeded under cavitation impulse loadings [11] has been chosen as a base for the prognostic system under development. Main assumptions of the model are as follow: (1) mass loss depends functionally on difference between the rates of energy absorption in the surface layer and energy consumption for retarding processes performance, accordingly to corresponding probabilities of its occurrence; (2) during the erosion process the micro-cracks are formed, which subsequently combine and propagate until the critical crack is generated. An average rate of micro-cracks multiplication depends on the amplitudes and distribution of the loadings as well as the strength properties of the material; (3) types of the probability functions of particular sub-processes are submitted, whereas parameters of the probability functions are derived from phenomenological procedures. Phenomenological approach warrants the dependence of the distributions on the morphology and some physical conditions of the material tested is regarded; (4) parameters of the model equations, i.e. parameters of the statistical distributions in the cores of integral equations and partition coefficients referred to participation of the specific sub-processes in the erosion are functionally interrelated with physical and strength parameters of the eroded material; (5) the problem is implicitly formulated for a unit area of the body.

In probabilistic approach an energy transfer to material under different mechanisms, corresponding to various component sub-processes can be formulated by the set of integral-differential Volterra equations of the second kind (1) [11]

$$\sigma(t)=\lambda_0 g(t)+\int_0^t \lambda_1 f_1(t-\tau)\sigma(\tau)d\tau+\int_0^t \lambda_2 h(t-\tau)\frac{dx}{d\tau}(\tau)d\tau+\int_0^t \lambda_3 h_1(\tau)\sigma(\tau)d\tau$$

$$\frac{dx(t)}{dt}=Ax(t)+\int_0^t \lambda_1 f_1(t-\tau)\sigma(\tau)d\tau \qquad (1)$$

$$\sigma_1(t)=\sigma(t)-\int_0^t \lambda_4 g_1(t-\tau)g(\tau)d\tau$$

Notations:

- σ – amount of energy absorbed under unit area of the material in the unit period of time under cavitation loading of the unit intensity;
- x – amount of energy released at the micro-cracks inception under unit area of the material in the unit period of time under cavitation loading of the unit intensity;
- g – rate of energy absorption in plastic deformation process under unit area of the material under cavitation loading of the unit intensity;
- f_1, h, h_1, g_1 –probability density distributions of energy consume in the processes of micro-cracks inception, micro-cracks coalescence, cracks origination on the material surface and micro-cracks closure;
- λ_i – partition coefficients constituting energy distribution in component sub-processes;
- σ_1 – amount of energy contributed in disintegration processes under unit area of the material in the unit period of time under cavitation loading of the unit intensity;

Adopted model is kinetic and its phenomenological nature arises due to correlation in spe between the calculation (model equations) parameters and the material properties. The latter may also be dependent on the loading conditions.

Sub-processes taken into account are stochastic in steady-state conditions, due to constant space and time distributions of the loadings. Assuming a'priori a particular form of the distributions enables deterministic formulation of the problem.

From the physical point of view, the qualities essential for quantification of the process are: (1) randomness of the extraction of the material debris resulting from the randomness of the loadings and material microstructure, wherewith the loadings probability functions with respect to impulse heights, direction, area of interaction are dependent on the environmental conditions, operation regime etc.; (2) fatigue nature of the process. Relationship between the cavitation erosion efficiency and the fatigue strength of the material was proved among others in the papers [1, 3, 14, 17, 25, 26]. Then, material destruction can be explained as after-effect of gradually cumulated energy of amount governed by the stress-strain cycle hysteresis or by bulk plastic deformations of substantial fragments of the surface layer; (3) integral-volume nature of the process resulting from the elastic dissipation of the energy in elastic-plastic materials and sequential and correlated order of energy accumulation – leading to lowering the resistance threshold and cracking; (4) strengthening of the loaded layer by increasing number of dislocations in the initial stage of the erosion and deceleration of the mass loss rate due to the micro-crack closure in the advanced stage of the erosion, the phenomena analysed i.e. in [8, 29]. Fatigue and bulky nature of the process are decisive for existence of the loading impulse threshold value [19, 23] as well as the threshold value for absorbed energy to originate material cracking [28].

