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DETERMINATION OF THE THERMAL AND STRESS-STRAIN STATE OF THE MEDIUM-PRESSURE ROTOR OF THE T-100/120-130 TURBINE AFTER DAMAGE TO THE BLADES

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In the period of shelling of energy facilities of Ukraine by the enemy, emergency damage to the working blades of the rotors and stators of the turbines occurs. Papers related to the determination of the thermal and stress-strain states of power equipment elements, which have a significant impact in the conditions of the CHPP operation after its damage, are quite relevant. The authors determine the thermal and stress-strain states that occur after damage to the medium-pressure rotor (MPR) of the T-100/120-130 power unit of the CHPP under emergency damage conditions. When calculating the thermal and stress-strain states of the MPR, taking into account the technical audit data on damage, a geometric model of the MPR was created, which takes into account all existing emergency damage and changes in the frame compared to the design one. When starting from the cold state of the T-100/120-130 turbine MPR, the maximum intensities of conditional elastic stresses at the moment of time of 16800 s in the zone of the seal groove behind the third non-regulated stage of the MPR are equal to σ_i*=127 MPa, and in the zone of the axial opening –* σ_i*=125 MPa. The maximum intensities of conditional elastic stresses at the moment of time of 18000 s in the zone of the seal groove behind the third non-regulated stage of MPR are equal to* σ_i*=123 MPa, and in the zone of the axial hole –* σ_i*=125 MPa when starting from an uncooled state. The maximum intensities of conditional elastic stresses during start-ups from the hot state of the T-100/120-130 turbine MPR at the moment of time of 6400 s (3000 rpm) in the zone of the first unregulated stage in the seal groove according to the MPR stage are equal to* σ_i*=201 MPa, and in zone of the axial opening they are equal to* σ_i*=161 MPa. The intensities of conditional elastic stresses at the moment of time of 7000 s (3000 rpm) in the zone of the first unregulated stage in the seal groove according to the degree of MPR* σ_i*=168 MPa and in the zone of the axial hole* σ_i*=161 MPa also are significant.*

Keywords*: combined heat and power plant, steam turbine, T-100/120-130, medium-pressure cylinder, medium-pressure rotor, power, pressure, temperature, loss, equipment resource, non-stationary thermal conductivity, thermal state, stress-strain state.*

Introduction

As a result of shelling of energy facilities of Ukraine by the enemy, there is emergency damage to the working blades of the rotors and the stators of the turbines. Papers related to the determination of the thermal and stress-strain states of elements of power equipment, which have a significant impact in the conditions of operation of the CHPP after its damage, are quite relevant.

The main causes of emergency shutdowns of steam turbines can also be vibration fatigue of the blades' material, erosive damage to the body of the blades, and resonance problems during the operation of power equipment in variable modes [1]. Real damage can occur in the process of simultaneous action of erosive damage of the blade body from moisture, cavitation, and the interaction between Coriolis centrifugal forces on the working blade surface [2–4].

Despite all the challenges and threats, the Ukrainian energy system is currently being integrated into the European one, which, of course, is part of Ukraine's strategic goal of joining the EU. At the same time, unlike the countries of the new wave of EU expansion, our state had sufficiently powerful and developed gas, oil transport and electricity networks connected to the EU transport networks, which allowed it to participate in the formation of the European energy policy and the common energy market, to play an important role in energy cooperation of EU countries.

Therefore, in order to extend the service life of 100 MW power units, especially after emergency damage to the rotor blades and turbine stators, it is necessary to carry out an assessment of the individual resource of the T-100/120-130 steam turbine with a capacity of 100 MW of the CHPP power unit based on an integrated approach that combines the results of non-destructive metal testing with strength and durability calculations, as well as a detailed study of the individual operation history of each power unit [5–6]. At the first stage, the thermal and stress-strain states of the medium-pressure rotor (MPR) of the T-100/120-130 turbine should be determined.

Research purpose

The purpose of the paper is to determine the thermal and stress-strain states of the T-100/120-130 turbine MPR of the CHPP power unit for prolonging operation under the conditions of the stressed state of the power system. In order to achieve the goal, the mathematical model of the thermal and stress-strain state of the MPR of the steam turbine after emergency damage was improved and relevant research was carried out.

Main material

A calculated study of the thermal and stress-strain states of the MPR of the T-100/120-130 steam turbine with a capacity of 100 MW of the CHPP power unit of the Ukrainian power system was carried out to establish the possibility of further operation. In the process of achieving the set goal, studies were conducted taking into account the available repairs and restorations of energy equipment according to technical audit data.

Operating modes, technical audit and geometric model of the T-100/120-130 steam turbine MPR

The start-up modes of the CHPP power unit are determined depending on the temperature of the outer surface of the high-pressure cylinder (HPC) flange in the steam inlet area. According to the operating instructions for the T-100/120-130 steam turbine of the CHPP power unit, start-up from the cold state is distinguished at the temperature of the metal of the outer surface of the HPC flange in the steam start-up zone $T^{out}_{fl\ HPC}$=100–150 °C; start-up from an uncooled state – at a temperature of $T^{out}_{fl\ HPC}$=200–240 °C; start-up from a hot state – at a temperature of $T^{out}_{fl\ HPC}$>380 °C. Charts of start-ups from cold and uncooled states like uncooled and hot states are taken separately for HPC. The charts are constructed in accordance with the data of the recorders of the T-100/120-130 power unit, provided by the boiler-turbine shop and given for start-up from the cold state on Fig. 1.

When calculating the thermal state of the MPR during start-up modes, the non-stationary problem of thermal conductivity is solved. This requires establishing the boundary conditions of heat exchange of I–IV type, which must necessarily correspond to the charts of the T-100/120-130 turbine start-ups from different thermal states. The power load from the steam pressure in the nominal and variable operating modes was also taken into account. Heat transfer coefficients α were calculated according to criterion dependencies [7, 8]. On other surfaces and edges of the model, boundary conditions of the III type were found using linear interpolation. Conditions of absence of heat exchange were set on the surface of the axial groove. For the idle mode of the turbine unit, thermal insulation conditions were also set for the entire flow part. P2MA alloy steel (25Kh1M1F) was chosen as the MPR material. Thermophysical and physico-mechanical characteristics of P2MA steel depending on temperature were set on the basis of these regulatory documents [7, 8].

