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DOI: https://doi.org/10.15407/pmach2021.03.034

UDC 621.125

CONTACT INTERACTION OF STEAM TURBINE INNER CASING ELEMENTS DURING PLASTIC DEFORMATION

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A structure's material plasticity influence on the pattern of contact interaction of its elements during operation is studied. The stress-strain state problem for the inner casing of a steam turbine high-pressure cylinder operating at supercritical steam parameters (over 240 atm and 565 °C) is solved. The problem is solved by using a finite-element software package. A model of thermoplasticity with kinematic and isotropic hardening is considered. In carrying out the study, experimental strain curves were used for the materials of the connection. The main dependencies used in solving the problem are given. The method of solving the thermal contact problem of interaction of flange connector elements in the conditions of plasticity is based on the application of a contact layer model. To be able to take into account changes in the load from the fastening in the process of combined strain of both the fastening and the casing, first proposed is a method of the three-dimensional modeling of the thermal tightening of the fastening of the horizontal casing connector by applying the linear coefficient of linear expansion of the material. The proposed approach allows modeling the stress of the initial tightening of studs by specifying a fictitious change (decrease) of the coefficient of linear expansion of a stud given as a separate body in the calculation scheme. The magnitude of the specified change in the coefficient of linear expansion is determined from the relationship between the stress of the initial tightening in the stud and the required, for its creation, elongation, which is implemented in the calculation scheme in the presence of different values of linear expansion of both the stud and the casing. To conduct the numerical experiment, an ordered finite-element grid of the casing design was constructed. A 20-node finite element was used in the construction of the casing grid and the fastening. The effect of force loads and the temperature field, in which the structural element under consideration is operated, is taken into account. An analysis of the results of distribution of equivalent stresses and contact pressure during operation is carried out. The difference between the obtained results and the results of solving the problem in the elastic formulation is noted.

***Keywords**: turbine, flange connector, casing, stress state, contact interaction, plasticity.*

Introduction

According to the International Energy Agency, more than 40% of electricity is generated using coal fuel, and more than 10% is generated using nuclear fuel. At both nuclear and thermal coal-fired power plants, those using steam turbine technology have become the most widespread. The equipment used in the plants of this type has reached a high level of perfection, which is why a significant increase in efficiency can be expected only if the initial parameters of the thermodynamic cycle have been increased. Increasing the efficiency of coal-fired power plants to 45–47%, and in the long run to 52–55%, will reduce the amount of harmful emissions into the atmosphere per unit of capacity and the cost of the energy produced. This can be achieved through the widespread introduction of power plants designed for supercritical steam parameters, i.e. pressures above 30 MPa and temperatures above 560°C. Within the European Union's energy program, it is planned to create a coal-fired power unit with an efficiency of about 55%, designed for steam parameters of 37.5 MPa and a temperature of 700–720 °C [1]. New technologies and materials will allow us to overcome these shortcomings in the coming decades and significantly increase the efficiency of coal, oil-fired and gas power plants [1–3].

Reconstruction of existing power plants and further development of turbine construction, associated with increasing the initial parameters of steam, increasing unit capacity of turbounits, and the desire to reduce their size and weight, largely depend on improving the reliability and durability of turbine parts and components, including cast cylinder casings [4–11].

The change in the temperature state of the turbine casing, which occurs, as a rule, unevenly in its various parts and with limited possibility of thermal expansion or compression due to the relationship with surrounding parts or external bodies, leads to the emergence of a system of forces between the interacting elements and the appearance of appropriate temperature stresses therein. This problem extends to two- and three-dimensional cases that require more complex methods of solution, and reduces the temperature field to a peculiar load [12].

The stationary temperature fields of high pressure cylinders (HPC), inner casings shielding the first pressure stages with high steam parameters, are formed mainly by radial heat fluxes with large gradients due to large differences in steam temperatures at the turbine inlet and in the first steam-extraction section. Due to the elimination of heat from the steam flow, the turbine casings operate in conditions of uneven heating, which changes the physical and mechanical properties of their materials and leads to the emergence of temperature gradients, accompanied by the unequal thermal expansion of individual structural parts. This expansion causes temperature stresses [3, 6, 12].

Determining the magnitude and nature of the action of temperature stresses is necessary for a comprehensive analysis of the strength of a structure. It is known that the temperature stresses themselves and in combination with the mechanical stresses from external loads can cause cracks and structural destruction. As a result of temperature stresses, significant plastic deformation may occur, which can lead to the complete or progressive destruction of the structure.

Since in most casing elements the transmission of forces between the parts is carried out by contact, and their temperature and strength are determined by the nature of contact pressure distribution, it becomes important to build refined models and methods for calculating the stress-strain state (SSS) of a structure in the 3D setting. In addition, ensuring the density of horizontal connector flange joints in HPC casings at different temperature modes of turbine operation requires special attention to solving applied thermal conductivity and thermal stress problems, as well as contact problems of interaction of structural elements [8–9].

