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INFLUENCE OF THERMAL AND MECHANICAL FACTORS ON THE STRESSED STATE OF LARGE COMPONENTS OF HYDROGENERATOR-MOTORS

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The work presented contains a detailed analysis of the existing ultimate power air-cooled hydrogenerator-motor design. It is shown that the umbrella-type hydrogenerator crosspiece perceives dynamic loads caused by forces acting in three planes. At the same time, to take them into account by analytical methods is impossible. In order to perform a three-dimensional calculation, it is necessary to take into account both the thermal and mechanical factors, as well as the specific features of the rolled metal. In the course of solving the problem set out above, taking into account thermal loads, a discrete crosspiece partition into the n-th number of sections is proposed. The convergence criterion for the solution to the inverse problem is based on maintaining the structure overall thermal balance, taking into account the limited accuracy of measuring devices. The main difference of the work was the justification of the choice of permissible stresses, taking into account the presence of bubbles in the metal structure, not exceeding their class of continuity for the selected rolled metal. It is proposed that an 'elementary defect' be introduced into the zone with the lowest safety margins as a circle with geometric data according to the restrictions on continuity. In this case, the correction of the selection of the finite element mesh parameters for the introduced defect is carried out as for the plate with eccentrically located holes. The mesh reduction continues to be carried out until the moment when the difference in the maximum stresses in the same mesh nodes is no more than 0.04%. Mechanical loads are specified in the classical formulation. In the course of the work it was found that the strength reserves of large generator components should be regulated by the quality of the rolled metal used, and the mechanical calculations should take into account thermal factors.

Keywords: *hydrogenerator, mechanical stresses, thermal process, metal defects.*

Introduction

The problem of calculating the stress state of large hydrogenerator units has not been completely solved yet. As a rule, non-resource components, such as crosspieces, in the course of their operation perceive and transmit dynamic loads from the rotor to the bearing, from the bearing to the crosspiece and from the crosspiece farther to the foundation. In this case, often allowed voltages are not always a limiting factor. The arising vibrations generated by insufficient structure rigidity, can lead to the unit destruction.

Problem formulation

To ensure the reliable operation of a hydrogenerator, it is necessary to revise the concept of calculating the stress state of its crosspiece and take into account the influence of thermal and mechanical loads, as well as the actual structure of the metal used in production. It is necessary to solve the following tasks:

1. Analyze the hydrogenerator general construction.
2. Develop a method for determining the boundary conditions, based on experimental data for the inverse thermal problem.
3. Present a method of taking into account its structural defects when selecting the allowed tensions.
4. Determine the crosspiece stress-strain state in a three-dimensional setting.

Hydrogenerator construction analysis

The hydrogenerator-motor construction under consideration is a vertical umbrella-type construction with one guide bearing (1) located in the oil bath of the crosspiece (3) over the rotor (9) and with the thrust bearing support (8) on the pump turbine cover (see Fig. 1).

The excitation of the hydrogenerator-motor is carried out from a system of thyristor independent excitation.