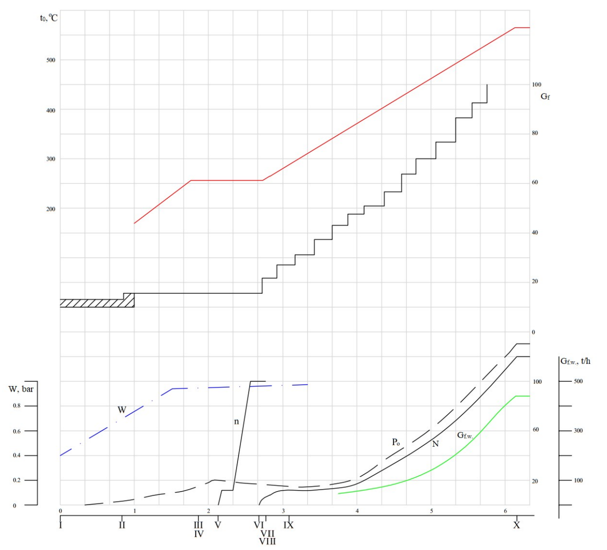


Fig. 1. Chart of the T-100/120-130 turbine start-up from a cold state

The results of the MPR metal testing of the T-100/120-130 steam turbine with a capacity of 100 MW of the CHPP power unit

Non-destructive testing was carried out by the structural division of the Metals Laboratory of the CHPP. According to the testing results for the MPR of the T-100/120-130 steam turbine with a capacity of 100 MW of the CHPP power unit, the following should be noted. The Metals Laboratory conducted a visual inspection of the MPR of the disk flanges, riveting and unloading holes, rims, ridges, webs and blades of the MPR blade device. Partial damage to the tape bandage of the blade feather was revealed (tears, signs of snagging) in the working blades of the 17th stage. In the working blades of the 18th stage, a partial absence of the tape bandage of the blades feather was found (20%), there are signs of the tape bandage snagging, and in the working blades of the 19th stage – a partial absence of the tape bandage of the blades feather (50%), there are mechanical dents with maximum dimensions length – width (25×25 mm) in the upper part of the feather of single blades. Also, partial damage to the tape bandage of the blade feather (rubbing, signs of snagging) was found in the working blades of the 20th stage. There is mechanical deformation of the edge of the blade feathers, a change in their shape (100%); traces of snagging and grinding of the end part of the blades in the working blades of 21–23th stages. Corrosion damage, signs of snagging and mechanical damage and other deviations from the requirements of the regulatory documents were not found on the working blades of 10–16th stages.

The outer surface of MPR elements is prone to uniform gas corrosion and is covered with scale that is tightly bonded to the base metal. Signs of corrosion, traces of erosive wear, traces of contact and mechanical damage, traces of electrical corrosion on the surface elements of the MPR were not detected. According to the results of a visual inspection of the blade apparatus of the 17–23th stages of the T-100/120-130 steam turbine MPR of the CHPP power unit, defects that do not comply with regulatory documents were found.

The Metals Laboratory performed color defectoscopy for MPR of the T-100/120-130 steam turbine with penetrating substances. The working blades of 10–23th stages (the trailing edge of the blade feather) were monitored in accessible places. On the trailing edges of the blade of the MPR of 10–19th and 21–23th stages, defects exceeding the permissible norms of regulatory documents, were not detected. Cracks with a length of 20 mm and 15 mm were found on the trailing edges of the 20th stage of MPR blade. The MPR and disks of 18–23th stages were tested (sheets with riveting and unloading holes, disk fillets, ridges and covering bandage of 10–16th stages), no defects were found.

When calculating the thermal and stress-strain state of the MPR and taking into account the data of the technical audit, a geometric model of the MPR was created. For a structurally complex MPR, the geometric model is made in a three-dimensional setting, taking into account the main structural elements, based on the passport drawing of the T-100/120-130 turbine (Fig. 2), taking into account the technological samples of the material of the equipment elements that were formed during mechanical processing cracks, fissures and grooves on the surfaces of the rotors. Technological samples of the material of equipment elements are obtained from experimental data of visual control and magnetic powder diagnostics, provided by operating organizations and the metal laboratory of the power station. Changing the project design of the main high-temperature elements of the steam turbine to the actual design in accordance with the repair and restoration works carried out during the period of operation will cause corresponding changes in the thermal, stress-strain states of the high-temperature elements of the steam turbine and will affect the overall period of operation. At the same time, such influence will not always be directed towards the deterioration of individual resources. Thus, the flow of the rotors grooves for the purpose of removing cracks with an increase in the size of the grooves causes a decrease in the stress level and an increase in the service life of the equipment. The geometric model of MPR is show in Fig. 2 for the part of the rotor from the axis of the front bearing bush to the disk of the 14th stage of pressure.

The MPR calculation model in a three-dimensional setting (Fig. 3) was discretized by 4–5 million finite elements with thickening of the grid in the radial direction and, especially, in zones that are stress concentrators. These include the root zones of the thermal grooves of the seals, the near-disk annular grooves of the rotor, etc. The grid of finite elements thickens to the top of the grooves according to the law of geometric progression, when each finite element closer to the top of the groove is 1.4 times smaller than the previous one. The size of the smallest element at the top of the crack samples is 0.2 mm.

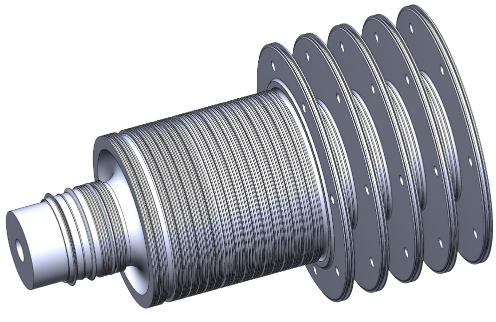


Fig. 2. Geometric model of the MPR of the T-100/120-130 turbine

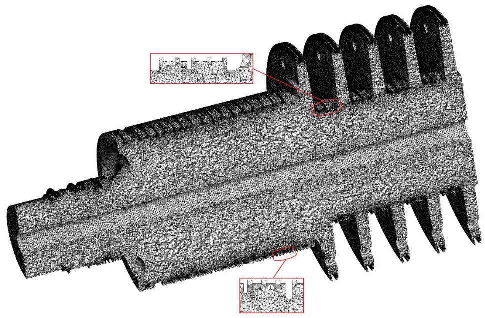


Fig. 3. Finite element model of the MPR of the T-100/120-130 turbine

Study of thermal and stress-strain states of MPRs of steam turbines of CHPPs

The calculated assessment of the thermal and stress-strain states of the MPR contains equations of unsteady thermal conductivity with boundary conditions of heat exchange on the rotor surfaces according to the developed software complex [1].