3.2. Logic of the prognostic system

Prediction of the erosion process by means of the model (1) is possible provided the values of the parameters of the equations and the loadings are known (input values). The prognostic system is formed if numerical implementation of the model is complemented with functional relationships between parameters of the model equations and values of the strength parameters of the material. Such relationships can be established in each case of strictly defined particular conditions of the erosion by means of adjusting the theoretical cumulative erosion curves to the experimental ones for a broad variety of the materials of differentiated properties. As a result a simulator of the loss processes is obtained. The ranges of the independent variable (time) and the dependent variables (mass loss or mass loss rate) are stated by imposing the compatibility with standard experimental curves. Units of the input values are also inferred from the way of the measurements, e.g. [Pa] or [N] can be preset as the loading measures. Convenient unit for volume loss quantification is [mm^3]. Primary hindrance in development of the system is the lack of indispensable experimental data, i.e. erosion characteristics of various materials destroyed under known cavitation loadings. Until now, the parallel system has been developed for prediction of solid particle erosion of the material. Its application is to be facilitated on the web portal PL-Grid Plus.

The present work is a part of the studies for verifying the correctness of the simulations of the erosion performance and contributes to development of due prognostic system. Hypothesis (T) that parameters of the model equations depend solely on the material properties and are not dependent on the loadings was put up and numerical implementation of the model (1) with simplified assumption T was tested. In the approach the average loading was taken as a scale parameter. The major effect of the verification of the hypothesis T renders possible the general functional relationships between model and strength parameters are established. Consequently, the prognostic system for prediction of the erosion of arbitrary materials under arbitrary loading conditions can be constituted.

3.3. Testing of the prognostic system

Values of the model equations parameters have been determined by adjustment of the volume loss determined numerically to the average experimental results (Figs 2 and 4). It was assumed that one set of the calculation parameters refers to one specific material: different sets of calculation parameters refer to the blades restored with SP-1 wire and EB-150 electrode. Because of the low variations of the cavitation loading along the blade the assumption on the loading uniformity was taken.

Probabilities of the extraction of random element of the size 1 mm^3 from the surface layer during 10 days long period were presented in Fig. 6 as the time function. The characteristics were derived for the loading equalled 2/13 of the real loading, met at the operating conditions of the turbine. Evaluation of the loading in the absolute units is possible only by obtaining the congruent curve for the same material eroded under known loading conditions or approximately by determining and comparing the *MDP* (*Mean Depth of Penetration*) for same material eroded under known loading conditions.

The probabilities found are functions of the values of model equations parameters, than the functions of the strength properties of the material. Corresponding functional relationships for the case of solid particle erosion were presented in [15]. Change in the values of the strength parameters induce the change of the model equations parameters which brings on the corresponding change of the extraction probability of the material element.

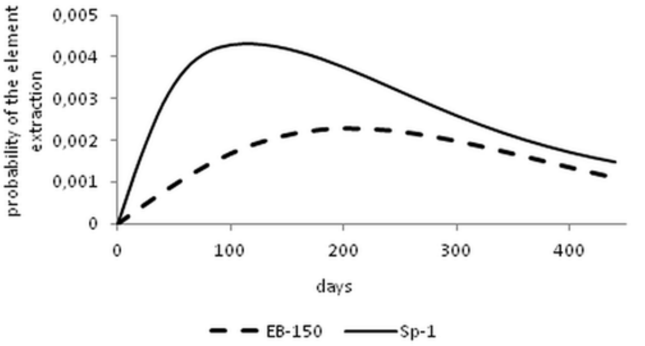


Fig. 6. Probability of the extraction of random element of the size 1 mm³ in 10 days long period under cavitation loading equalled 2/13 of the loading met in operating turbine

Table 1. Percentile change of probability of a single volume element extraction from SP-1 blade when value of one single input parameter is changed of 20%.

	$0,8\lambda_0$	$1,2\lambda_0$	$0,8\lambda_3$	$1,2\lambda_3$	$0,8\lambda_4$	$0,8\nu_1$	$1,2\nu_1$	$0,8\nu_2$	$1,2\nu_2$
after 164 days	20% decrease	20% increase	9,5% decrease	10,7% increase	6,9% increase	1% decrease	0,7% increase	13% decrease	8,7% increase
after 284 days	20% decrease	20% increase	17,3% decrease	21,6% increase	26,1% increase	2,5% decrease	2,5% increase	25,1% decrease	22,9% increase
after 438 days	20% decrease	20% increase	26% decrease	37% increase	73,6% increase	2,2% decrease	2,3% increase	21,5% decrease	29,1% increase

Table 2. Percentile change of probability of a single volume element extraction from EB-150 blade when value of one single input parameter is changed of 20%.

