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ELASTIC STRESS-STRAIN STATE OF ELEMENTS OF THE INTERNAL HIGH-PRESSURE CASING FOR STEAM TURBINES

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The elastic stress state of internal high pressure (HP) casings of 300 and 500 MW steam turbines is estimated using a three-dimensional computational structural model. The internal molded HP casings, which have a complex spatial form and work under conditions of complex power and thermal loading, are some of the most responsible and expensive steam turbine elements, limiting turbine resources. The simplified computational models used in engineering practice did not allow us to evaluate a number of factors determining stress-strain state (SSS) peculiarities. To clarify the distribution of stresses across the structure of internal HP casings, the SSS problem is solved in a three-dimensional setting with taking into account both the operating conditions and contact interaction of flanges. To determine the degree of influence of individual factors on the SSS, the factors are taken into account sequentially. At this stage, the SSS problem of the internal HP casing is solved in an elastic setting, without taking into account the influence of temperature stresses and deformations. The solution to the contact problem in the flange connections of internal HP casings is based on the application of the contact layer model. Probable contact zones are represented by contact elements, the mechanical interaction of contact surfaces being determined by their mutual penetration. The problem of determining the SSS of the internal HP casings of the K-325-23.5 and K-540-23.5 turbines in a three-dimensional setting is solved with using the finite element method (FEM), the total number of elements being 19,553 and 1,780,141, respectively. The created finite element (FE) models take into account the contact interaction of the flanges of the two casing halves in the horizontal connector zone. In contact zones, the mesh thickens. Results of the calculated estimation of the SSS of the internal HP casings of 300 and 500 MW steam turbines are given for the elastic deformation, taking into account the influence loads arising during the installation and operation of the turbines.

Keywords: *turbine, flange connection, horizontal connector, internal casing, high pressure cylinder, stress-strain state, differential pressure, boundary conditions, calculated estimation, joint face.*

Problem Formulation

The operation of steam turbines under conditions of increasing unevenness of the energy consumption schedule indicates that the reliability and maneuverability of power units along with other factors [1] is determined by the level of stresses arising in structural turbine components.

The object of the study in this paper is highly-stressed internal HP casings of the existing K-325-23.5 and K-540-23.5 turbines working at high steam parameters.

The aim of this paper is to calculate the peculiarities of the SSS of the internal HP casings on the basis of using three-dimensional models and identify the most stressed casing zones that require increased attention in the design and operation of these turbines.

The calculated definition of stresses in the internal HP casing having a complex spatial shape and working under conditions of complex power and thermal loading (Fig. 1–2) from three-dimensional models allows us to evaluate the influence of a number of factors. The latter determine the stress state peculiarities that cannot be established on the basis of models used in engineering practice due to their incompleteness, the proximity of the formation of boundary conditions, and the use of the physico-mechanical properties of materials [2].

To assess the strength of a molded HP casing, which is one of the most critical and expensive resource-limiting elements of a steam turbine, it is necessary to investigate its SSS caused by inhomogeneous temperature fields and internal steam flow pressure, with operating conditions taken into account.