A method of solving the boundary value problem of non-stationary thermal conductivity with the setting of the boundary conditions of heat exchange on MPR surfaces based on the created geometric 3D models using Solidworks software complexes is proposed. The boundary conditions corresponded to such operating modes as starts from cold, hot and uncooled states, as well as stationary operating mode.

Characteristic points for MPR, in which boundary conditions were set in accordance with the recommendations of regulatory documents [7, 8], are shown in Fig. 4.

When determining the boundary conditions of heat exchange, the patterns of steam leaks in the seals, real charts of start-ups from different thermal states (cold, hot and uncooled) were taken into account.

The equation of non-stationary thermal conductivity has the form [7, 8]

$$\mathrm{div}[\lambda(T)\cdot \mathrm{grad}(T)] = c(T)\cdot\gamma(T)\cdot\frac{\partial T}{\partial \tau},$$

where λ, c, γ are functions of temperature and coordinates under the initial condition $T_0=T(x, y, z, 0)=f_0(x, y, z)$ and boundary conditions of the I–IV type.

Boundary conditions of the I–IV type have the form

$$T_w = f(x,y,z,\tau);$$

$$q = -\lambda\left(\frac{\partial T}{\partial n}\right) = f_2(x,y,z,\tau);$$

$$-\lambda\left(\frac{\partial T}{\partial n}\right) = \alpha(t_{med} - t_w);$$

$$\begin{cases} T_{w1} = T_{w2} \\ -\lambda_1\left(\dfrac{\partial T}{\partial n}\right)_1 = -\lambda_2\left(\dfrac{\partial T}{\partial n}\right)_2 \end{cases}.$$

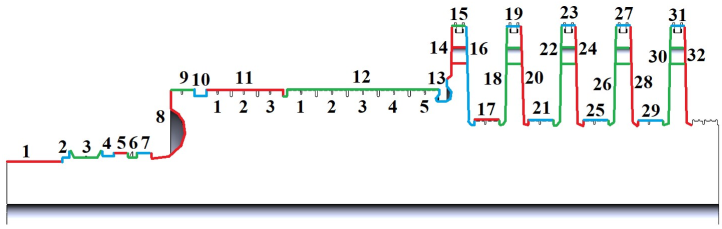


Fig. 4. Characteristic points of heat exchange boundary conditions for the MPR of the T-100/120-130 turbine

When determining the boundary conditions of MPR heat exchange, it is necessary to have information about its characteristic dimensions and to perform a detailed calculation of the flow part at the nominal operating mode. In the course of a detailed calculation of the compartment, the main thermodynamic parameters of the steam (pressure, temperature, specific volume), enthalpy differences, loss values, and velocity values on the average cross-section for the nozzle and working blades of each studied stage are determined. In non-stationary operating modes, the calculated estimate of the above parameters of the steam is used for losses corresponding to the start-up charts of the MPR power unit (Fig. 1).

After determining the main parameters of the steam at the nominal and variable operating modes, the boundary conditions were determined in accordance with the regulatory document [7, 8].

The following criterion equations were used:

– from the steam to the interscapular surfaces of the MPR

$$Nu = 0.206 \cdot \mathrm{Re}^{0.66} \cdot s_r^{-0.58};$$

$$s_r = \frac{\sin\beta_1}{\sin\beta_2}\sqrt{\frac{2b_0}{\bar{t}\cdot l\cdot \sin(\beta_1+\beta_2)\cdot \cos^2\left(\frac{\beta_1-\beta_2}{2}\right)}}.$$

The length of the surface in the direction of the blade was used to determine the Reynolds and Prandtl similarity criteria. In this case, the velocity is the arithmetic mean value of the relative velocity at the inlet and outlet of the working blade, and the temperature is the arithmetic mean temperature of the medium at the inlet and outlet of the working blade;

– similarity equation for rotor stage disks rotating in a large volume

$$Nu = 0.0197\cdot(n+2.6)^{0.2}\cdot \mathrm{Re}^{0.8}\cdot \mathrm{Pr}^{0.6},$$

where n is the exponent in the equation of temperature pressure change along the disk radius

$$t_w - t_{med} = c\cdot r^n;$$

– for disks of rotor stages rotating in the casing between adjacent diaphragms

$$Nu = 0.0256\cdot(1-z_\varphi)^{0.75}\cdot \mathrm{Re}^{0.75}\cdot \mathrm{Pr}^{0.6}\cdot\left(\frac{s}{r}\right)^{0.25};$$

– for sections of the rotor with direct-flow seals, the equation of convective heat exchange

$$\begin{cases} Nu = \dfrac{0.256\cdot \mathrm{Re}^{0.6}\cdot \mathrm{Pr}^{0.43}}{\left(\dfrac{s}{\delta}\right)^{0.085}\cdot\left(\dfrac{h}{\delta}\right)^{0.075}}, \text{ at } \mathrm{Re} = 2.4\cdot 10^2 \ldots 8.7\cdot 10^3 \\ Nu = \dfrac{0.0454\cdot \mathrm{Re}^{0.8}\cdot \mathrm{Pr}^{0.43}}{\left(\dfrac{s}{\delta}\right)^{0.1}\cdot\left(\dfrac{h}{\delta}\right)^{0.1}}, \text{ at } \mathrm{Re} = 8.7\cdot 10^3 \ldots 1.7\cdot 10^5 \end{cases},$$

where s is the step between the ridges of the seals; h is the distance between the surface of the rotor and the cylinder body; δ is the clearance between the rotor surface and the ridges of the seals;

– for stepped seals

$$\begin{cases} Nu = 2.04\cdot \mathrm{Re}^{0.5}\cdot\left(\dfrac{h}{\delta}\right)^{-0.56}\cdot \mathrm{Pr}^{0.43}, \text{ at } \mathrm{Re} \le 1\cdot 10^4 \\ Nu = 0.476\cdot \mathrm{Re}^{0.7}\cdot\left(\dfrac{h}{\delta}\right)^{-0.56}\cdot \mathrm{Pr}^{0.43}, \text{ at } 6\cdot 10^3 < \mathrm{Re} < 1.2\cdot 10^5 \end{cases};$$

– for diaphragm and intermediate seals with straight-flow or stepped labyrinths

$$Nu = \frac{0.052}{k}\cdot \mathrm{Re}^{0.9}\cdot\left(\frac{\delta}{h}\right)^{0.7}\cdot \mathrm{Pr}^{0.43}, \text{ at } 3.5\cdot 10^3 < \mathrm{Re} < 2.5\cdot 10^4,$$

where z is the number of seal ridges; p_1, p_2 are full pressure before and after the labyrinth; k is the flow rate for a given type of seal, determined by equation

$$k = \frac{G}{f\sqrt{\dfrac{g(p_1^2-p_2^2)}{z\cdot R\cdot T}}};$$

– for surfaces of the rotor shaft in contact with air

$$Nu = 0.11\cdot(0.5\cdot \mathrm{Re}^2 + Gr)^{0.33};$$

– for the part of the rotor surface located in the bearings

$$Nu = 6 \cdot (\mathrm{Re}_{\text{м}} \cdot \mathrm{Pr}_{\text{м}})^{0.23} \cdot \frac{d_n}{l_n},$$

where d_n is the diameter of the neck of the rotor shaft; l_n is the the length of the oil-washed surface of the neck of the rotor shaft.