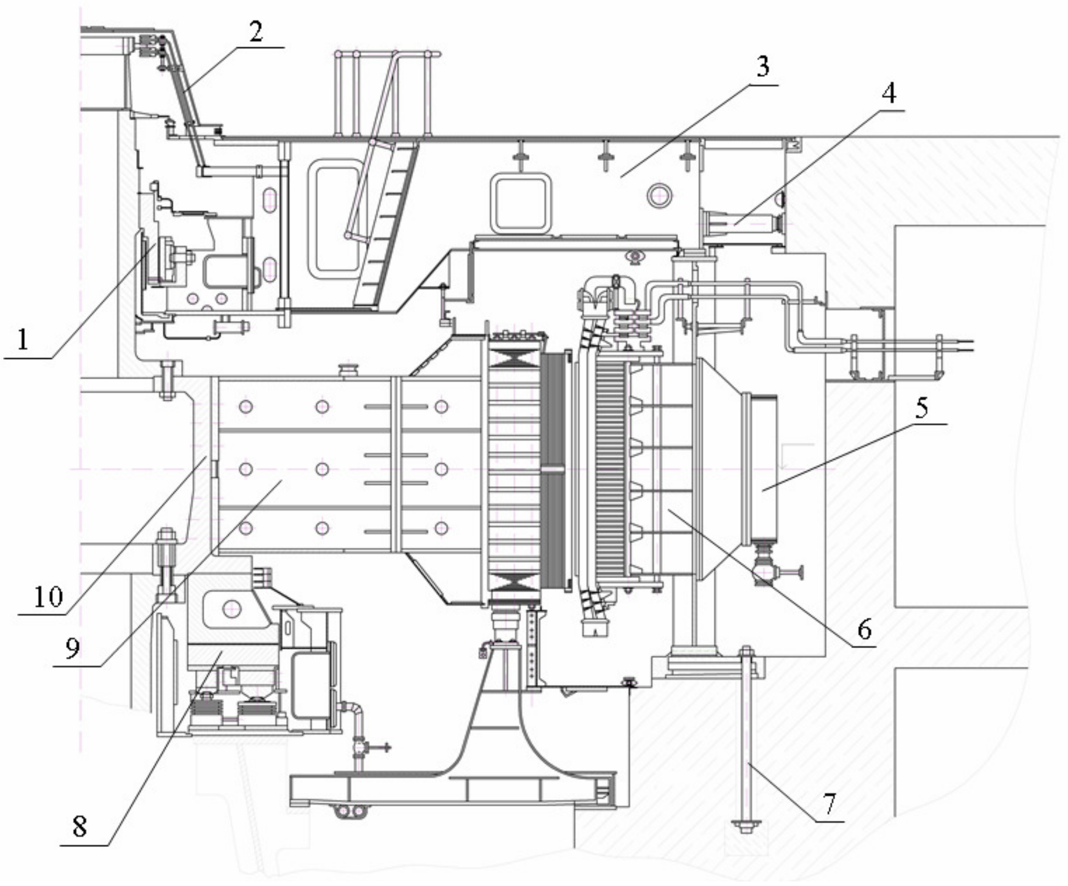


Fig. 1. General arrangement of a hydrogenerator-motor

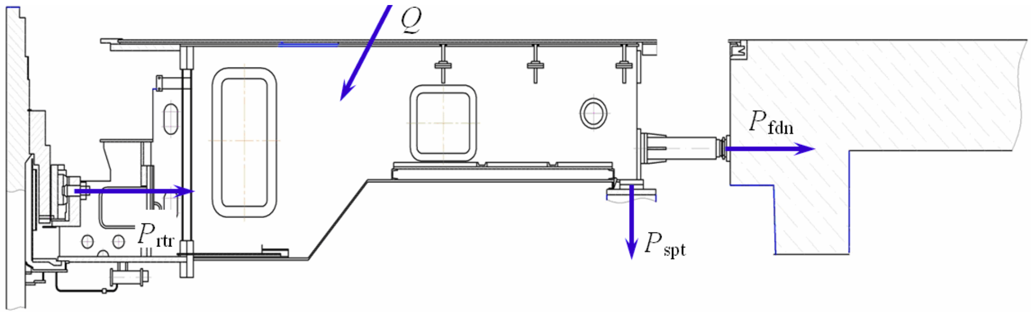


Fig. 2. Calculation scheme of mechanical loads:
P_{rtr} – loads from the action of the rotor horizontal forces; P_{spt} – load on the stator support;
P_{fdn} – load on the foundation; Q – thermal load

The rotor frame insert (10) is connected to the turbine pump shaft by means of flanges. To the upper part of the rotor frame insert, a shaft-extension is fastened, on which the guide bearing insert and contact rings are placed.

The stator (6) is installed on the foundation inside the hydrogenerator-motor shaft and fixed to the foundation by means of anchor studs (7). The upper shelf of the stator housing serves as a support for the crosspiece with spacer jacks (4). The corrugated crosspiece cover is at one level with the floor of the computer room.

In the central part over the crosspiece there is a support (2), inside of which a yoke for slip rings is fastened. The pump-turbine shaft cover, installed on the beams under the hydrogenerator-motor rotor, is a platform for servicing the thrust bearing and brakes.