Among the various formulations and results of the study of interaction problems, thermo-contact problems are the most complex and least studied ones, and therefore the need to create effective methods for solving them is obvious. The main difficulty of calculations is that the temperature problem is related to the mechanics problem due to initially unknown contact conditions, since the SSS of the parts and the nature of their interaction depend on temperature distribution, and the temperature field, in turn, is determined by contact conditions. Additional difficulties arise due to physical and geometric nonlinearity, as well as non-stationarity of contact problems with variable areas of contact and slip. Therefore, in practice, widely used are engineering calculation methods based on certain assumptions [1–5]. For example, [7–9] describe an approximate approach for determining the forces in the studs and stresses in the flanges of the horizontal connector, as well as an approach for determining the temperature stresses in turbine casings.

Thus, the development of approaches to the 3D modeling of the thermal tightening of the fastening of the horizontal casing connector, which would allow us to more precisely take into account the change in the geometry of the casing elements due to thermal loads, is an urgent problem and requires detailed study.

Problem Statement and Description of Calculation Methods

The object of study in this paper is the high-stressed inner casing of the HPC of a K-540-23.5 turbine whose design has been accepted in JSC "Turboatom" as a basis for creating a series of new-generation turbines designed to operate at supercritical parameters of steam.

The transfer of forces for a number of steam turbine parts is carried out by contact between the interacting surfaces with the influence of heat transfer, so the problem is solved in the thermo-contact setting.

In solving the problem we used, as initial data, the following power loads on the casing:

1) distributed load on bores for the installation of diaphragms and end seal holders in the casing, the load of group "I", figure 1;

2) different, along the longitudinal axis, drop in pressure on the walls of the casing (determined from the load diagram as the difference between the pressure on the outer wall of the casing and the pressure on the inner wall of the casing), the load of groups "III" and "II", respectively, figure 1;

3) the thermal tightening of the fastening of the flange connector made of steel EP-182 (20Kh1M1F1TR), the load of group IV, figure 1;

4) the Earth's gravitational field acting on the turbinecasing;

5) thermo-contact interaction in the flange connection at the connection point.