Thus, on the heat exchange surfaces of the MPR of the T-100/120-130 turbine, boundary conditions of the III type were set using hyperbolic interpolation, and on the surface of the axial channel – boundary conditions of the II type were set. Schemes of steam leaks in the flow part and in the seals were taken into account, as well as real work charts under typical operating modes, namely stationary and start-ups from cold, uncooled and hot states.

The stress-strain state of the MPR was evaluated in the elastic-plastic setting using the finite-element method of discretization of the computational domain. The main types of stress were taken into account, namely temperature stress, non-uniformity of temperature fields, pressure stress and centrifugal force [7, 8]. The mathematical model included:

– the equilibrium equation in tensometric form

$$\{\sigma_i\}_j + \rho X_i = 0\,;\ i, j{=}1, 2, 3;\ \ p_i = f(x, y, z, 0)\,,$$

where $\{\sigma_i\}_j$ are normal and tangential stresses in MPR elements; X_i is the mass force acting in the elements of the rotor (centrifugal force, gravity, resistance reactions, etc); p_i is the external distributed load; ρ_i is the density of turbine steel;

– equations of the compatibility of deformations and the law of elasticity in matrix form

$$\{\varepsilon_{ij}\} = [a]\{\sigma_{ij}\} + \{\beta \cdot \Delta T\}\,,$$

where $\{\varepsilon_{ij}\}$ is the deformation vector; $[a]$ is the matrix of elasticity coefficients; $\{\sigma_{ij}\}$ is the stress vector; $\{\beta \cdot \Delta T\}$ is the vector of temperature deformations; β is the volumetric expansion coefficient; ΔT is the change in temperature of MPR elements during operation.

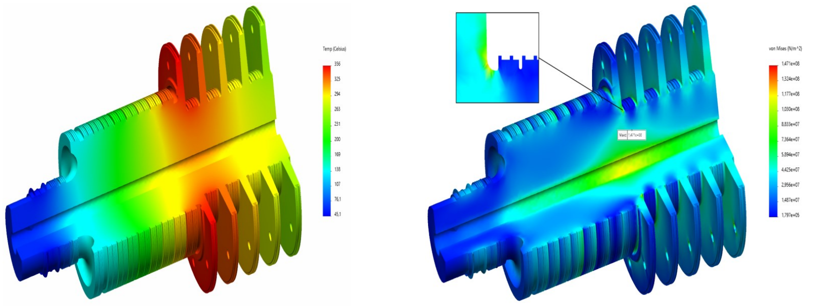
Discussion of results

A numerical study of the thermal and stress-strain state of the MPR of the T-100/120-130 turbine was performed for the most typical operating modes, namely: nominal heating at an electric power of 100 MW, start-ups from cold, uncooled and hot state of the metal. The metal temperature of the 10–14$^{\text{th}}$ stages disks decreases from 356 ºC to 254 ºC (Fig. 5, a). The temperature of the segments of the rotor seals decreases from 334 ºC to 133 ºC. The obtained data on the temperature distribution, as well as the non-uniformity of the temperature fields when solving the stress-strain state problem, are initial. In addition, the forces from the pressure of the steam medium, centrifugal forces, reactions of the supports, concentrated masses of the working blade apparatus, etc., are taken into account. Variable operating modes are presented in a non-stationary setting, taking into account the unevenness of temperature fields over time, which is depicted in the form of the dynamics of the temperature gradient change for the most characteristic areas [9, 10].

The determined stress-strain state shows that for the design structure when working at the nominal parameters of the steam, the highest stresses σ_i=147.1 MPa are observed in the fillet rounding of the 10$^{\text{th}}$ stage disk from the side of the 11$^{\text{th}}$ stage disk (Fig. 5, b). The high stress intensity in this area is associated with a sharp drop in shaft mass in the area of end seals (left) and in the area of diaphragm seals after the disk (right). Similar high stress intensities σ_i=118 MPa are visible in the region of the axial opening of the MPR under the 10$^{\text{th}}$ pressure stage.

It should be noted that information on the non-uniformity of temperature fields in the form of non-stationary temperature gradients is of considerable interest for the start-up modes of power equipment. In the MPR, 6 characteristic areas of research are chosen. They are shown in Fig. 6: 1 – rotor axial opening in the area of the 1st pressure stage; 2 – grooves in front of the second clip of the front end seals; 3 – grooves of the first clip of the front end seals; 4 – fillet behind the 1st stage; 5 – diaphragm sealing according to the 3rd stage; 6 – unloading hole of the 5th stage disk.

The dynamics of changes in temperature gradients and metal temperature during start-up from a cold state in the characteristic research areas of the MPR of the T-100/120-130 turbine is shown in Fig. 7.



a b

Fig. 5. Thermal (a) and stress-strain (b) state at the nominal operating mode (100 MW) of the MPR of the T-100/120-130 turbine

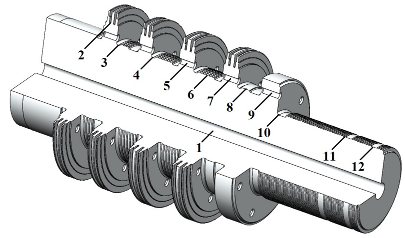
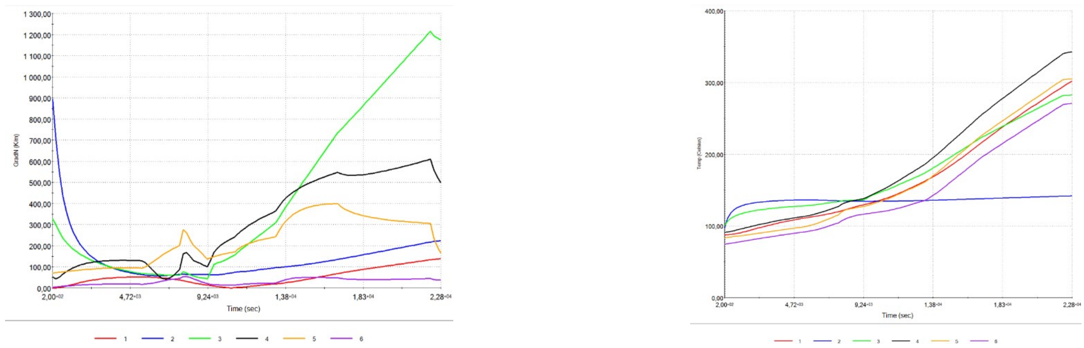