The hydrogenerator-motor ventilation is carried out in a closed cycle with a partial extraction of hot air for heating the engine room. The air coolers (5) are located around the hydro-generator-motor stator housing. Cold and hot air zones are separated by the upper and lower air-dividing shields.

The direction of the hydrogenerator-motor rotation in the generator mode is clockwise, in the driving mode it is counter-clockwise, if viewed from above.

Figure 2 shows the design diagram of load transfer from hydroelectric unit elements to foundation plates.

Proceeding from the scheme presented, it can be concluded that the acting loads are of different factors and they can only be taken into account in a three-dimensional setting.

To calculate the mechanical strength of the crosspiece with the help of the basic analytical method, tensions are specified along one horizontal axis with the subsequent determination of compliance and resonant frequencies.

The total deflection of the crosspiece arm and crosspiece central part will be established according to

$$\overline{U} = \overline{U}_1 + \overline{U}_2 + \overline{U}_3 + \overline{U}_4 + \overline{U}_5 ,$$

where $\overline{U}_1$ is the deflection of the arm end from the twisting forces of the central part; $\overline{U}_2$ are the displacements caused by the action of torque; $\overline{U}_3$ is the displacement from the cross-cutting force; $\overline{U}_4$ are the displacements from the action of gravity on the ribs; $\overline{U}_5$ are thermal displacements.

In this case it is considered that the crosspiece temperature corresponds to the temperature of the components in the engine room.

A new method for determining the thermal state of a 300 MW hydrogenerator-motor crosspiece is presented in [1]. The possibility of transition from a two-dimensional setting to a three-dimensional one is established. However, to solve the problem, it is necessary to choose the initial and boundary conditions for the thermal problem. According to the method indicated in [2], the thermal state of the whole hydroelectric generator design can be determined by the CFD method in a three-dimensional setting. To specify the initial and boundary conditions, it is first necessary to establish the structure heat.

Thermal problem solution

There are the following types of losses for hydrogenerator-motors:

- ventilation;
- mechanical;
- electric – in the rotor and stator windings;
- electric – in the stator and the rotor active steel;
- additional.

To maintain the thermal balance of the structure, the ventilation losses must balance all the others.

However, it is not always possible to accurately determine the additional losses, and therefore it is proposed to consider the possibility of solving the inverse thermal problem based on temperature measurements at operating hydrogenerators.

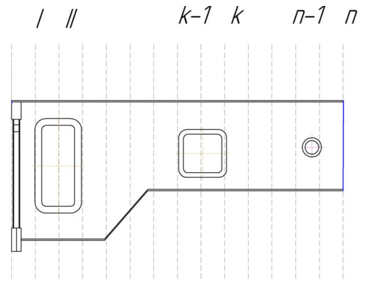


Fig. 3. Crosspiece mathematical model

To determine the thermal state of the hydrogenerator crosspiece, it is necessary to solve the inverse thermal problem, i.e. to restore the initial and boundary conditions for the determination of mechanical stresses.

To solve the thermal problem, it is proposed to discretely split the crosspiece into the n-th number of sections (see Fig. 3).

In this case, the calculation of the temperatures of the main structural elements can be defined as

– the plate center temperature

$$t_{0k} = t + \frac{q_v \delta}{\alpha} + \frac{q_v \delta^2}{2\lambda},$$

– the plate surface temperature

$$t_{ck} = t + \frac{q_v \delta}{\alpha},$$

– the heat flow density

$$q_k = -\lambda\left(\frac{q_v\delta}{\lambda}\right) = q_v\delta .$$

Then, for the steady-state solution, at which T=const, q=const, the criterion equation is used, where the local and average heat transfer coefficients for the developed turbulent air flow regime ($Ra \geq 6 \cdot 10^{10}$) at T_w=const and at q_w=const can be found by the formulas [3]

$$Nu_{f,x} = 0{,}15\ Ra_{f,x}^{0{,}333}\ \varepsilon_t\ ,\ \overline{Nu}_f = 0{,}15\ Ra_f^{0{,}333}\ \varepsilon_t\ .$$