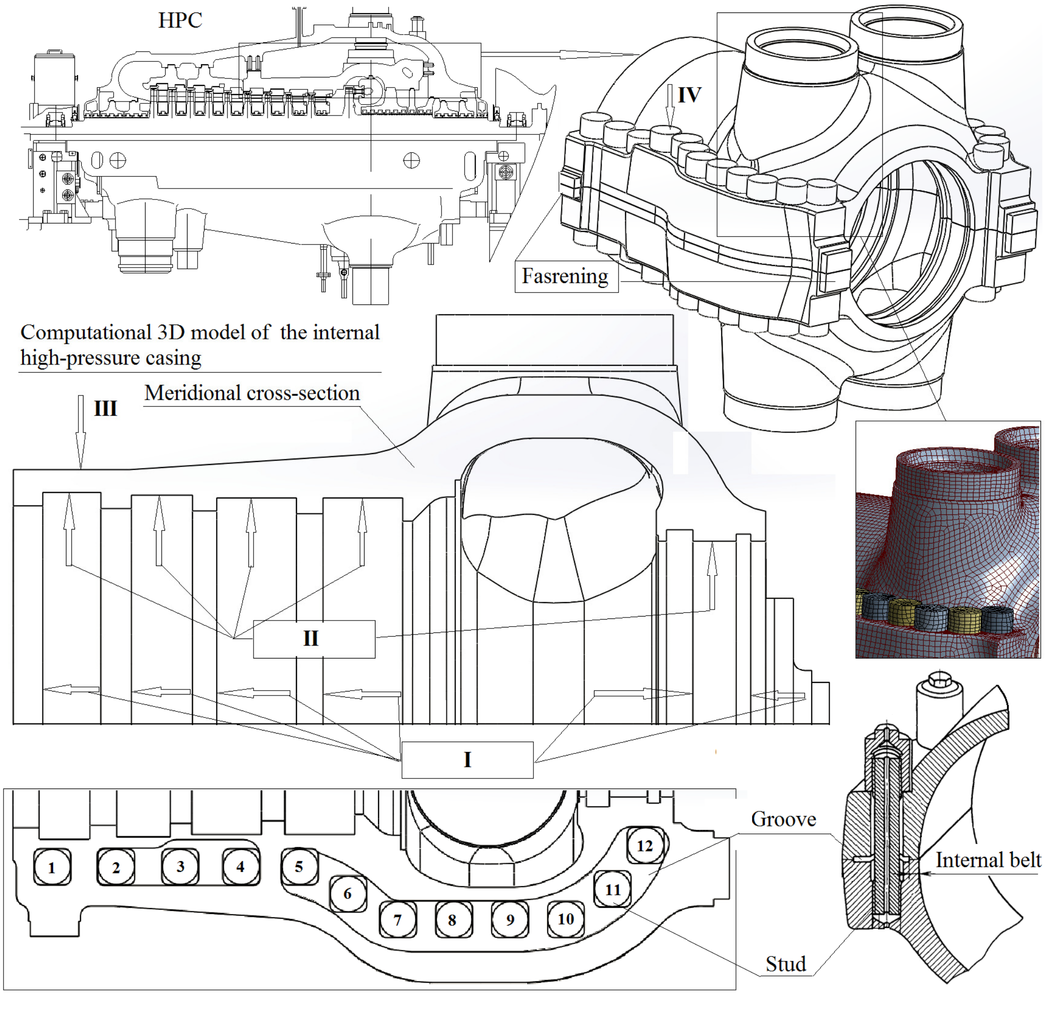

Fig. 1. 3D model of the inner casing of the HPC of the K-540-23.5 turbine

The method of solving thermo-contact problems, used in this paper, through the use of the finite element method (FEM) is based on the application of a contact layer model, which allows us to take into account the dependence of thermal conductivity of the contact on the contact pressure with account taken of heat transfer. When solving a thermo-contact problem, it is assumed that at the boundary of the collision of flange connection elements, there is a perfect thermal contact and equality between temperatures and heat fluxes

$$T_1(x_k, y_k, z_k, t) = T_2(x_k, y_k, z_k, t), \quad \lambda_1\left(\frac{\partial T}{\partial n}\right)_k = \lambda_2\left(\frac{\partial T}{\partial n}\right)_k,$$

where $\lambda_1(T)$, $\lambda_2(T)$ are the thermal conductivity coefficients of the contacting bodies, which depend on temperature T.

Of all the possible stationary modes, the nominal one is most important [13], which is why it was used to find the temperature loads. Temperature limit conditions were set based on the results of the calculation of the thermal state of the turbine, which was carried out in accordance with the methods approved by the regulatory methods of JSC "Turboatom". This allowed us to obtain, using the finite-element (CE) software complex, the temperature distribution in the casing (figure 2).

The boundary conditions that simulate the fastening of the casing in the computational 3D model are: rigid fastening in terms of the lower casing part resting on claws and limiting the displacement along the connector plane in the place where the claws of the inner casing rest in the outer casing grooves (Fig. 1).

The 3D model of the K-540-23.5 steam turbine casing, developed using the geometric modeling package Autodesk Inventor Professional, is shown in figure 1 [8, 9, 14]. The upper and lower halves of the casings are connected by 24 pins. For convenience of calculation and analysis, each stud has its own number assigned.

The FE model of the internal casing is shown in figure 2. Taken as a FE is a 20-node hexagonal element for connected calculations in the 3D setting, which has a degree of freedom in both displacement and temperature [8]. This element supports nonlinear models of the mechanical and thermal properties of the material and allows calculating the SSS due to plastic strain [15].

When splitting the original model, about 197 thousand FEs were obtained, of which ~ 46 thousand were contact elements, from which, through the creation of a special layer, the contact interaction is modeled (figure 1).

