IMPACT OF STEAM EROSION ON AERODYNAMIC CHARACTERISTICS OF THE TIP SECTION OF A LONG ROTOR TURBINE BLADE

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ABSTRACT
The erosion of the inlet part of turbine blade tips generates serious changes both in profile shape and also in the pitch/chord ratio. These shape changes naturally affect aerodynamic performance of blades. To assess this effect, aerodynamic performance of original and eroded steam turbine rotor blade tip section is assessed based on aerodynamic tests and simulations.

The problem was studied on two models of prismatic blade cascades. Eroded shape of the leading part of the profile was designed on the basis of wear tests as well as on predictions by various wear erosion models. Both experiments and CFD were used to get detailed insight into the problem. Experiments were performed in a suction type high-speed wind tunnel for planar blade cascades. Optical and pneumatic measurement techniques were used for data acquisition. Numerical simulations were employed to assess erosion effects in the finite cascade mounted in the wind tunnel test section. Simulations were done using in-house codes.

KEYWORDS
long rotor blade, steam turbine, erosion, tip section, CFD, experiment, transonic flow

NOMENCLATURE

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Subscripts</th>
<th>Units</th>
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<tr>
<td>A</td>
<td>area</td>
<td></td>
<td>m²</td>
</tr>
<tr>
<td>AR</td>
<td>aspect ratio</td>
<td>0, total</td>
<td>-</td>
</tr>
<tr>
<td>b</td>
<td>cascade width in axial direction</td>
<td>1, inlet</td>
<td>m</td>
</tr>
<tr>
<td>c</td>
<td>profile chord</td>
<td>2, exit</td>
<td>m</td>
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<tr>
<td>F</td>
<td>force</td>
<td>exp</td>
<td>N/m</td>
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<tr>
<td>M</td>
<td>Mach number</td>
<td>In</td>
<td>-</td>
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<tr>
<td>p</td>
<td>Pressure</td>
<td>is</td>
<td>Pa</td>
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<tr>
<td>Re</td>
<td>Reynolds number</td>
<td>nom</td>
<td>-</td>
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<tr>
<td>s</td>
<td>pitch</td>
<td>ig, original</td>
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INTRODUCTION

Water droplets of secondary liquid component in the wet working steam cause blade erosion in the last stage of steam turbine’s low-pressure cylinder. The process of steam condensation in the last stages is a complicated thermodynamic process, resulting in blade erosion, as well as in lower efficiency in stages working with wet steam (Šťastný, 2015). The expansion of working steam often exceeds the Wilson Zone in the last stages of low-pressure cylinders. The condensation process begins in nucleation stages. Water droplets nucleation for turbine design conditions is expected to start in the rotor wheel that is the third from the last one. The nucleation shifts to the nozzle row of the next-to-last stage in the case of off-design operation mode. The prevailing large droplets of secondary liquid phase have diameter of (5÷10) μm. These relatively large droplets are “supplemented” with much bigger drops, diameter of which ranges from 85 μm to 180 μm. The formation of these large water droplets results from disintegration of water film on the trailing edge of preceding blades. Erosion effect due to water droplets impact affects mainly the rotor blades of the last stages.

![Figure 1: Stator turbine blade with suction slits for the water layer removal.](image1)

![Figure 2: Tip of a rotor blade with erosion wearing of the leading part.](image2)

Active and passive protection is used to prevent the steam erosion. The passive protection involves for example deposition of carbide materials on the leading edges of steel blades. The titanium blades are usually equipped with laser-welded erosion resistant titanium. Usually, it is sufficient to protect the upper third of the blade’s leading edge span.

The active protection requires a modification of the stator blade. The blades are hollow with suction slots on the surface, which extract the condensed water layer from the blade surface (see Fig. 1). Extraction of condensed water using slots reduces the erosion of the leading edge of a rotor blade by up to 50% (Tanuma and Sakamoto, 1991). Both types of protection are often applied together in the turbomachinery practice. Active and passive protections together reduce the erosion wearing up to app.16% in comparison with the situation without the protection (Synáč et al., 2021).