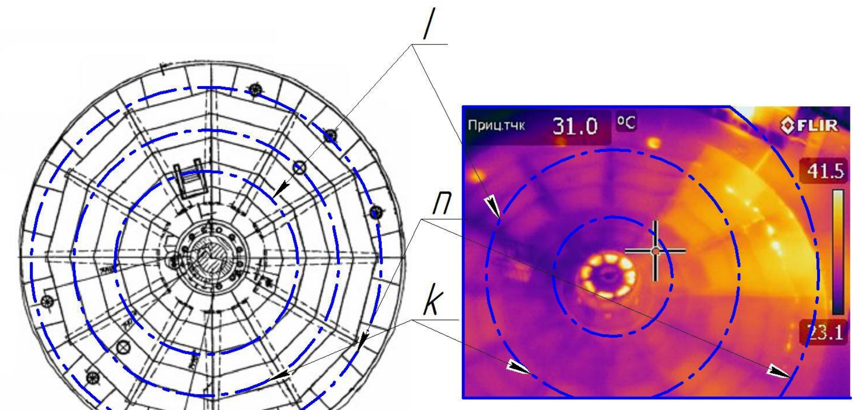
The defining parameters are geometric ones and the temperature of the fluid medium away from the heat exchange surface (outside the thermal boundary layer) $T_0 = T_f$.

The cooling medium flow transition regime, which occurs at Rayleigh numbers $10^9 < \mathrm{Ra}_{f,x} < 6 \cdot 10^{10}$, is characterized by flow instability.

The problem convergence rule is chosen as follows: for any area within the region $[k, k-1] \in [I, n]$, the rule is satisfied (see Fig. 4)

$$\begin{cases} T_{\mathrm{calc}\,{}^{\mathrm{R_k}-R_{k-1}}\!/_2} - T_{\mathrm{meas}\,{}^{\mathrm{R_k}-R_{k-1}}\!/_2} \leq \varepsilon_{\mathrm{meas}} \\ T_{\mathrm{calcR}_k} - T_{\mathrm{measR}_k} \leq \varepsilon_{\mathrm{meas}} \\ T_{\mathrm{calcR}_{k-1}} - T_{\mathrm{measR}_k-1} \leq \varepsilon_{\mathrm{meas}} \end{cases},$$

where T_{calc} is the temperature obtained by the calculation method; T_{meas} is the temperature measured; $\varepsilon_{\mathrm{meas}}$ is the instrument measurement error.



a b

Fig. 4. Determination of the temperatures of the area under study:
a – calculation scheme; b – the temperature measured
by a thermal imager inside the machine room

In this case, the heat, taking into account the measurement error, is calculated by the formula $Q = \sum q_i \pm \varepsilon$, where $\sum_{i=1}^{n} q_i = Q$ is the total heat flux.

The total amount of heat received (given) by the crosspiece in the process of cooling (heating) can be determined by the following formula $Q = c_p \rho V (t_0 - t)$, where c_p is the metal specific heat; ρ is the density of steel; V is the structure working volume determined by the methods of three-dimensional modeling; t_0 is the initial temperature; t is the current temperature value.

In this the cooling (heating) rate gradient m will tend to zero, and the Biot and Fourier numbers must be constant $m = \dfrac{\alpha F}{c_p \rho V}\Psi$, $\Psi = \dfrac{\overline{\vartheta}_F}{\overline{\vartheta}_V}$, where α is the heat transfer coefficient by air; F is the area of the elements being cooled; Ψ is the proportionality constant, equal to the ratio of the mean surface excess temperature $\overline{\vartheta}_F$ in the stage of the regular regime to its volume-averaged temperature $\overline{\vartheta}_V$.

Effect of metal defects

In view of the fact that in the manufacture of the operating hydroelectric generators, either the GOST 380-2005 grade 3 steel rolled metal or its closest substitute S235 DINEN 10025-2 is used, there may be defects in the metal structure.

At that, it should be noted that obvious defects should be eliminated during production, and the possibility of hidden defects should be regulated by calculation methods.

Defects of rolled and forged metal include the following: obvious, hidden, critical, significant and insignificant, corrigible and incorrigible.