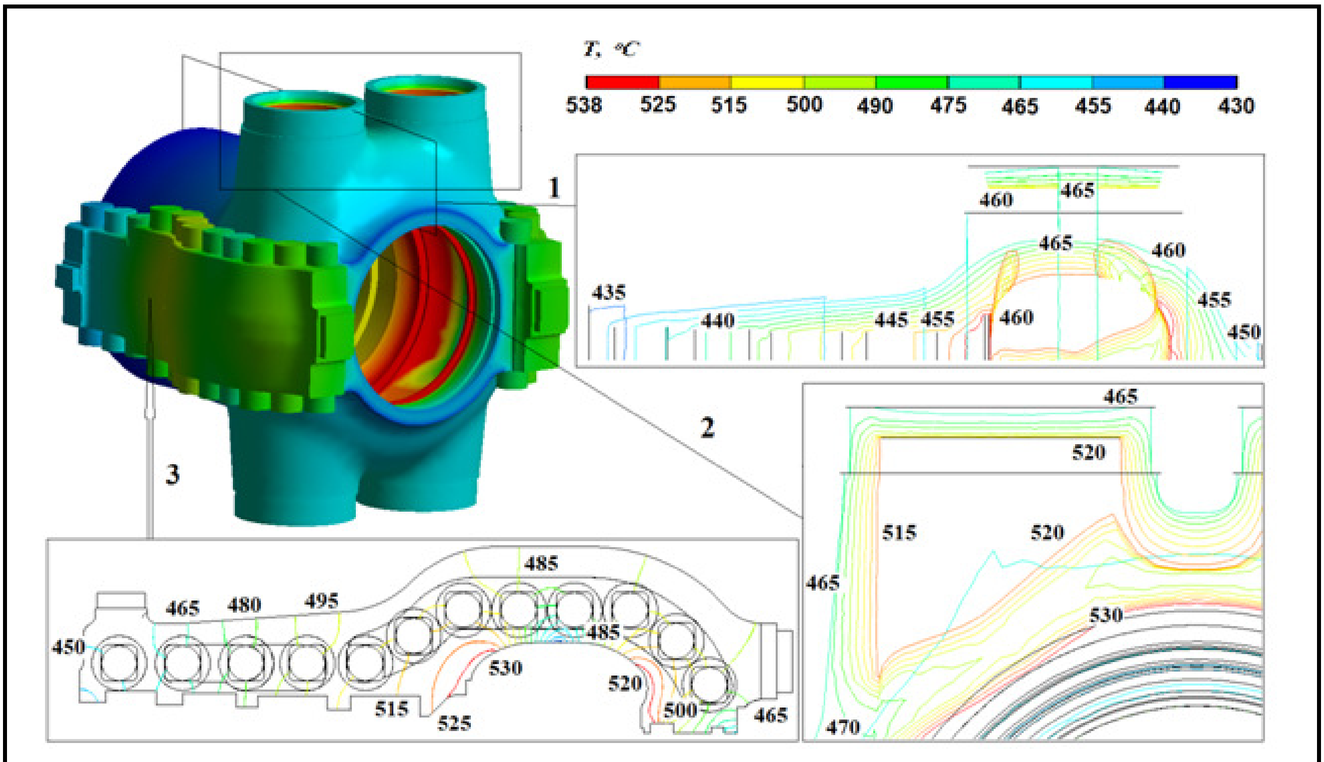

Fig. 2. Temperature field of the internal casing of the HPC of the K-540-23,5 turbine in the nominal mode of operation: 1 – meridional section; 2 – cross-section in the steam inlet area; 3 – sealing surface of the horizontal connector flange

In the contact zones, which mainly affect the transfer of forces between the interacting elements, there is a thickening of the mesh with a decrease in the FE size to 1 mm, which increases the accuracy of the calculation. When modeling the contact interaction, an 8-node contact FE was used by analogy with [8, 9, 16].

When using the method of calculating the contact interaction described in [16] to construct a matrix of stiffness of the contact surface, taken was the value of mutual penetration on the sealing surface of the flanges close to the height of roughness, namely 0.0025 mm [17, 18].

This FE model has several zones of contact interaction. When modeling the inner casing in the thermo-contact setting, both the contact interaction of the flanges with each other and the contact interaction of the fastening and the flanges of the casing were considered. In contrast to the results presented in [8, 9], the above became possible due to the use of the 3D modeling of the thermal tightening of the fastening of the horizontal casing connector.

Method of the 3D Modeling of the Thermal Tightening of the Fastening of the Horizontal Casing Connector

The computational method of modeling thermal tightening forces proposed in previous works [8–11] allows us to determine, in the elastic setting, the SSS of the casing and fastening with an accuracy that would fully satisfy the requirements of engineering calculations during the design of turbines that are still in operation. According to this method, set as the initial data were the loads from the fastening of the horizontal connector to the bearing surfaces of the nuts. However, the solution of the problem of the thermal stress of the casing with account taken of the temperature and plastic strains as well as thermal contact interaction of the casing flanges, where the connection of the temperature problem with the problem of mechanics is provided through previously unknown boundary conditions in the contact, since the SSS and contact action pattern depend on the distribution of temperature fields and a temperature field is determined by the conditions of interaction, requires somewhat different, improved approaches.

In addition, strengthening the requirements for improving the efficiency of turbine units includes not only improving the flow paths of the cylinders, but also increasing the maneuverability of the turbine. This requires a significant reduction in the width of the flanges of the horizontal connector, which simultaneously with the introduction of the groove on the horizontal connector and the increase in the diameter of the fastening changes the value of the main load factor, which depends primarily on the cross-sectional area of the stud and the cross-sectional area of the flange (one connection span)

$$\chi = 0{,}5\chi_0 = 0.5\frac{f_s E_s}{f_s E_s + f_f E_f},$$

where f_s is the cross-sectional area of the stud, mm^2; f_f is the cross-sectional area of the flange, mm^2; E_s is the modulus of elasticity of the stud material, MPa; E_f is the modulus of elasticity of the flange material (casing), MPa.

The above circumstances do not allow the use of a calculation scheme in which the tightening forces of the fastening B_0, caused by the required initial tightening of the studs, are applied to the casing as specified, and change little due to the combined strain of the fastening and casing from internal pressure [19]. This was justified on turbine casings of earlier releases, for which the main load factor fluctuated within χ=0.05–0.15, and the force from the fastening on the casing was obtained as

$$P = B_0 + \chi F = B_0 + (0{,}05...0{,}15)F,$$

where F is the steam force on one stud.