In the case of high off-design operation (namely for lower power, increased back pressure in a condenser, small aerodynamic loading etc.), the flow of steam in the last stage of low-pressure cylinder is reversed. The steam back flow carries water drops (coarse dispersion) from exit diffuser and the trailing edge erosion takes place. This kind of erosion affects not only the upper part of the blade, but also the area near the blade root. The reverse flow affects the whole last stage in the case of ventilation regime, i.e. when the last stage does not produce power.

The disintegration of the water film downstream of the trailing edge depends on many parameters, the importance of which is not sufficiently clarified until now. Process of steam erosion
depends strongly on intensity of turbulence, Mach number, Laplace, Reynolds and Weber numbers as well as on normal component of droplet velocity at the moment of impact on the buckets.

An example of erosion wear in the tip region of a rotor blade is shown in the Figure 2. The company Doosan Skoda Power, Ltd. introduced a model of erosion wear of the blades in the last stages of low pressure sections. The model is based on the published mathematical model of flow in a turbine (Krzyzanowski, 1991), supplemented with experimental data from measurements on the facility for material erosion wear testing (Ruml and Straka, 1995). Based on this semi-empirical model of erosion wear, an in-house code was developed for classification of buckets erosion damage throughout the whole turbine life cycle.

The changes in the shape of the leading part of profile together with reduction of profile chord length (and increasing of pitch/chord ratio in the tip region) lead to changes in aerodynamic characteristics and kinetic energy losses in the tip region of the rotor buckets. Due to the erosion wear, the relatively very short inter-blade channel in the original tip section becomes even shorter. The issues are more complex due to relatively high velocities, which belong mainly to the supersonic or transonic region. Because of the high velocities, tip section performance is very sensitive even to relatively small changes in blade profile and cascade geometry.

**ORIGINAl TIP SECTION**

The original tip section represents geometric shape of the tip blade profile used for the titanium rotor blading (Doosan Skoda Power, Ltd.). This profile was designed for the last stage of steam turbine operating at 3000 rpm. Power of the steam turbines is around 1000 MW. The tip section profile cascade with a short convergent-divergent inter-blade channel is designed for very small flow turning. The value of the stagger angle of profiles in the cascade is $\gamma = 78.8^\circ$ and the pitch/chord ratio is $s/c_{ig} = 0.93$. Two nominal regimes related to two intended applications are shown in the Table 1.

<table>
<thead>
<tr>
<th>Table 1: Nominal regimes at the tip section</th>
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<tr>
<td><strong>Model of turbine</strong></td>
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<tr>
<td>$M_1$ [-]</td>
</tr>
<tr>
<td>$M_2$ [-]</td>
</tr>
<tr>
<td>$\alpha_{1nom ig}^\circ$</td>
</tr>
<tr>
<td>$\alpha_{1nom er}^\circ$</td>
</tr>
<tr>
<td>Re (in the steam) [-]</td>
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The optimal chord length of the downscaled model, intended for experiments and numerical simulations, has been determined as $c_{ig} = 0.15$ m. The profile is schematically depicted in the Figure 3 (black line). The position of profiles in the cascade is shown in Figure 4a. Thus, the aspect ratio of prismatic blades for experiment in aerodynamic wind tunnel is $AR = 1.07$.

![Figure 3: Original (blue-red line) and wear (red line)) variant of the profile](image-url)
ERODED TIP SECTION

Modeling of the erosion wear of the blade material (titanium-aluminum-vanadium alloy) has shown poor steam erosion resistance. In situation, when both the active and passive protection is not applied, the loss of titanium material in the leading part of the tip profile represents approximately 6% of the original profile chord after $2.10^5$ turbine operation hours. These data are valid for the turbine operating at full power (Regime 1). At lower power (Regime 2), the erosion wear is approximately one tenth in comparison to the full power turbine.

Figure 5: Example of manufactured model of prismatic blade cascade (the eroded variant).