Fig. 6. Characteristic research areas of the MPR of the T-100/120-130 turbine with repair restorations

During start-ups from a cold state for the MPR, the temperature gradients are most significant at the time points of 16800 s and 228000 s (Fig. 7, a), while the maximum of the temperature gradient occurs in the zone of the third groove of the diaphragm seals behind the third stage of the MPR. It is at these moments of time that the stress intensity values reach their greatest values, which indicates the dominant influence of temperature stresses on the general stress-strain state of MPR.

During start-ups from a cold state for the MPR, the thermal state reaches 330 °C in the zone of the first unregulated stage, and in the zone of the axial hole it is equal to 300 °C at the moment of time of 228000 s (Fig. 7, b). The thermal state for the MPR reaches 250 °C in the zone of the first unregulated stage, and in the zone of the diaphragm seal grooves it is equal to 185 °C in the third stage at the moment of time of 16800 s.



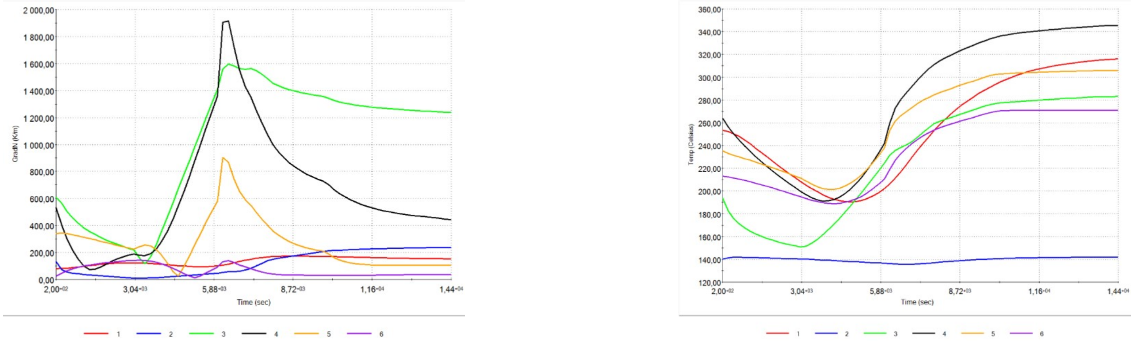
a b

Fig. 7. The dynamics of changes in temperature gradients (a) and temperatures (b) in the characteristic research areas of the MPR of the T-100/120-130 turbine when starting from a cold state of the metal

The dynamics of changes in temperature gradients and metal temperature during start-up from a hot state in the characteristic research areas of the MPR of the T-100/120-130 turbine is shown in Fig. 8.

During start-ups from a hot state for the MPR, the temperature gradients are most significant at the time points of 6400 s and 7000 s (Fig. 8, a), while the maximum temperature gradient occurs in the area of the front end seals and the first groove of the diaphragm seals behind the first stage of the MPR.

The thermal state during start-ups from a hot state for MPR reaches 360 °C in the zone of the first unregulated stage, and in the zone of the axial hole it is equal to 320 °C at the moment of time of 14400 s (Fig. 8, b). The thermal condition for the MPR reaches 300 °C in the zone of the first unregulated stage, and in the zone of the diaphragm seal clips it is equal to 280 °C in the third stage at the moment of time of 7000 s.



a b

Fig. 8. Dynamics of changes in temperature gradients (a) and temperatures (b) in the characteristic research areas of the MPR of the T-100/120-130 turbine during start-ups from a hot metal state

During start-ups from the cold state of the MPR of the T-100/120-130 turbine, the maximum intensities of conditional elastic stresses at the time of 16800 s are equal to σ_i=127 MPa in the zone of the seal groove of the third unregulated MPR stage, and σ_i=125 MPa in the zone of the axial opening (Fig. 9, b). The intensities of conditional elastic stresses at the moment of time of 22800 s in the zone of the seal groove at the first unregulated stage of MPR σ_i=123 MPa, and in the zone of the axial opening σ_i=120 MPa are also significant.

During start-ups from the hot state of the MPR of the T-100/120-130 turbine, the maximum intensities of conditional elastic stresses at the moment of time of 6400 s (3000 rpm) in the zone of the first unregulated stage in the seal groove behind the stage of the MPR to σ_i=201 MPa, and in the zone axial hole they are equal are equal to σ_i=161 MPa (Fig. 10, b). The intensities of conditional elastic stresses at the moment of time of 7000 s (3000 rpm) in the zone of the first unregulated stage in the seal groove behind the stage of the MPR σ_i=168 MPa, and in the zone of the axial hole σ_i=161 MPa are also significant.