Since the problem of the distribution of forces and temperatures between the fastening and flange is not statically defined, it is solved subject to the condition of common strains. During the action of the external force on the connection before the opening the connector, the compression of the parts connected is reduced as much as the stud is stretched [19, 20].

Due to the above, to be able to take into account changes in the load from the fastening in the process of the combined deformation of the fastening and the casing, it is proposed to simulate the initial tightening of the studs by specifying a fictitious change (reduction) of the coefficient of linear expansion of the stud, specified as an individual body in the calculation scheme.

By applying the above coefficient of linear expansion of the material during the three-dimensional modeling of the thermal tightening of the horizontal casing connector, it was possible to more accurately take into account the change in the geometry of the casing elements due to thermal loads. The magnitude of the specified change in the coefficient of linear expansion is determined from the relationship between the stress of the initial tightening in the stud $\sigma^{\mathrm{in}}_{\mathrm{mid\,sec}}$ and the required for its creation elongation Δl_{s}, implemented in the calculation scheme in the presence of different values of linear expansion of a stud and casing

$$\Delta l_{\mathrm{s}} = \frac{\sigma^{\mathrm{in}}_{\mathrm{mid\,sec}}}{E_{\mathrm{s}}} l_{\mathrm{s}}\,; \quad \Delta l_{\mathrm{s}} = \left(\alpha_{\mathrm{c}} t_{\mathrm{op}} - \alpha_{\mathrm{s}} t_{\mathrm{op}}\right) l_{\mathrm{s}}\,; \quad \alpha_{\mathrm{c}} t_{\mathrm{op}} - \alpha_{\mathrm{s}} t_{\mathrm{op}} = \frac{\sigma_0}{E_{\mathrm{s}}}\,,$$

where l_{s} is the length of the stud, mm.

The given coefficient of linear expansion of the stud material is determined by the formula

$$\alpha_{\mathrm{s}} = \alpha_{\mathrm{c}} - \frac{\sigma_0}{E_{\mathrm{s}} t_{\mathrm{op}}}\,.$$

The coefficient of linear expansion of the stud material depending on the metal temperature and the coefficient of linear expansion of the casing material (15Kh1M1FL steel) depending on the metal temperature, obtained from [21] is shown in figure 3.

Figure 4 shows the modulus of elasticity of the materials of the casing and fastening, depending on the temperature of the metal, obtained from [21].

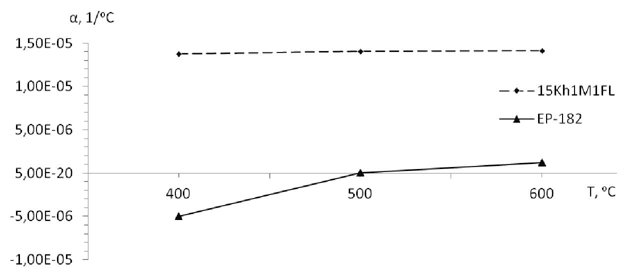

Fig. 3. Coefficients of linear expansion of the materials

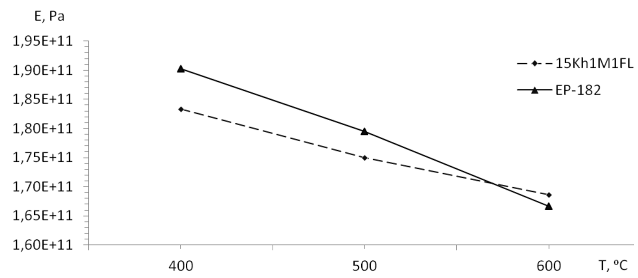

Fig. 4. Modulus of elasticity of the materials

Methods to Numerically Model the Processes of Complex Plastic Deformation of the Inner Casing

The calculated strength assessment of casing structural elements operating under thermo-mechanical non-stationary load requires that the elastic strain of structural materials be analyzed, because in the process of elastic deformation the rate of damage accumulation is determined, and the adequacy of modeling these processes affects the accuracy of calculated durability assessments.

For the mathematical model of plastic flow with kinematic and isotropic hardening, proposed in [22, 23], which describes the deformation processes for arbitrary complex load modes, which are accompanied by the rotation of the main surfaces of stress and strain tensors, a calculation method for determining the SSS of the inner casing plasticity has been developed.

The most adequate and practically used theory of plastic flow is the theory based on the concept of isotropic and kinematic hardening [22, 23]. The key role in it is given to the yield surface and its change in the process of deformation.