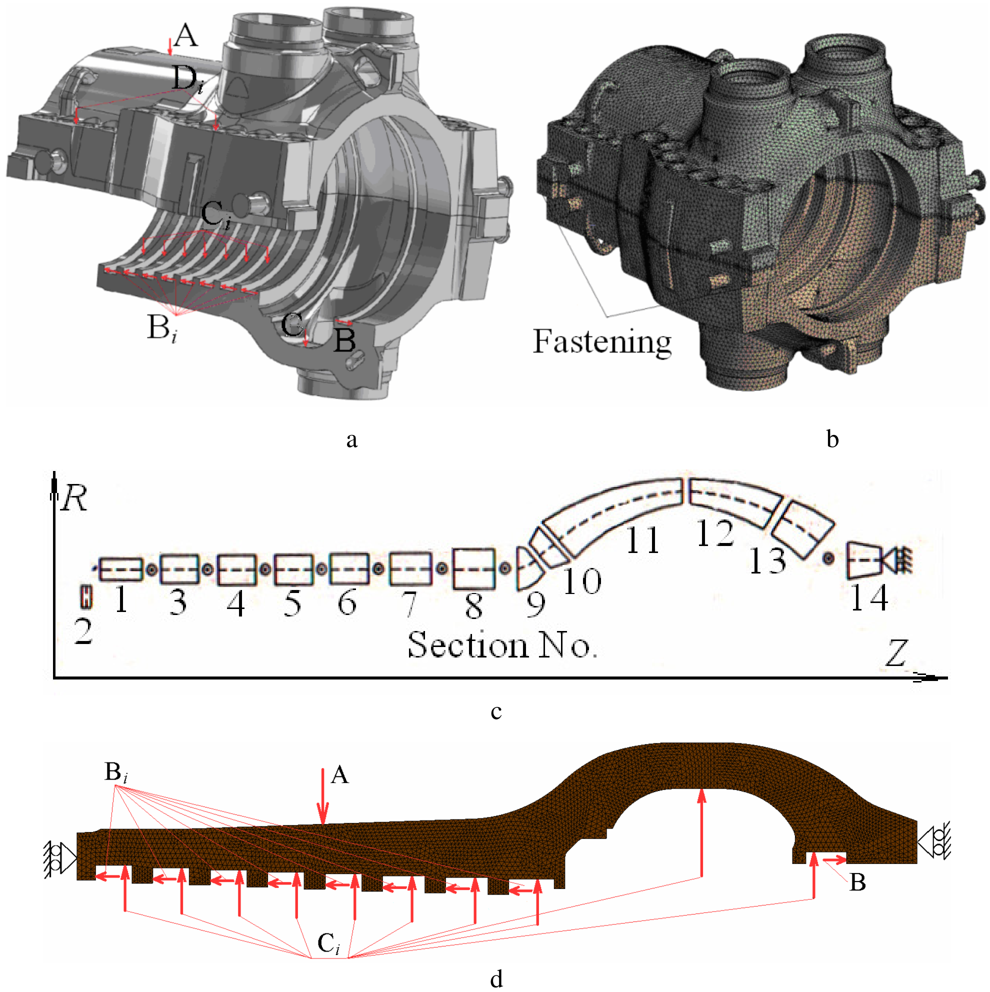

Fig. 1. Computational models of the internal HP casing for the K-325-23.5 turbine:
a – computational model of the casing in accordance with method 1; b – FE model of the casing in the three-dimensional setting; c – computational model (according to method 2); d – computational model (according to method 3)

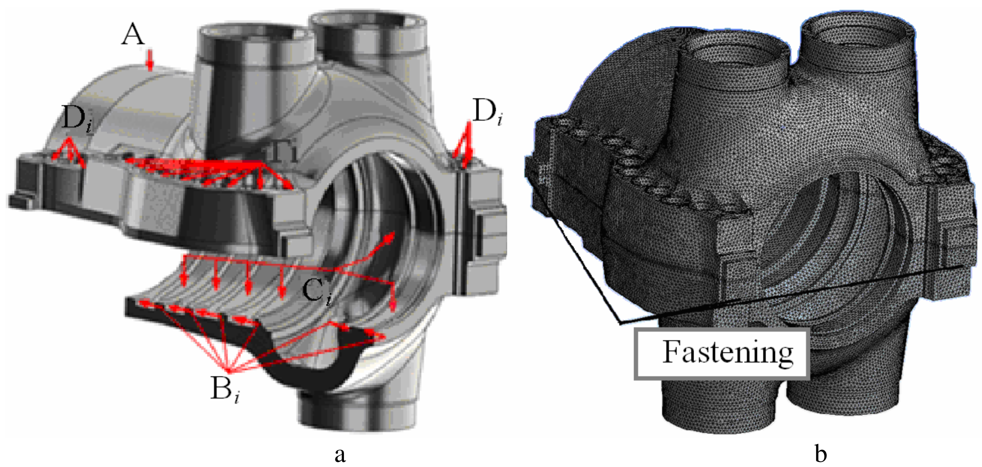

Fig. 2. Computational model of the internal HP casing for the the K-540-23.5 turbine:
a – loading scheme; b – FE model of the casing in the three-dimensional setting