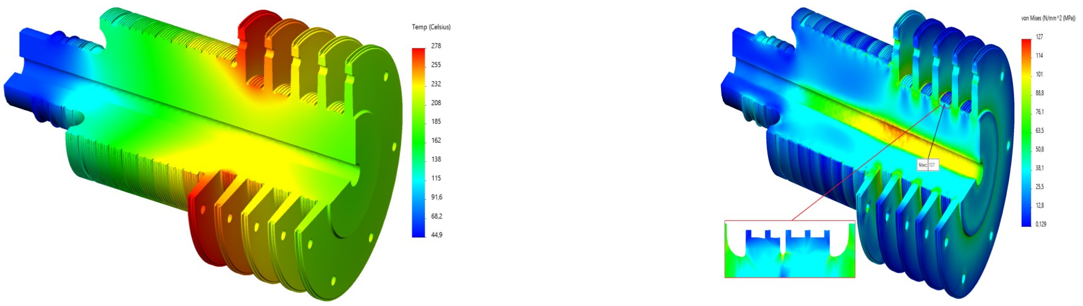


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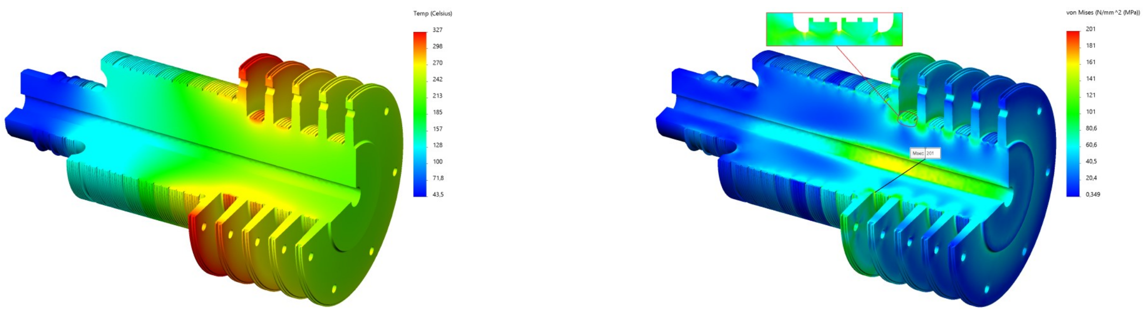
Fig. 9. Thermal (a) and stress-strain (b) states of the MPR of the T-100/120-130 turbine at the moment of time of 16800 s during start-up from the cold state



a b

Fig. 10. Thermal (a) and stress-strain (b) states of the of the MPR of the T-100/120-130 turbine at the moment of time of 6400 s during start-up from the hot state

The dynamics of changes in temperature gradients and metal temperature during start-up from an uncooled state in the characteristic research areas of the MPR of the T-100/120-130 turbine is shown in Fig. 11.

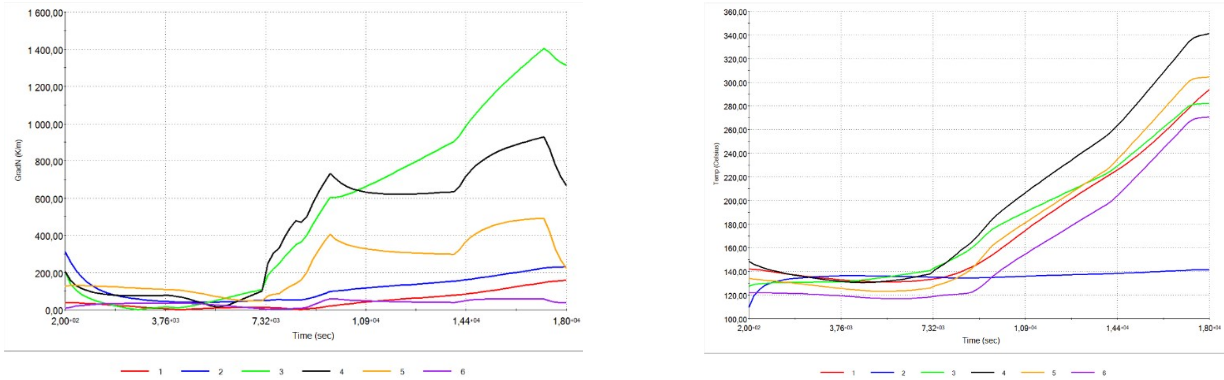
During start-up from an uncooled state for the MPR, the temperature gradients are most significant at the moments of time of 14100 s and 18000 s (Fig. 11, a), while the maximum of the temperature gradient occurs in the area of the front end seals and the first groove of the diaphragm seals behind the first stage of the MPR.

The thermal state during start-ups from an uncooled state for MPR reaches 340 °C in the zone of the first unregulated stage, and in the zone of the axial hole it is equal to 295 °C at the moment of time of 18000 s (Fig. 11, b). The thermal state for the MPR reaches 260 °C in the zone of the first unregulated stage, and in the zone of the diaphragm seal clips it is equal to 235 °C in the third stage at the time of 14100 s.

The intensities of conditional elastic stresses at the moment of time of 14100 s in the zone of the seal groove for the third unregulated MPR stage are σ_i=115 MPa, and in the zone of the axial opening they are σ_i=110 MPa during start-up from an uncooled state.

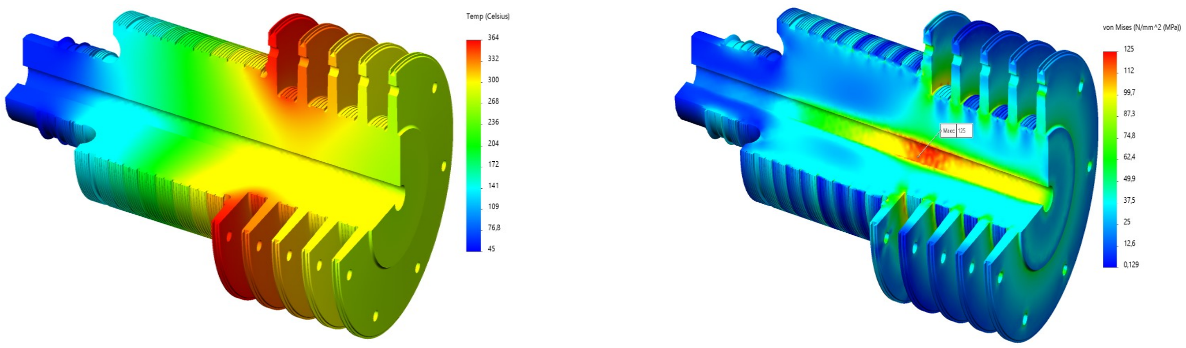
The maximum intensities of conditional elastic stresses at the moment of time of 18000 s in the zone of the seal groove behind the third unregulated stage of MPR are equal to σ_i=123 MPa, and in the zone of the axial opening they are equal to σ_i=125 MPa (Fig. 12, b).

When analyzing the stress-strain state of the MPR of the T-100/120-130 turbine, it should be noted that the maximum intensities of conditional elastic stresses occur during start-ups from a hot state at a time of 7000 s (3000 rpm) in the zone of the first unregulated stage in the seal groove behind the stage of MPR and are equal to 168 MPa, in the zone of the first unregulated stage in the seal groove behind the stage of MPR they are 201 MPa, and also in the zone of the axial hole the intensity of conditional elastic stresses they reach 161 MPa.



a b

Fig. 11. The dynamics of changes in temperature gradients (a) and temperatures (b) in the characteristic research areas of the MPR of the T-100/120-130 turbine during start-up from an uncooled state of the metal



a b

Fig. 12. Thermal (a) and stress-strain (b) states of the of the MPR of the T-100/120-130 turbine at the time of 18000 s during start-up from the uncooled state

Conclusions

1. When studying the thermal state of the MPR of the T-100/120-130 turbine during operation at nominal steam parameters, it was established that for the project design when operating at nominal steam parameters, the highest stresses σ_i=147.1 MPa are observed in the 10th stage rounding of the disk from the side of 11th stage disk. The high intensity of stresses in this area is associated with a sharp drop in the mass of the shaft in the area of end seals and in the area of diaphragm seals after the disk. Similar significant stress intensities σ_i=118 MPa are visible in the area of the axial opening of the MPR under the 10th pressure stage.