Isotropic hardening corresponds to a change in the yield surface, and at this hardening, during loading, the surface expands evenly in all directions and retains the initial position of its center. The same mechanism of hardening is supposed to be used both at stretching and compression. An increase in stresses above the yield strength leads to an increase in the limit of proportionality during unloading, while the amplitude of elastic stresses is twice the value of the highest stresses achieved. Isotropic hardening is used for both small and large strains, but it cannot be used for cyclic loads [22].

In the case of kinematic hardening, the yield surface is displaced without changes in size. This model takes into account the Bauschinger effect, which occurs in metals when the sign of the load changes. Taking into account the Bauschinger effect is important when calculating cyclic loads accompanied by plastic strains, both in the case of modeling low-cycle fatigue at relatively low stresses and strains, and at a disproportionate load. At large strains (more than 5–10%), the model of kinematic hardening is not used [23].

The used model of thermoplasticity with kinematic and isotropic hardening describes the processes of complex plastic deformation of structural materials (metals and their alloys) under monotonic and cyclic, proportionate and disproportionate modes of thermopower loading. In the notations adopted in [22, 23], to change the radius C_p of the yield surface F_p during isotropic hardening, with account taken of the separation of the processes of monotonic and cyclic loading, the following structure of the equation is adopted:

$$C_p = [q_\chi H(F_p) + a(Q_s - C_p)\Gamma(F_p)]\dot{\chi} + q_3\dot{T}\ ; \tag{1}$$

$$C_p = C_p^0 + \int_0^t \dot{C}_p dt\ ,\quad \dot{\chi} = \left(\frac{2}{3}\dot{e}_{ij}^p \dot{e}_{ij}^p\right)^{1/2},\quad \chi_m = \int_0^t \dot{\chi} H(F_p) dt\ ;\quad \chi = \int_0^t \dot{\chi}\, dt\ ; \tag{2}$$

$$q_\chi = \frac{q_2 A\psi_1 + (1-A)q_1}{A\psi_1 + (1-A)},\quad Q_s = \frac{Q_2 A\psi_1 + (1-A)Q_1}{A\psi_1 + (1-A)},\quad (0 \le \psi_1 \le 1,\ i=1,\ 2); \tag{3}$$

$$A = 1 - \cos^2\theta\ ,\quad \cos\theta = n_{ij}^e n_{ij}^s\ ,\quad n_{ij}^e = \frac{\dot{e}_{ij}}{(\dot{e}_{ij}\dot{e}_{ij})^{1/2}}\ ,\quad n_y^s = \frac{S_{ij}}{(S_{ij}S_{ij})^{1/2}}\ ; \tag{4}$$

$$H(F_p) = \begin{Bmatrix} 1, & F_p = 0\ \rho_{ij}\rho_{ij} > 0 \\ 0, & F_p < 0\ \rho_{ij}\rho_{ij} \le 0 \end{Bmatrix},\ \Gamma(F_p) = 1 - H(F_p)\ , \tag{5}$$

where q_1, q_2, q_3 are isotropic hardening moduli; Q_1, Q_2 are cyclic isotropic hardening moduli; a is the constant that determines the speed of the process of stabilization of the hysteresis loop; Q_s is the value of the radius of the yield surface in the stabilized state at $\rho_{\max}$ and T ($\rho_{\max}$ is the maximum modulus of the variable ρ_{ij} in the load history); C_p^0 is the initial value of C_p.

In equation (1), the first term describes the isotropic hardening due to the monotonic plastic strain ($H(F_p)$=1 i $\Gamma(F_p)$=0), the second term, the cyclic hardening of the material ($H(F_p)$=0 i $\Gamma(F_p)$=1), and the third one describes the change in the radius of the yield surface when the temperature changes.

The modulus of isotropic hardening q_χ takes into account the change in the isotropic hardening of the material, depending on the direction of deformation at a given point of the trajectory, the angle θ between the vector of increase of the deflector of deformations having the guide cosines n_{ij}^e and the normal to the yield point at the point determined by the guide cosines n_{ij}^s.

At proportionate loading, fulfilled are the following conditions: the angle θ=0; the parameter

$$A = 0\ ,\ q_\chi = q_1\ ,$$

where q_1 is the modulus of the isotropic hardening of the material (uniaxial stretching of the material).

Disproportionate loading is in correspondence with the conditions

$$\theta = \pi/2\ ,\ A = 1\ ,\ q_\chi = q_2\ ,$$

where q_2 is the modulus of hardening under the tangential load on the yield surface ("neutral" loading).

For cyclic isotropic hardening under cyclic proportional loading in (1) (5), determined similarly is θ=0 and Q_s=Q_1, and for cyclic disproportionate loading, θ=π/2 and Q_s=Q_2.

The calibration coefficients (weights) ψ_1 and ψ_2 are parameters that allow us to adjust the effect of the moduli q_1, q_2, Q_1, Q_2 on the isotropic hardening of the material.