A consistent consideration of these factors in determining and analyzing the SSS of the internal HP casing will make it possible to determine the degree of their influence on the real SSS picture, which will further allow us to evaluate the compliance of the results at each stage of solving the problems set by comparing them with the data of experiments and operation.

At this stage, the SSS problem of the internal HP casing is solved in an elastic setting, without taking into account the influence of temperature stresses and deformations as well as with taking into account:

– the distributed load on the bores for installing diaphragms in the casing (in the loading diagram – loads of group "B", Fig. 1, a, d, Fig. 2, a);

– different longitudinal pressure on the walls of the casing (determined from the loading scheme as the difference between the pressure on the external casing wall "A", and pressures on the internal casing wall – load of group "B" group, Fig. 1, a, d, Fig. 2, a);

– the degree of tightening flanged joint fasteners made of EP-182 (20Kh1M1F1TR) steel and modeled in accordance with [3] (in the loading diagram – loads of group "G", Fig. 1, a, Fig. 2, a);

– contact interaction in the flanged joint in the joint area.

– influence of weight loads.

The boundary conditions simulating the fastening of the casing in calculated three-dimensional models are: the rigid fastening in the area where the lower casing half rests on claws and the restricting movement along the joint face in the area where the casing claws rest against the external casing grooves (Fig. 1, 2). In the two-dimensional computational models, the casing is fixed at the ends with the prohibition of axial displacements.

Figs. 1, 2 show the calculated diagrams of the casings, made of steel grade 15Kh1M1FL, for determining SSS:

– FE models for calculating SSS in a spatial three-dimensional setting of the internal HP casings for the K-325-23.5 and K-540-23.5 turbines with the use of the FEM (Fig. 1, b, Fig. 2, b) – hereinafter referred to as method 1;

– a shell model for studying SSS by solving boundary-value static problems according to the theory of thin-walled shells of revolution with a branched meridian under axisymmetric load (Fig. 1, c) – hereinafter referred to as method 2 (used by JSC "Turboatom");

– an FE model designed for calculating SSS by solving the axisymmetric boundary value problems of the theory of elasticity and plasticity using the FEM (Fig. 1, d) – hereinafter referred to as method 3.

The physico-mechanical properties of materials (Young's modulus E, Poisson's ratio ν, density ρ) used in the manufacture of the internal HP casing and fasteners are given in Table 1[4].

Table 1. Physico-mechanical properties of the materials of the internal HP casing and fasteners

Material	Physico-mechanical properties		
	$E \cdot 10^{-3}$, MPa	ν	ρ, kg/m^3
EP-182 (casing studes)	215	0.3	7,850
15Kh1M1FL (casing)	217	0.3	7,800

A common disadvantage of using two-dimensional computational models (Fig. 1, c, 1, d) is the lack the possibility of taking into account the pipes and flanges of the horizontal connector.

The three-dimensional models of the internal HP casings, with quaternary cutouts in their lower halves, for the K-325-23.5 and K-540-23.5 steam turbines, were developed in the Autodesk Inventor Professional software package, and are now presented in Figs. 1, a and 2, a. The upper and lower halves of the casings are connected with 22 and 24 studs, respectively.