2. During start-ups from a cold state for MPR, the temperature gradients are most significant at the time points of 16800 s and 228000 s, while the maximum of the temperature gradient occurs in the zone of the third groove of the diaphragm seals behind the third stage of the MPR. During start-ups from an uncooled state, the temperature gradients are significantly larger at time points of 14100 s and 18000 s, while the maximum temperature gradient occurs in the area of the front end seals and the first groove of the diaphragm seals behind the first stage of the MPR.

During start-ups from a hot state, temperature gradients occur at time points of 6400 s and 7000 s, while the maximum of the temperature gradient occurs in the area of the front end seals and the first groove of the diaphragm seals behind the first stage of the MPR. It is at these moments of time that the stress intensity values reach their greatest values, which indicates the dominant influence of temperature stresses on the general stress-strain state of MPR.

3. The maximum intensities of conditional elastic stresses at the moment of time of 18000 s are equal to 123 MPa in the zone of the groove seal for the third unregulated stage of the MPR, and 125 MPa in the zone of the axial hole – during start-ups from an uncooled state. During start-ups from a cold state of the MPR of the T-100/120-130 turbine, the maximum intensities of conditional elastic stresses at the moment of time of 16800 s are equal to 127 MPa in the zone of the seal groove behind the third unregulated stage of the MPR, and 125 MPa in the zone of the axial opening. The greatest intensities of conditional elastic stresses occur during start-ups from the hot state of the MPR of the T-100/120-130 turbine at the time of 6400 s (3000 rpm) and are equal to 201 MPa in the zone of the first unregulated stage in the seals groove according to the stage of the MPR, and in the zone axial opening they are equal to σ_i=161 MPa.

4. To increase the reliability of turbine elements, reduce heat loads and improve operating conditions, it is recommended to modernize the control system of the main parameters of the turbine with the registration of parameters affecting the reliability and resource of the turbine; comply with the charts of the manufacturing plant; implement systems of testing and technical diagnostics of the thermal and stress-strain state of the MPR of the T-100/120-130 turbine in real time

References

1. Chernousenko, O. Yu., Ryndiuk, D. V., & Peshko, V. A. (2020). *Otsinka zalyshkovoho resursu ta podovzhennia ekspluatatsii parovykh turbin velykoi potuzhnosti* [Estimation of residual life and extension of operation of high-power steam turbines]. Part 3: monograph for scientists and doctors of philosophy in the specialty 144 "Heat Power Engineering". Kyiv: National Technical University of Ukraine "Igor Sikorsky Kyiv Polytechnic Institute", 297 p. (in Ukrainian).
2. Mazur, Z., Hernandez-Rossette, A., & Garcia-Illesoas, R. (2006). L-0 blades failure Investigation of a 110 MW geothermal turbine. Proceedings of ASME 2006 Power Conference (May 2–4, 2006, Atlanta, Georgia, USA), pp. 281–289. https://doi.org/10.1115/POWER2006-88024.
3. Suzuki, T., Matsuura, T., Sakuma, A., Kodama, H., Takagi, K., & Curtis, A. (2005). Recent upgrading and life extension technologies for existing steam turbines. Proceedings of ASME 2005 Power Conference (April 5–7, 2005, Chicago, Illinois, USA), pp. 577–582. https://doi.org/10.1115/PWR2005-50342.
4. Sanders, W. P. (1988). Turbine steam path engineering for operations and maintenance staff. Canada, Toronto: Turbo-Technic Services Inc.
5. Chernousenko, O., Usatyi, O., Peshko, V., & Bovsunovsky, A. (2024). Research of the possibility of operating a NPP turbine without a stage of damaged blades. In: Ball, A. D., Ouyang, H., Sinha, J. K., Wang, Z. (eds) Proceedings of the UNIfied Conference of DAMAS, IncoME and TEPEN Conferences (UNIfied 2023). TEPEN IncoME-V DAMAS 2023. Mechanisms and Machine Science, vol. 152. Springer, Cham. https://doi.org/10.1007/978-3-031-49421-5_6.

6. Chernousenko, O., Butovsky, L., Rindyuk, D., Granovska, O., Moroz, O. (2017). Analysis of residual operational resource of high-temperature elements in power and industrial equipment. *Eastern-European Journal of Enterprise Technologies – Energy-saving technologies and equipment*, vol. 1, no. 8 (85), pp. 20–26. http://dx.doi.org/10.15587/1729-4061.2017.92459.
7. (2021). *Kontrol metalu i prodovzhennia terminu ekspluatatsii osnovnykh elementiv kotliv, turbin i truboprovodiv teplovykh elektrostantsii* [Metal control and extension of service life of the main elements of boilers, turbines and pipelines of thermal power plants]. Regulatory document of the Ministry of Fuel and Energy of Ukraine. Typical instruction SOU-N MPE 40.17.401:2021. Kyiv: HRIFRE, Ministry of Fuel and Energy of Ukraine, 214 p. (in Ukrainian).
8. Shulzhenko, M. H., Hontarovskyi, P. P., Matiukhin, Yu. I., Melezhyk, I. I., & Pozhydaiev, O. V. (2011). *Vyznachennia rozrakhunkovoho resursu ta otsinka zhyvuchosti rotoriv i korpusnykh detalei turbin* [Determination of estimated resource and evaluation of rotor life and body parts of turbines: Methodological guidelines. Regulatory document SOU-N MEV 0.1–21677681–52:2011: approved by the Ministry of Energy and Coal Mining of Ukraine: effective as of 07.07.11. Kyiv: Ministry of Energy and Coal Mining of Ukraine, 42 p. (in Ukrainian).
9. Chernousenko, O. Yu., Peshko, V. A., & Usatyi, O. P. (2023). Changes in the thermal and stress-strain state of the HPC rotor of a powerful NPP turbine after the blades damage. *Journal of Mechanical Engineering – Problemy Mashynobuduvannia*, vol. 26, no. 3, pp. 15–27. https://doi.org/10.15407/pmach2023.03.015.
10. Chernousenko, O. Yu. & Peshko, V. A. (2019). Assessment of resource parameters of the extended operation high-pressure rotor of the K-1000-60/3000 turbine. *Journal of Mechanical Engineering – Problemy Mashynobuduvannia*, vol. 22, no. 4, pp. 41–47. https://doi.org/10.15407/pmach2019.04.041.