Technological defects include different types of up to 10–15 mm deep single and group cracks. In this case, different types of cracks are distinguished: stamping cracks, stress cracks, hairline cracks, or flakes arising inside thick rolled metal or forged pieces (more than 30 mm in diameter).

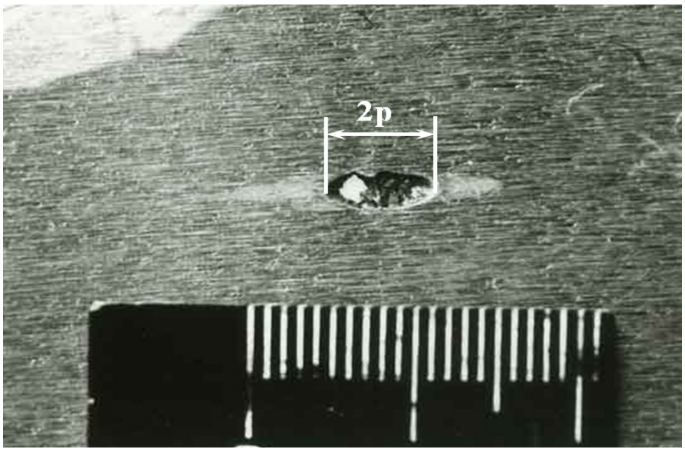


Fig. 5. Metal structure defect

Flakes can be observed on macro- and microsections in the form of straight, sometimes winding and zigzag lines with a length of several tens of fractions of a millimeter to 10–15 mm or more. In small cross-sections of products from rolled steel (less than 2–30 mm in diameter), flakes are never detected in contrast to cast steel.

In addition, there are other types of technological defects: hairlines (20–30 mm long, sometimes reaching up to 100–150 mm), fissures, pigeon holes, laps and forging folds (arising when the rolling edge of metal or the elevation won't weld to the main mass of the rolled metal) as well as scabs, whose thickness varies from tenths of a millimeter to 3–5 mm or more.

Figure 5 shows a blister in a metal [4]. Its maximum dimensions are strictly limited by normative and technical documentation, the 2nd class of continuity being widely used.

It is proposed that an 'elementary defect' be introduced into the zone with the lowest safety margins, the effect being a circle with geometric data according to Table.

In this case, the correction for selecting the finite element mesh parameters for the introduced defect must be carried out in accordance with GOST 25.504-82. For a plate with h-thick eccentrically located holes under tension (see Fig. 6), the reduction of the mesh element must be carried out until the difference in the maximum stresses in the same nodes becomes no more than 0.04%.

A further reduction in the size of a mesh finite element will lead to an insignificant decrease in the error, which indicates the problem non-dependence on the mesh. Such an analysis is carried out when solving all subsequent problems.

The maximum stresses in the zone of defect location exceed the average ones according to the law

$$\sigma_{H\infty} = \frac{P}{h(B+b)}, \; \sigma_{HA-C} = \sigma_{H\infty} \frac{\sqrt{1-(p/b)^2}}{1-\frac{p}{b}\left[1-\frac{b}{B}\left(1-\sqrt{1-(p/b)^2}\right)\right]}$$

where P is the acting load; h, B, b and p are the geometric parameters shown in figure 6.

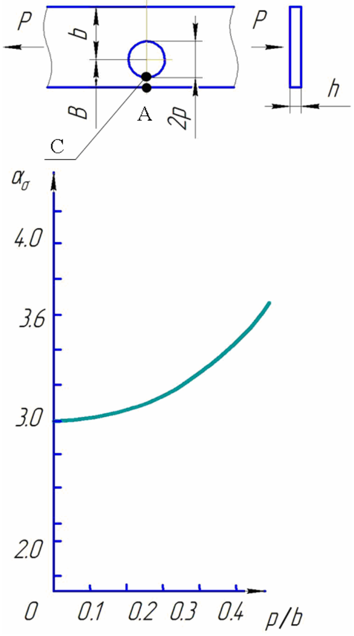


Fig. 6. Determination of defect concentrator coefficient

Continuity indicators for rolled steel plates

Class of continuity	Continuity Indicators					
	S_1, cm^2	S_2, cm^2	S_3, cm^2	S, %		L, mm
				per 1 m^2, not more than	for a sheet metal unit area, not more	
01	As agreed by the manufacturer and the customer					
0	5	20	1.0	1.0	0.3	30 – for a sheet metal with a thickness of up to 60 mm including, 50 – for a sheet metal with a thickness of over 60 mm
1	10	50	2.0	2.0	0.5	50
2	20	100	2.0	3.0	1.0	100
3	50	250		5.0	2.0	200