The shape of eroded version is derived from the original version of the profile using the in-house code for classification of buckets’ erosion damage and based on the experience with shapes of eroded leading parts of tip section profiles gained during the previous turbine refurbishments. The eroded profile (red color) is compared with the original shape (black color) in the Figure 3. The chord length of downscaled eroded profile used for experiment and CFD simulations is $c_{er} = 0.1441$ m. Thus the pitch/chord ratio increased to $s/c_{er} = 0.979$. The difference in the pitch to chord ratio between the original and eroded variant is approximately 4%, and the axial chord of the eroded cascade is shorter by 20.5%. Changes in the throat opening are insignificant. The aspect ratio of prismatic blades increased to value $AR_{er} = 1.13$. Very short inter-blade channel represents the limit case, when the aerodynamic throat still exists (see Figure 4b). The nominal regimes of operation for the eroded tip cascade are identical with those for the original version. The only change is of the inlet flow angle $\alpha_{1nom er}$. The changes in the Reynolds number (difference in the chord size) are regarded as negligible.

MEASURED MODELS

The designed prismatic profile blade cascades consist of 8 blades and seven inter-blade channels. Each cascade is divided in two blocks. Both the upper block and the lower block consist of 4 blades. Blades are made of steel and they are fixed in the blocks in - proper positions by steel strips. The middle inter-blade channel (between blades 4 and 5 in Fig. 6) is -formed by fastening both blocks of the cascade -to the sidewall of the wind tunnel test section with optical window. - Consequently, the middle inter-blade channel is unobstructed for use of optical methods (see Figure 5).

The static pressure taps were located on the suction side of the profile No.5 and on the pressure side of the profile No 4 i.e. surfaces defining the middle inter-blade channel. Taps are located in the middle span and their chord-wise position $x/c\sim 0.5$ for original and $x/c\sim 0.48$ for the eroded variant.
EXPERIMENTS

The experiments were carried out in the high-speed aerodynamic laboratory of the Institute of Thermomechanics of the Czech Academy of Sciences in Nový Knín. The high-speed wind tunnel for 2D cascade measurements was equipped with a special test section intended for investigation of flow in prismatic profile cascades having small flow turning angles - see Matějka et al. (2013).

An adjustable supersonic inlet nozzle is upstream of the test section. The nozzle with parallel sidewalls has continuously deformable upper and lower wall. This allows for setting inlet Mach number up to $M_1 = 2.0$. The exit Mach number is controlled by adjustable control nozzle, that is situated downstream of the settling chamber. To improve inlet flow field periodicity, the test section is equipped with perforated inserts. More detailed description regarding the wind tunnel can be found for example in Luxa et al. (2015). The perforated adjustable tailboard is usually mounted downstream the trailing edge of the lower lateral profile No. 1 (see Figure 6). At a proper setting, the tailboard supresses origin of parasitic shock waves and allows for required expansion at the exit of the blade cascade However, in the current case, no proper setting of the tailboard has been found. After a number of experiments, the intention to apply the tailboard was abandoned. The presence of parasitic shock waves in the flow field is in this case lesser problem regarding the experimental data than the suppression of expansion both in the exit part of the inter-blade channel and in the exit flow field downstream the cascade.

![Figure 6: Arrangement of the test section (left) and position of the test section in the wind tunnel (right).](image)

The inlet flow field parameters are measured by a Prandtl probe, which was placed upstream the cascade inlet and by static pressure taps on the sidewalls. The large distance between the probe and the cascade leads to the reduction of the probe disturbances at the proximity of inlet cascade plane. The isentropic exit Mach number was evaluated from the inlet total pressure and the static pressure, which was measured downstream the cascade in the settling chamber of the tunnel (see Fig. 6).

![Figure 7: The field of vision for optical measurement (a – original, b – eroded).](image)
Optical measurements included interferometry (method of infinite fringe) and schlieren method in Toepler configuration. The field of vision for optical measurement covered part of the cascade’s middle inter-blade channel only. Size of the field is limited by the diameter of glass optical windows for interferometry (0.16 m). Displayed part of the flow field is practically identical for both measured variants of the cascade (see Figure 7). The fringes in interferograms are lines of constant index of refraction and thus, the evaluation is based on application of Gladstone – Dale law (see Šafařík and Luxa (2000)) in the dry air, and on the assumptions of isentropic thermodynamic process.