The FE three-dimensional models of the above internal HP casings are shown in Figs. 1, b and 2, b. During the creation of the FE mesh, both hexahedral and tetrahedral elements were considered, however, due to the significant complexity of curved casing surfaces, as well as with the purpose of simplifying the dimensionality of the iterative calculation for modeling, the tetrahedral element was adopted [5]. When the two initial models were partitioned, about 192,653 and 1,780,141 tetrahedral FEs were obtained, respectively. During the creation of the FE mesh, we used the volume SSS element shown in Fig. 3, where I, J, K, L, M, N, O, P, Q, R are mesh nodes and 1 (J-I-K), 2 (I-J-L), 3 (J-K-L), 4 (K-I-L) are mesh faces. This is a three-dimensional quadratic element of the problems of mechanics of a deformable rigid body with ten nodes and three degrees of freedom in each node: displacements in the direction of the X, Y, and Z axes of the nodal coordinate system.

The FE has a quadratic representation of displacements, and is able to use an irregular mesh shape, which is important when creating computational FE models on the basis of solid models imported from various system design software.

The above-mentioned three-dimensional models also include symmetrical contact interaction of the flanges of the two halves of the internal HP casing, which allows us to more accurately determine its SSS. The FE model under consideration has several contact interaction zones. During the modeling of the casing as a whole, only the mutual contact interaction of the flanges was considered, and the contact interaction between the fasteners and flanges of the casing was not taken into account, since higher compliance of the studs, compared to that of the flange, provides a relatively stable load during the casing deformation. The modeling of the flange joint, taking into account all of the above FEM contact interactions, is difficult because it will lead to the solution of a complex high dimensional nonlinear problem requiring detailed researches.

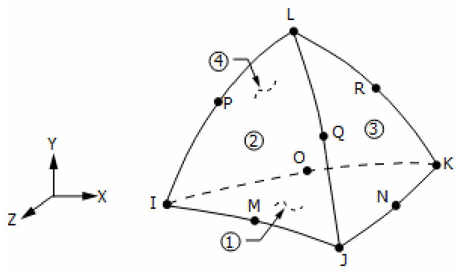

Fig. 3. Geometry of a ten-node FE

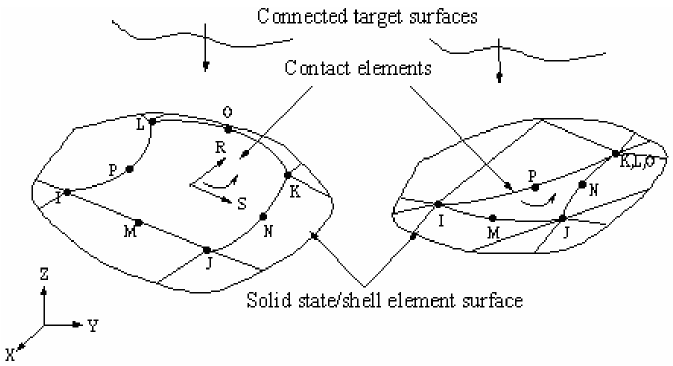

Fig. 4. Geometry of an eight-node contact FE

In the contact zones, mainly affecting 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. During the modeling of contact and slip interaction between three-dimensional "target" surfaces and the surface being deformed (and defined by this element), an eight-node contact FE was used (Fig. 4).

During the splitting of the two-dimensional FE model, 6,145 FEs were obtained.

Taking into account that the casing under consideration is in a complex stress state, its strength was estimated based on the analysis of principal stresses according to the von Mises – Genki Theory of Limit State, also known as the Maximum Distortion Energy Theory, or the Fourth Strength Theory [6]. This theory is based on the premise that the quantity of the potential distortion energy, accumulated by the moment when there occurs a dangerous state (creep of material), is the same both for a complex stress state, and simple tension. The above-mentioned strength theory is also well confirmed by experiments with plastic materials with the same tensile and compressive yield strength [7].