With the stationary cyclic deformation of the material with a constant strain amplitude and T=const, the radius of the yield surface C_p tends to Q_s=const, and the parameters of the hysteresis curve tend to their stabilized values, which are determined by the value Q_s and depend on the current values of T and $\rho_{\max}$.

In the computational FE package, when solving elastic-plastic problems, the modeling of the SSS can be achieved by using nonlinear dependencies for the evolution of the radius of the yield surface and the coordinates of its center [22, 23]. The numerical modeling of high-temperature plasticity was carried out using the theory of plastic flow with isotropic hardening.

The SSS Analysis of the Inner Casing of the HPC of the K-540-23.5 Turbine in the Plastic Setting

The obtained results of solving the problem of the thermoplastic SSS of the casing (Figs. 5, 6) allowed us to characterize the degree of relaxation and redistribution of stresses in the structure compared with the results obtained during the solution of the problem in the elastic setting [9].

We can conclude that the main reason for the curvature of the casing is the temperature difference across the wall thickness, which causes uneven stress distribution.

Note that in the flange area the temperature difference in the thickness of the casing is maximum (60 °C), while in the hottest upper part of the casing it does not exceed 10 °C (Fig. 2).

The solution of the SSS problem of the flange connection in the setting considered allowed us to estimate the change in the pattern of the contact pressure distribution in the connection. The obtained results showed a significant difference in the level of contact pressure on the sealing surface of the flange. Thus, the values of the contact pressure at the front edge of the casing, at the place of installation of the front end seal holder (in place of stud No. 12), are almost completely negative, in contrast to the results obtained in the elastic setting [9]. This indicates the need to take into account the plastic phenomena when studying the SSS of the inner casing of the turbine.

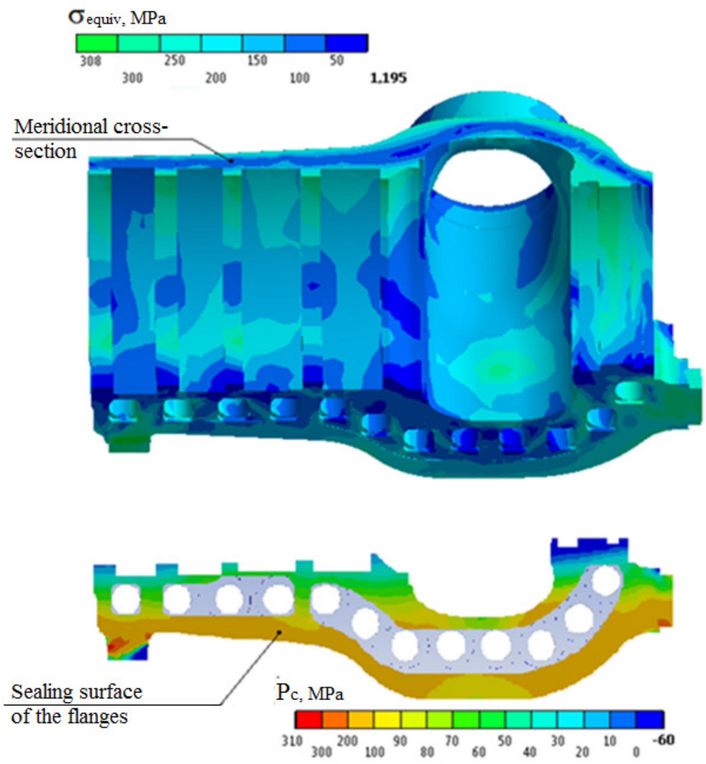

Fig. 5. SSS of the turbine casing in the thermoplastic setting with isotropic hardening

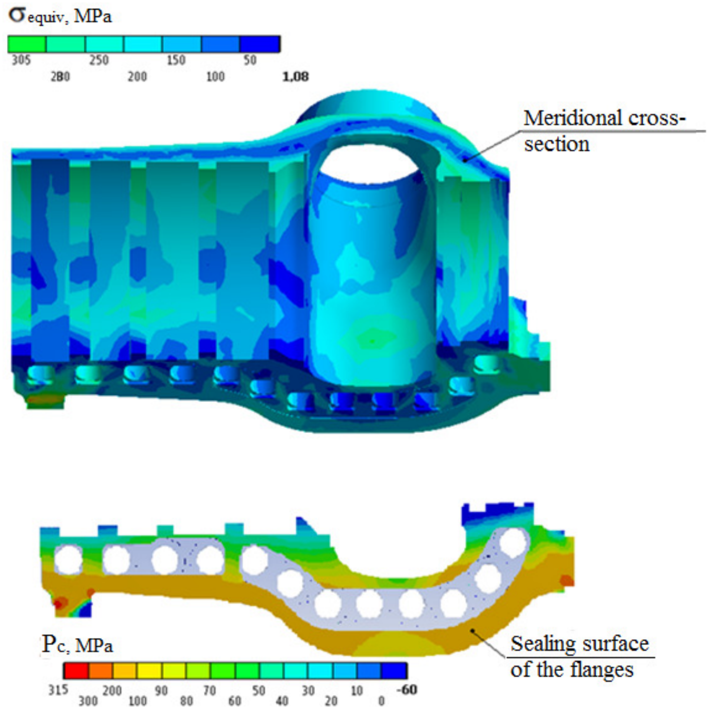

Fig. 6. SSS of the turbine casing in thermoplastic setting with kinematic hardening