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Визначення теплового та напружено-деформованого стану ротора циліндра середнього тиску турбіни т-100/120-130 після пошкодження лопаток

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У період ворожих обстрілів енергетичних об'єктів України мають місце аварійні пошкодження робочих лопаток роторів і направляючих апаратів турбін. Роботи, пов'язані з визначенням теплового й напружено-деформованого станів елементів енергетичного обладнання, які в умовах експлуатації ТЕЦ після її пошкодження мають значний вплив, є досить актуальними. Авторами визначаються тепловий та напружено-деформований стани, які мають місце після пошкодження ротора середнього тиску турбіни Т-100/120-130 енергоблоку ТЕЦ в умовах аварійних пошкоджень. При розрахунковій оцінці теплового й напружено-деформованого станів ротора середнього тиску (РСТ), беручи до уваги дані технічного аудиту щодо пошкоджень, створена геометрична модель РСТ, яка враховує всі наявні аварійні пошкодження і зміну конструкції у порівнянні з проєктною. При пусках з холодного стану РСТ турбіни Т-100/120-130 максимальні інтенсивності умовних пружних напружень у момент часу 16800 с у зоні канавки ущільнень за третім нерегульованим ступенем РСТ дорівнюють σ_i*=127 МПа, а в зоні осьового отвору –* σ_i*=125 МПа. Максимальні інтенсивності умовних пружних напружень у момент часу 18000 с у зоні канавки ущільнень за третім нерегульованим ступенем РСТ дорівнюють* σ_i*=123 МПа, а в зоні осьового отвору –* σ_i*=125 МПа при пусках з неостиглого стану. Максимальні інтенсивності умовних пружних напружень при пусках із гарячого стану РСТ турбіни Т-100/120-130 у момент часу 6400 с (3000 об/хв.) дорівнюють в зоні першого нерегульованого ступеня в канавці ущільнень за ступенем РСТ* σ_i*=201 МПа, а в зоні осьового отвору* σ_i*=161 МПа. Також значними є інтенсивності умовних пружних напружень у момент часу 7000 с (3000 об/хв.) в зоні першого нерегульованого ступеня в канавці ущільнень за ступенем РСТ* σ_i*=168 МПа і в зоні осьового отвору* σ_i*=161 МПа.*

***Ключові слова**: теплофікаційна електростанція, парова турбіна, Т-100/120-130, циліндр середнього тиску, ротор середнього тиску, потужність, тиск, температура, втрата, парковий ресурс, нестаціонарна теплопровідність, тепловий стан, напружено-деформований стан.*

Література

1. Черноусенко О. Ю., Риндюк Д. В., Пешко В. А. Оцінка залишкового ресурсу та подовження експлуатації парових турбін великої потужності (частина 3): монографія для науковців та докторів філософії за спеціальністю 144 «Теплоенергетика». Київ: НТУУ «КПІ імені Ігоря Сікорського», 2020. 297 с.
2. Mazur Z., Hernandez-Rossette A., Garcia-Illesoas R. L-0 blades failure Investigation of a 110 MW geothermal turbine. Proceedings of ASME 2006 Power Conference (May 2–4, 2006, Atlanta, Georgia, USA). 2006. P. 281–289. https://doi.org/10.1115/POWER2006-88024.
3. Suzuki T., Matsuura T., Sakuma A., Kodama H., Takagi K., Curtis A. Recent upgrading and life extension technologies for existing steam turbines. Proceedings of ASME 2005 Power Conference (April 5–7, 2005, Chicago, Illinois, USA). 2005. P. 577–582. https://doi.org/10.1115/PWR2005-50342.
4. Sanders W. P. Turbine steam path engineering for operations and maintenance staff. Canada, Toronto: Turbo-Technic Services Inc., 1988.
5. Chernousenko O., Usatyi O., Peshko V., Bovsunovsky A. Research of the possibility of operating a NPP turbine without a stage of damaged blades. In: Ball A. D., Ouyang H., Sinha J. K., Wang Z. (eds) Proceedings of the UNIfied Conference of DAMAS, IncoME and TEPEN Conferences (UNIfied 2023). TEPEN IncoME-V DAMAS 2023. Mechanisms and Machine Science. 2024. Vol. 152. Springer, Cham. https://doi.org/10.1007/978-3-031-49421-5_6.
6. Chernousenko O., Butovsky L., Rindyuk D., Granovska O., Moroz O. Analysis of residual operational resource of high-temperature elements in power and industrial equipment. *Eastern-European Journal of Enterprise Technologies – Energy-saving technologies and equipment.* 2017. Vol. 1. No. 8 (85). P. 20–26. http://dx.doi.org/10.15587/1729-4061.2017.92459.
7. СОУ-Н МПЕ 40.17.401:2021. Контроль металу і продовження терміну експлуатації основних елементів котлів, турбін і трубопроводів теплових електростанцій. Типова інструкція. Офіц. вид. Київ: ГРІФРЕ: Міністерство палива та енергетики України, 2021. 214 с.
8. Визначення розрахункового ресурсу та оцінка живучості роторів і корпусних деталей турбін. Методичні вказівки: СОУ- Н МЕВ 40.1–21677681– 52:2011 / М. Г. Шульженко, П. П. Гонтаровський, Ю. І. Матюхін, І. І. Мележик, О. В. Пожидаєв. Київ: ОЕП «ГРІФРЕ»: М-во енергетики та вугільної пром-сті України, 2011. 42 с.
9. Chernousenko O. Yu., Peshko V. A., Usatyi O. P. Changes in the thermal and stress-strain state of the HPC rotor of a powerful NPP turbine after the blades damage. *Journal of Mechanical Engineering – Problemy Mashynobuduvannia*. 2023. Vol. 26. No. 3. P. 15–27. https://doi.org/10.15407/pmach2023.03.015.
10. Chernousenko O. Yu., Peshko V. A. Assessment of resource parameters of the extended operation high-pressure rotor of the K-1000-60/3000 turbine. *Journal of Mechanical Engineering – Problemy Mashynobuduvannia*. 2019. Vol. 22. No. 4. P. 41–47. https://doi.org/10.15407/pmach2019.04.041.