Results of the crosspiece stress-strain state investigation

The solution to the problem of mechanical strength was carried out using the SolidWorksSimulation software package. Three-dimensional tetrahedral solid-state elements were used as a computational mesh, the mesh thickening being performed both inside the structural holes and in the defect location zone. The calculation conditions are given according to the scheme shown in figure 2. The defect size corresponds to the 2nd class metal continuity.

Figures 7 and 8 show the crosspiece stress state calculation results made by the finite element method. The crosspiece temperature field for this construction is given in figure 9.

According to the results obtained, it can be concluded that the total deflection of the crosspiece arm and central part can only be calculated in a three-dimensional setting, the continuity of the metal not being determinative for displacements. It should be noted that in terms of mechanical strength, the presence of permissible defects in accordance with the requirements of normative and technical documentation can only be justified when performing calculations that take into account the geometric, thermal and strength factors, as well as the features of manufacturing sheet metal types.

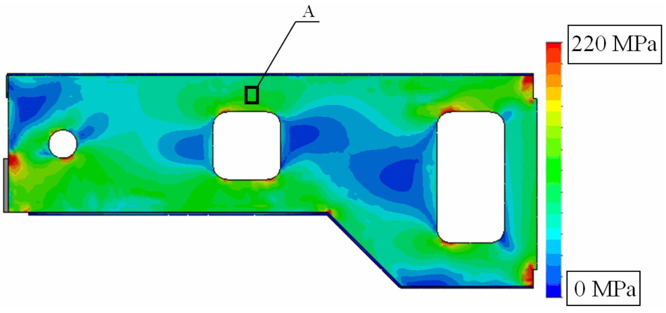


Fig.7. Stress determination

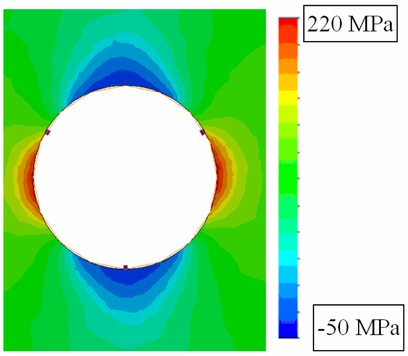


Fig. 8. Stretching stresses in the defect location zone (view A in figure 7)

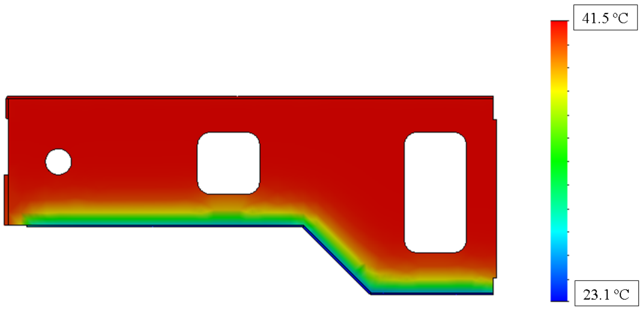


Fig. 9. Temperature diagram/profile

Conclusions

The paper presents a method for determining the stress-strain state of a high power hydroelectric generator-engine crosspiece. The structural features determining the force effect on the umbrella-type hydrogenerator-motor crosspiece in a three-dimensional setting are studied. The proposed method makes it possible to estimate the stressed state of non-resource components of hydroelectric generators taking into account mechanical and thermal loads, as well as introduce restrictions on the continuity of metal at the design stages. The choice of permissible stresses based on various factors for the main types of structural steels is grounded.