Two experimental techniques of pneumatic measurement were applied: 2D traversing measurement downstream the cascade and measurement of the static pressure distribution on the sidewall at the cascade inlet and outlet (see Fig. 8).

![Figure 8: Layout of the test section for pneumatic measurements (the eroded variant).](image)

Two experimental techniques of pneumatic measurement were applied: 2D traversing measurement downstream the cascade and measurement of the static pressure distribution on the sidewall at the cascade inlet and outlet (see Fig. 8).

![Figure 9: Distributions of $M_{2is}$ along the pressure tap row downstream the original cascade variant (left) and eroded variant (right).](image)

Static pressure distributions were measured along two pitches upstream the leading edges (31 static pressure taps) and along two pitches downstream the plane of trailing edges (31 static pressure taps) on the sidewall of the test section. The pressure taps rows at the exit are 21 mm distant from trailing edge plane for both cascades. At the inlet, the distance of the leading edges is 12 mm in the case of original variant and 15 mm for the eroded cascade. Distributions of $M_{is}$ evaluated from the row of static pressure tappings downstream the cascade are shown in Fig. 9. These distributions illustrate exit flow periodicity.

In the case of 2D traversing measurements, the distributions of static and total pressure and exit flow angle were measured by conical five-hole probe. The probe is continuously traversed along the straight path corresponding to one cascade pitch in the middle of blade height 0.187c behind the trailing edges in the case of original variant and 0.146c mm in the case of the eroded cascade respectively.

Due to the experimental cost savings, all the traversing measurements were performed only once. The accuracy of the traversing measuring equipment enabled to measure the exit flow angle
\( \beta_2 \) and kinetic energy loss coefficient \( \zeta \) with absolute uncertainties less than \( 2^\circ \) and 0.004, respectively. Measurement uncertainties were evaluated as a combined standard uncertainty of indirectly measured quantity (JCGM (2008)). The loss coefficient \( \zeta \) (1) was evaluated using the data reduction method (see Amecke and Šafařík (1995)). This method is based on solving all the conservation laws (mass, momentum, energy), the equation of state for an ideal gas and the condition of adiabatic flow.

\[
\zeta = 1 - \frac{M_{1}^2}{M_{2is}^2}
\]  

(1)

The range of measured Mach numbers was practically identical for both cascades. The measurements were carried out in the range of the inlet and exit Mach numbers \( 0.76 \leq M_1 \leq 1.6 \) and \( 1.6 \leq M_{2is} \leq 2.15 \). The geometric incidence angle \( \phi = 0^\circ \) was set in cases with \( M_1 \geq 1 \). For subsonic inlet Mach number, the incidence angle ranges for original variant and eroded variant within interval \( 0^\circ \leq \phi \leq +3^\circ \) and \( 0^\circ \leq \phi \leq +2.65^\circ \) respectively. The inlet flow angle in the case of supersonic inlet velocities was set automatically according the unique incidence rule. This rule defines relation between inlet flow angle and supersonic inlet Mach number - see Starken (1986) or Luxa et al. (2014). The range of Reynolds number (related to the profile chord \( b \) and the isentropic exit Mach number \( M_{2is} \)) in experiments is shown in the Table 2.

<table>
<thead>
<tr>
<th>Table 2: Experiment: Reynolds number</th>
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<tbody>
<tr>
<td>Cascade</td>
</tr>
<tr>
<td>original</td>
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<tr>
<td>eroded</td>
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<table>
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<tr>
<th>Table 3: CFD simulations - regimes</th>
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<tr>
<td>Cascade</td>
</tr>
<tr>
<td>----------</td>
</tr>
<tr>
<td>Regime 1 (full power)</td>
</tr>
<tr>
<td>original</td>
</tr>
<tr>
<td>eroded</td>
</tr>
<tr>
<td>Regime 2 (low power)</td>
</tr>
<tr>
<td>original</td>
</tr>
<tr>
<td>eroded</td>
</tr>
</tbody>
</table>