The three component values of stresses σ_0 at a volumetric stress state are the roots of the cubic equation determined by the components of the stress vector:

$$\begin{vmatrix} \sigma_x - \sigma_0 & \frac{1}{2}\sigma_{xy} & \frac{1}{2}\sigma_{xz} \\ \frac{1}{2}\sigma_{xy} & \sigma_y - \sigma_0 & \frac{1}{2}\sigma_{yz} \\ \frac{1}{2}\sigma_{xz} & \frac{1}{2}\sigma_{yz} & \sigma_z - \sigma_0 \end{vmatrix} = 0.$$

The principal stresses are denoted by σ_1, σ_2, σ_3. These stresses are ordered so that σ_1 is the largest positive stress, and σ_3 is the largest negative one.

In the calculation of the principal stresses σ_1, σ_2, and σ_3, the equivalent/von Mises stresses are expressed as follows:

$$\sigma_{eq} = \sqrt{\left\{\frac{\left[(\sigma_1-\sigma_2)^2+(\sigma_2-\sigma_3)^2+(\sigma_1-\sigma_3)^2\right]}{2}\right\}}.$$

These equivalent stresses are associated with equivalent strains by the following relation:

$$\sigma_{eq} = 2\varepsilon_{eq}G,$$

where $G = E/(2(1+\nu))$ is the shear modulus; E is Young's modulus; ν is Poisson's ratio.

Analysis of Calculation Results

From the analysis of the results of calculating the SSS of the internal HP casing of the K-325-23.5 turbine according to calculation methods 1–3, it follows that maximum stress values can be reached in areas where the toroidal part of the casing mates with steam supply pipes. The equivalent stresses in the cylindrical part of the casing are small.

Fig. 5 shows the equivalent stresses obtained as a result of calculation by methods based on the FEM (in two-dimensional and three-dimensional settings) and by a method based on the equations of the axisymmetric problem of elasticity theory in a two-dimensional setting, where 1 refers to the calculation results according to method 1; 2, according to method 2; and 3, according to method 3, the numbers of the sections being shown in Fig. 1, c.

From the results shown in Fig. 5, it follows that the stresses obtained by methods No. 1, 2 (or No. 3), practically coincide, and there is a pronounced difference in the nature of the distribution of the equivalent stresses in the region of transition of the cylindrical part of the casing to the toroidal one (section Nos. 9 to 14 in Fig. 5). This is probably due to the influence of such geometric stress concentrators as steam supply pipes and horizontal connector flanges, whose influence is not taken into account in simplified two-dimensional models.

In two-dimensional models, the internal HP casing was fixed at the ends with the prohibition of axial displacements, which caused, as follows from Fig. 5, some increase in stress in these zones.

As a result of the calculations, stresses were obtained in the walls of the internal HP casing for the K-325-23.5 turbine (Fig. 5, 6).

The problem of determining the SSS of the internal HP casing for the K-500-240-2 turbine was solved on the basis of a three-dimensional model, which is the upper and lower casing halves assembled together. Figs. 7 and 8 show the values of the equivalent stresses on the symmetrical half of the casing [8], taking into account the weight load, different longitudinal pressure on the walls of the casing, and the distributed load on the bores for installing diaphragms in the casing.

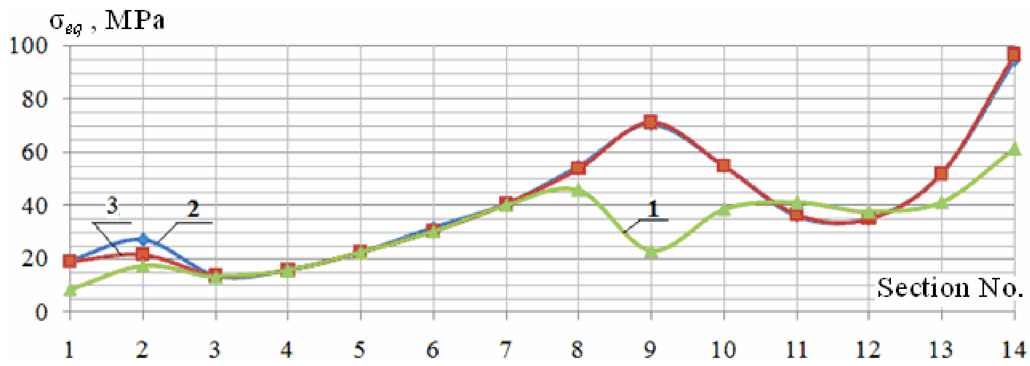

Fig. 5. Distribution of the equivalent stresses in the meridional section of the internal HP casing for the K-325-23.5 turbine