	$0,8\lambda_0$	$1,2\lambda_0$	$0,8\lambda_3$	$1,2\lambda_3$	$0,8\lambda_4$	$0,8\nu_1$	$1,2\nu_1$	$0,8\nu_2$	$1,2\nu_2$
after 164 days	20% decrease	20% increase	0,1% decrease	0,1% increase	2,3% increase	9,2% increase	9,6% decrease	5,7% decrease	3,2% increase
after 284 days	20% decrease	20% increase	0,8% decrease	0,8% increase	9% increase	3% decrease	0,1% decrease	17% decrease	11,4% increase
after 438 days	20% decrease	20% increase	2% decrease	2% increase	36,2% increase	11,4% decrease	10,7% increase	37,9% decrease	33,8% increase

In the Tables 1 and 2 the relative changes of the element extraction probabilities after one single input parameter is changed of 20% are presented. Model equations parameters selected for the analysis exhibit the foreseeable interrelation with the amount of energy delivered in the rupture test (toughness), fatigue strength and mechanical strengthening of the material. As it is, λ_0 is proportional to the difference between the energies consumed in the rupture tests of standard and investigated materials; λ_3 is proportional to the difference between the fatigue strengths of standard and investigated materials; λ_4 is proportional to the strengthening achieved under standard cavitation loading. Other parameters used for calculations, not revealed explicitly in the equations set (1) were: (a) standard deviation ν_1 in normal statistical distribution g – proportional to the product of the fatigue strength and hardness of the material and (b) distance parameter ν_2 in probability density distribution g_1 of the Rice type - proportional to the product of the fatigue strength, yield point and ultimate strain of the material.

Specification of the quantities in the procedure for evaluation of the volume loss comprised:
(1) input data - loadings, model equations parameters: partition coefficients for the component sub-processes and dimensionless parameters of the statistical distributions of the sub-processes, area under the loading, duration of the process and
(2) output data - volume loss of the material vs time or the rate of the volume loss of the material vs time were computed.

Units of the quantities inserted have been implicit by comparison to experimental curves. Numerical calculations were performed with the own numerical program PCE [13]. Eight parameters of the model equations were chosen for computation handling: partition coefficients referred to participation of the energy absorption in plastic deformations, cracking and erosion retarding, parameters of the statistical distributions in the cores of integral equations and parameter for evaluation of the loadings.

4. Discussion

4.1. Analysis of the results

In the operating conditions the cavitation erosion in Banki-Michel turbine is developed both on the dorsal side of the blade and along the whole length of the leading edge. The process is slightly non-uniform: a bit greater damages were observed nearby the left end of the leading edge and nearby the right side attachment of the blade. In any part of the blade the predominant damage process was brittle cracking generated at the material surface.

It turned up that monitoring of the volume loss process in the leading edge zone was impossible, because in the course of the material pieces extraction the leading edge is cut down. As a result, the filling method is of no use in the advanced stage of the erosion.

Typical performance of the process on the lateral surface of the blade is featured by occurrence of the acceleration erosion stage just after incubation stage. In the next stage the rate of the erosion decreases and reach the constant value implying the erosion process steady-state. In case of the blades restored with SP-1 wire, the incubation period was regarded by default – it has not been recorded due to invalid assumption on the low rate of the blades erosion in the initial period of the process. Following that assumption, the first maintenance control happened 164 days after the turbine activation. Substantial volume losses were found thus the opportunity of finding the erosion characteristics in the incubation period has been lost. However, one keep in mind that typical incubation stage in case of restored but not annealed blades may not appear.

The large dispersion of the experimental results obtained by the measurements at the same areas of different blades made of the same material and the measurements done over different areas of the same blade was observed. The sources of the uncertainty should be: (1) deficient filling of the pits and their mapping. The filling method stops to be applicable if volumes of the local jags and pinholes are less than 0.2 mm³; (2) the randomness of the process. Therefore, the only way to decrease the statistical error is an increase in number of the samples tested.