**NUMERICAL SIMULATION**

Two nominal regimes (i.e. with subsonic inlet Mach number) were simulated for both cascades (see Table 3). Mathematical model of the transonic flow is based on the Navier-Stokes equations describing balance of mass, momentum and energy in 2 dimensions. Ideal gas is imposed as fluid and the mean turbulent flow is approximated by Favre averaging of the governing equations. The more detailed description of the in-house calculation method is mentioned in Louda and Příhoda (2019). The turbulence model is Shear Stress Transport model (Menter 1994). The solution domain boundary approximates wind tunnel test section with suitable inlet and outlet channels. The model of finite cascade with 8 blades is geometrically arranged according to measurements. The subsonic inlet boundary condition prescribes total values of pressure and temperature and horizontal flow direction. The outlet Mach number is set by the outlet static pressure.
The governing equations are discretized by a cell-centered finite volume method with quadrilateral finite volumes. The grid consists of approx. 200 structured blocks and has approx. 400,000 finite volumes. The scheme of the blocks is shown in the Figure 10. Each blade is surrounded with O-grid with nearly perpendicular grid lines, refined near surface so that the maximal non-dimensional distance from wall $y^+ < 0.7$ is achieved. The choice of grid density is based on numerous simulations of tip profile cascades at similar flow conditions in periodic (infinite) as well as finite configurations. Used grids enable to capture important wave structures as trailing edge shock waves and its reflection from adjacent blade. Relatively less resolved are wakes behind trailing edges which diffuse approximately two blade chords downstream. Details of the mesh structure around the leading part of the profiles are depicted in Figure 11. The upwind discretization in space uses the AUSMPW+ method and higher order of accuracy is achieved by linear interpolation with van Leer limiter. The discretization in time is implicit Euler method. The linear system of equations is solved iteratively by combination of direct block 3-diagonal solver and Gauss-Seidel sweeps.

**RESULTS AND DISCUSSION**

The flow fields at the cascade inlet at nominal inlet Mach number are shown in the Figure 12. The flow field along the suction side of original variant is characterised by continuous expansion. The maximal values of isentropic Mach number upstream the inner branch of exit shock wave ranges from $M_{is} = 2.25$ to $M_{is} = 2.4$ according to the backpressure (interval of exit isentropic Mach number was $1.611 < M_{2is} < 1.860$). Flow accelerates near the leading edge along the blade pressure...
side and the value of isentropic Mach number remains practically constant approximately up to the inter-blade passage, where the expansion takes place. The expansion from subsonic to supersonic velocity within the inter-blade passage and downstream is accompanied by origin of the exit shock wave near the trailing edge of the profile. The shape changes of the profile leading part together with the inter-blade channel shortening lead to serious changes in the flow field in case of the eroded variant. On the suction side, the flow field is affected by secondary shock wave (marked as ‘a’ in Fig. 12b), which originates as a consequence of the over expanded flow near the eroded leading edge (see Dvorak 1987). The intensity of the secondary shock wave is reduced by the supersonic expansion arising from the pressure side of the adjacent profile. Downstream of the secondary shock wave the fluid expands further up to the area of exit shock wave-boundary layer interaction (marked as ‘b’ in Fig. 12). Downstream the interaction, towards the trailing edge along the flat part of the profile’s suction side, the value of the isentropic Mach number is almost constant similarly to the original blade shape. On the pressure side at leading part of the eroded profile, the sudden change of the profile contour together with other significant geometric changes result in continuous process of subsonic expansion passed to subsonic compression (marked as ‘c’ in Fig. 12b). The isentropic Mach number finally stabilizes near the same value as in the original cascade case and is followed by expansion close to the entrance to the inter-blade passage.

Figure 12: The interferometric pictures of a part of the flow field - nominal condition (PS - pressure side, SS - suction side).

Figure 13: The interferometric pictures of a part of the flow field - off-design condition.

The situation changes dramatically at off-design conditions and at negative incidence angles when the inlet Mach number exceeds the sound velocity (Figure 13b). The simple supersonic expansion appears on the point where the profile shape suddenly changes and the supersonic region
is terminated by normal shock wave. In case of the original variant, only a small local supersonic region terminated by insignificant normal shock appears near the leading edge on the suction side (see Figure 13a).