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Вплив теплових і механічних факторів на напружений стан великих вузлів гідрогенераторів-двигунів

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Виконано детальний аналіз конструкції гідрогенератора-двигуна граничної потужності з повітряним охолодженням. Показано, що хрестовина гідрогенератора зонтичного типу сприймає динамічні навантаження, обумовлені силами, що діють у трьох площинах. Проте їхній облік аналітичними методами є неможливим. Для тривимірного розрахунку необхідно врахувати теплові та механічні фактори, а також особливості застосовуваного листового прокату. Під час розв'язання поставленої задачі з урахуванням теплових навантажень пропонується дискретне розбиття хрестовини на n-е кількість ділянок. Критерій збіжності для розв'язання оберненої задачі ґрунтується на збереженні загального теплового балансу конструкції з урахуванням обмеженої точності вимірювальних приладів. Обґрунтовано вибір припустимих обмежень з урахуванням наявності раковин у структурі металу, що не перевищують свого класу суцільності для вибраного металопрокату. Пропонується в зону з найменшими запасами міцності ввести «елементарний дефект» як окружність з геометричними даними згідно з обмеженнями по суцільності. Проте корекція підбору параметрів сітки скінченних елементів для введеного дефекту здійснюється? як і для пластини з ексцентрично розташованими отворами. Сітку зменшують до того моменту, за якого різниця по максимальних напруженнях в одних і тих же вузлах стає не більше 0,04%. Механічні навантаження задаються в класичній постановці. В процесі роботи встановлено, що запаси міцності крупних вузлів генератора мають регламентуватися якістю використовуваного металопрокату, а механічні розрахунки – враховувати теплові фактори.

***Ключові слова**: турбогенератор, механічні напруження, тепловий процес, дефекти металу.*

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DESIGN FORECASTING OF THERMAL STRENGTH AND RESOURCE OF STEAM TURBINE STRUCTURAL COMPONENTS

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Effective and reliable operation of power units is closely connected with the provision of the thermal strength and durability of their elements and components. The needs of the modern energy market lead to the operation of equipment in variable modes, which causes accelerated wear-out of its resource. The problem of extending the resource of power equipment is becoming increasingly important due to the fact that its ageing processes outstrip its replacement rate. Therefore, in order to ensure the reliable operation of power units, a calculated estimate of the thermal stability and durability of their elements is essential, based on the application of new methods and calculation models, taking into account a number of important factors (damageability, material property heterogeneity, contact interactions, presence of cracks, influence of non-stationary temperature fields, etc.) The paper gives an overview of methodical and software as well as the results of the calculated research of the thermal strength, resource and crack resistance of steam turbine elements, which have been performed at A. Podgorny Institute of Mechanical Engineering Problems of the National Academy of Sciences of Ukraine during the last 15 years. The calculated estimate of the resource of power unit parts and components, as well as substantiation of the possibility of its extension were performed within the framework of the normative document developed by the authors of this paper for determining the estimated resource and survivability of rotors and turbine structural units with more reasonable reserve coefficients. The developed methodical ware allowed us to make calculations of steam turbine elements in newly specified formulations, taking into account the peculiarities of real operating conditions. The developed computerized system for diagnosing the thermal-stress state and wear-out of high-temperature steam turbine rotor resources, taking into account the real operating modes of turbine units, obtained on the basis of the parameters of the automatic control system of technological processes, allows one to more accurately estimate the time of their trouble-free operation. Formulations and a brief analysis of the results of the considered problems of thermal strength and resource of turbine elements are presented.

***Keywords**: design forecasting, thermal strength, resource, crack resistance, steam turbine elements.*

Introduction

Increasing the reliability and efficiency of power units is closely related to ensuring the thermal strength of their elements and components. A characteristic feature of modern energetics is the operation of equipment in variable modes, which leads to an accelerated wear-out of its resource. The problem of extending the resource of power equipment is becoming increasingly important due to the fact that its ageing processes outstrip its replacement rate. Therefore, in order to ensure the reliable operation of power units, a calculated estimate of the thermal stability and durability of their elements [1] is essential, based on the application of new methods and calculation models, taking into account a number of important factors (damageability, material property heterogeneity, contact interactions, presence of cracks, influence of non-stationary temperature fields, etc.)