4.2. Discussion on the assumption and uncertainties

An important issue in the problem is how the erosion depends on the characteristics of the loadings – would the credible results are obtained if the average value of the loading is employed. It is a major concern because it yields radical simplification of the simulating calculations and makes the scaling of the process possible. Due to phenomenological nature of the prognostic system the parameter for quantifying the loadings can be derived from experimentally recorded loadings distribution. According to the hypothesis *T* the parameter for quantifying the loadings was taken as scaling parameter. Effective adjustment of the computed and experimental points in Figs 2 and 4 supports the opinion that erosion characteristics (the shape of the cumulative erosion curve) depends only on the material properties of the Banki-Michel turbine blades and cavitation loading may be implemented in mathematical formulation of the model as scaling parameter without significant loss of the precision. Having proved the hypothesis *T* the direct benefits of using the prognostic system *in spe* arise:

(1) the user of the system is not forced to refer to current experiments – he is only to know the cavitation loadings and properties of the material the blades are manufactured of;

(2) the user obtains the possibility to scale the volume loss computations with respect to the loading.

Analysis of the results presented in Tables 1 and 2 lead to the conclusion that in peculiar conditions of the erosion the efficiency of the process:

(1) is decreased proportionally to the toughness increase,

(2) depends on the fatigue strength of the material. Dependence is more pronounced for the weaker material. The influence of the fatigue strength is getting higher in time,

(3) depends substantially on the material capacity to mechanical strengthening: the lower level of achievable strengthening the higher probability of the volume element extraction, than the more effective erosion,

(4) depends on the rate of strengthening so that an increase in the rate makes a decrease in erosion efficiency. Reduction of the efficiency is less in the advanced stage of the erosion. The trends found agree with predictions and prove the correctness of the assumed conception of the prognostic system.

Results relating to parameter ν_1 show that influence of the rate of energy absorption in tensile test on the cavitation erosion process is insignificant and ambiguous, e.g. in case of EB-150 increase in ν_1 value led to decrease in erosion efficiency at early stage (after 164 days) and to increase in erosion efficiency after 438 days of exposition.

There can be regarded the following sources of inaccuracy of the cavitation erosion prediction with the system submitted:

- inaccuracies of physical nature subsequent to the randomness of the process and significant dispersion of the experimental results. That kind of the inaccuracy can be reduced by employing more experimental erosion curves for the system development.
- inaccuracies resulted from model formulation - its simplifications and assumptions, e.g. incorrect selection of the statistical distributions, assumption on the inter-independence of the model parameters making the sequence of the erosion damage events abandoned. Such attitude is inconsistent with physical model of the erosion [12] which consider the sub-processes as inter-dependent. Another inaccuracies resulted from model formulation include changes of the cracks development suppression or change of the surface morphology during the process, which generate additional nonlinearities of the relationships.
- inaccuracies resulted from the errors of the numerical approach, e.g. an error referred to ambiguity of determining of the model equation parameters by adjustment of the experimental curves.

4.3. Reliability of the system

Correctness of the assumptions, uniqueness of the calculation parameters derivation, effectivity of the numerical procedures and computational feasibility should be the subject of further works based on the broad spectra of the process characteristics. Moreover, the repetition of the erosion runs of various differentiated materials at the conditions allowing the loading impacts to be measured would help in verification of the results. It would turn to complete of the system, mainly due to determination of the functional relationships between calculation and material parameters.

5. Remarks, conclusions and indications

1. Due to inevitable occurrence of the strong cavitation loadings in Banki-Michel turbine and no possibility to cut them out in conditions domain pivotal for effective operation of the machine, development of the tool for the erosion prediction is getting indispensable. Appropriate prognostic system can be based on the mathematical model presented in [12].
2. Analysis of the damage probabilities exhibits the blades of Banki-Michel turbine should be manufactured of the material of high toughness. Additionally, material of high fatigue strength and strengthening rate should be chosen if it is to suffer the strong cavitation loadings for a long period of exposition.
3. Acceptable adjustment of the computed volume losses to the experimental characteristics proves that eventual dependence of the model equations parameters on the loading is minor. It is a reason that the approach established is valid notwithstanding the assumption that profile of the erosion characteristics is determined by the set of calculation parameters and intensity of cavitation loading operates in the system formulation procedures as constant factor.
4. Due to random nature of the process, the reduction of uncertainty level and e.g. more accurate determination of the functional relationships between model equation parameters and strength parameters of the turbine blades material is feasible by multiplication of the experimental tests.

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