![Graph showing isentropic Mach number distribution](image1)

**Figure 14: Isentropic Mach number distribution along the profile for one of the nominal conditions (Regime 2) of the flow - experiment and CFD ((M₁ ~ 0.8, M₂is ~ 1.6)).**

**Figure 15: Contours of Mach number – original blades**

**Figure 16: Contours of Mach number – eroded blades**

The distribution of isentropic Mach number along the profile is depicted for both profile shapes in the Figure 14. The experimental data are compared with data obtained from CFD simulation. The last part of the distribution on the suction side evaluated from the experiment is dashed because behind the shock wave, there is uncertainty about shift of the interference fringes. Fringes are densely packed within the shock wave and thus counting them is complicated. The agreement of the experimental and computational data is good except for the intensity and location (for original variant) of the shock on the suction side. The comparison may be affected by different flow conditions in adjacent inter-blade channels, observed in numerical simulations, combined with the fact, that optical measurements are evaluated from these different channels for different parts of the blade (see Fig. 6 for optical window). The shock in original variant moreover just interacts with a shock reflection from the lower free jet boundary on the suction side in the investigated interblade channel (blade No. 5); see Fig. 15. In the case of eroded variant (Fig. 16), the shock reflected from the jet boundary interacts with suction side in the lower adjacent interblade channel (blade No. 4).

The values of kinetic energy loss coefficient (1) related to the value from experiment $\zeta_{\text{exp}}$ (nom In), which is valid for the Regime 2 in the case of original shape, are shown and compared in the Table 4.
Lower loss in case of the eroded variant is due to lower chord length and it is also connected to the higher velocities on the suction side of the original variant and thus stronger exit shock waves and more dissipative wake.

Table 4: Kinetic energy loss: experiment and CFD

<table>
<thead>
<tr>
<th>Cascade</th>
<th>Original variant</th>
<th>Eroded variant</th>
</tr>
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<tbody>
<tr>
<td>Regime 1 ((M_1 \sim 0.8, M_{2}\bar{v} \sim 1.8))</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(\zeta_{\text{exp nom in}})</td>
<td>experiment 0.825</td>
<td>0.619</td>
</tr>
<tr>
<td>(\zeta_{\text{exp nom in}})</td>
<td>CFD 0.598</td>
<td>0.475</td>
</tr>
<tr>
<td>Regime 2 ((M_1 \sim 0.8, M_{2}\bar{v} \sim 1.6))</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(\zeta_{\text{exp nom in}})</td>
<td>experiment 1</td>
<td>0.817</td>
</tr>
<tr>
<td>(\zeta_{\text{exp nom in}})</td>
<td>CFD 0.660</td>
<td>0.426</td>
</tr>
</tbody>
</table>

Figure 17: Dimensionless pressure force in tangential direction for \(M_1 \sim 0.8\).

The dependence of tangential dimensionless pressure force (2) on inlet Mach number evaluated from gained data is shown for both versions in the Figure 17. The pressure force descends with increasing the inlet Mach number. The increasing of the inlet Mach number causes negative values of incidence angle and thus the reduction of pressure loads acting on the profile. Despite the changes of the shape of the profile on account of the erosion processes, the values of dimensionless pressure force do not differ considerably.

\[
FA^{-1} p_{01}^{-1} = b^{-1} p_{01}^{-1} \int_0^b \left[ p_{\text{pressure}}(x) - p_{\text{suction}}(x) \right] dx
\]  

CONCLUSIONS

The experimental and numerical research on two versions of the tip section intended for long turbine rotor blade provide new information about changes in aerodynamic characteristics of the blade tip section as a result of erosion damage processes.

With respect to the shortening of the profile chord, small changes of the shape of curved camber line of the blade take place in the eroded part of the tip section. The real pressure loadings of both profiles are similar with respect to changes of real dimension of the profile surface.

The values of energy loss coefficient, obtained from research on eroded version, are lower for the both nominal regimes than the values valid for the original version. The 2D numerical research (in-house software) on finite cascades built into real geometry of aerodynamic tunnel provides smaller values of kinetic energy loss in comparison with experiment. These differences are probably closely related to more complicated processes in the complex flow field, influence of 3D flow
structures in experiment and other simplifying conditions both of experiment and numerical simulation.

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