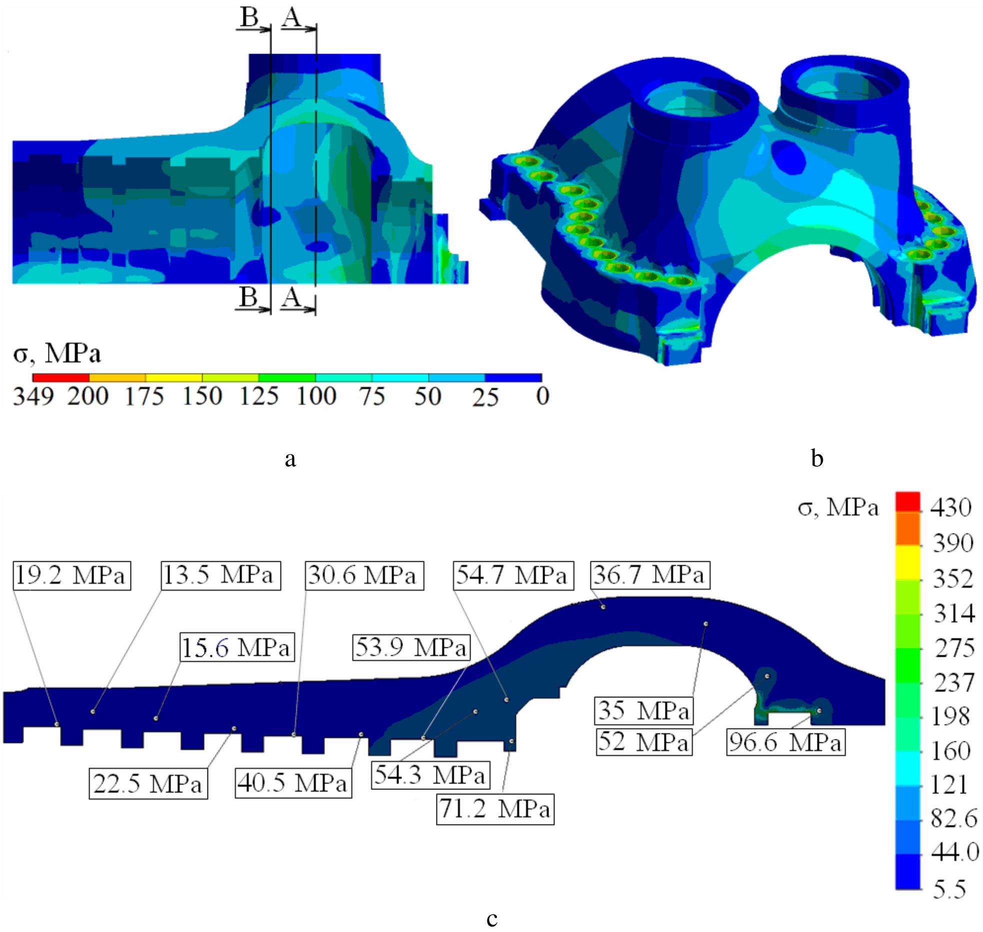

Fig. 6. SSS of the internal HP casing for K-325-23.5 turbine:
a – distribution of the equivalent stresses in the meridional section of the casing (method 1); b – distribution of strains along the Y axis (lower part); c – distribution of the equivalent stresses in the meridional section of the casing (method 3)