Conclusions

1. The method of the three-dimensional calculations of the SSS of a steam turbine casing has been improved taking into account the thermo-contact interaction of its structural elements and calculations of the plasticity of its materials. Compared with the existing approaches, the proposed one allows us to more precisely take into account the influence of various factors on the SSS of the inner casing of a high-temperature steam turbine.

2. A technique of a three-dimensional modeling of the thermal tightening of the fastening of the horizontal casing connector by applying the aforementioned coefficient of linear expansion of material is first offered. An approach is proposed that

allows us to model the stress of the initial tightening of the studs by specifying a fictitious change (decrease) of the coefficient of linear expansion of a stud given as a separate body in the calculation scheme. The magnitude of this change in this coefficient is determined from the relationship between the stress of the initial tightening in the stud and the elongation required for its creation, implemented in the calculation scheme by the presence of different values of linear expansion of the stud and casing. This allowed us to take into account the change in the geometry of the casing elements due to thermal loads.

3. Based on the results of solving the SSS problem of the flange connection, with account taken of the plastic properties of the materials and temperature fields in the elements of the inner casing of a steam turbine, the following conclusions can be made:

– the value of the curvature of the flange connector plane primarily depends on the intensity of temperature stresses;

– the process of plastic deformation of the casing material is most active in the toroidal part of the casing at the point of its connection with the flange;

– the problem of contact interaction is essentially nonlinear, since the connection of the temperature problem with the problem of mechanics is provided through previously unknown boundary conditions in the contact. This is due to the fact that SSS and pattern of the contact interaction depend on the distribution of temperature fields, and a temperature field is determined by the interaction conditions.

4. The results of solving the problem of the SSS of the casing with account taken of the plastic properties of materials according to the theory of flow with isotropic and kinematic hardening and the contact interaction of its elements showed a slight difference. This is due to the lack of alternate loads.

The proposed method for the analysis of the thermal stress state of a turbine casing can be used to make recommendations on how to cool high-temperature steam turbine casings during their operation.

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Received 04 August 2021

Контактна взаємодія елементів внутрішнього корпусу парової турбіни при пластичному деформуванні

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Вивчається питання впливу пластичності матеріалів конструкції на характер контактної взаємодії її елементів під час експлуатації. Розв'язується задача про напружено-деформований стан внутрішнього корпусу циліндра високого тиску парової турбіни, розрахованої на надкритичні параметри пари (понад 240 ата і 565 °С). Розв'язання задачі здійснюється шляхом використання скінченно-елементного програмного комплексу. Розглянуто модель термопластичності з кінематичним та ізотропним зміцненням. Під час проведення дослідження для матеріалів з'єднання використано експериментальні криві деформування. Наведено основні залежності, що використовуються при розв'язанні поставленої задачі. Методика розв'язання термоконтактної задачі взаємодії елементів фланцевого з'єднання в умовах пластичності базується на застосуванні моделі контактного шару. Для можливості врахування змін навантаження від кріплення в процесі спільної деформації як кріплення, так і корпусу вперше запропоновано методику тривимірного моделювання термозатяжки кріплення горизонтального роз'єму корпусу завдяки застосуванню наведеного коефіцієнта лінійного розширення матеріалу. Запропонований підхід дозволяє моделювати напруження початкової затяжки шпильок шляхом задання фіктивної зміни (зменшення) коефіцієнта лінійного розширення шпильки, заданої як окреме тіло в розрахунковій схемі. Величина зазначеної зміни коефіцієнта лінійного розширення визначена із залежності між напруженням початкової затяжки в шпильці і необхідним для його створення видовженням, реалізованим в розрахунковій схемі наявністю різних величин лінійного розширення шпильки і корпусу. Для проведення чисельного експерименту побудовано впорядковану скінченно-елементну сітку моделі корпусу. При побудові сітки елементів корпусу та кріплення використано 20-вузловий скінченний елемент. Враховується дія силових навантажень та температурного поля, в якому експлуатується елемент конструкції, що розглядається. Проведено аналіз результатів розподілу еквівалентних напружень та контактного тиску під час експлуатації. Відзначено відмінність отриманих результатів порівняно з результатами розв'язання задачі в пружній постановці.

***Ключові слова**: турбіна, фланцеве з'єднання, корпус, напружений стан, контактна взаємодія, пластичність.*

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