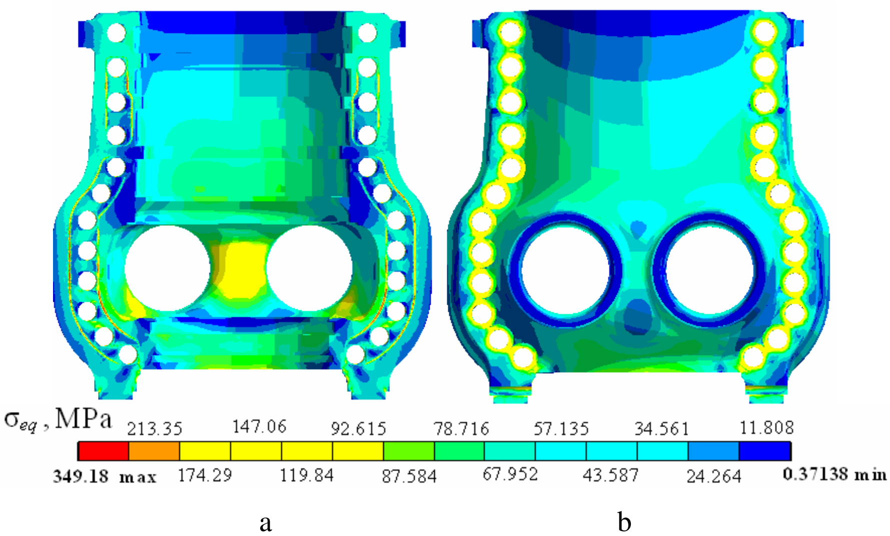

Fig. 7. Distribution of the equivalent stresses on the internal HP casing:
a – external side view; b – internal side view

As follows from Fig. 7, the maximum local stresses are observed on the shallow groove, and are about 349 MPa, which is associated with the deformation of the material from high contact pressure on the seal surface. In the upper casing part, namely, in the area of the bridge between the steam supply pipes, the average stresses through the wall thickness are about 75 MPa. In the flange area, a surge of stresses is observed only in the area of the supporting surface near the nut, and is about 120 MPa, the average stresses in the area of the casing flanges being insignificant (less than 32 MPa), which quite meets regulatory requirements [9].

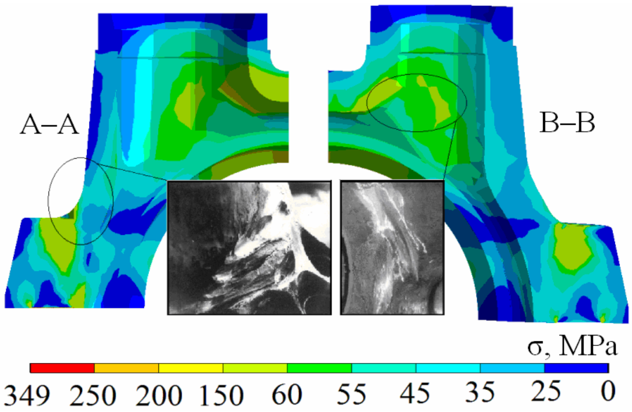

Fig. 8. Distribution of the equivalent stresses in sections A-A (left) and B-B (right) with the indication of the places with crack initiation during turbine operation

Obviously, in the characteristic cross-sections (Fig. 7, 8) where, according to the statistics of the defects detected, cracks initiated during turbine operation for a long period of time, there is an increase in stresses both on the external surface in the area where the toroidal part of the casing mates with the horizontal connector flange (section A-A) and on the internal surface in the area where the steam inlet mates with the cylindrical casing part (B-B).

In general, the stresses on cross-sections are small (about 55 MPa), and are within established norms [9], which, apparently, is associated with the solution to the problem in the setting proposed, without taking into account the influence of temperature fields on the SSS of the internal HP casing [10, 11, 12].

Conclusions

For the first time, an estimate is made of the SSS of the internal HP casings for 300 and 500 MW steam turbines with the elastic deformation of the casings in a three-dimensional setting, which is the first step in solving the problem with taking into account a number of factors that occur during operation. As a result, it has been established that:

– the SSS of the internal HP casings is three-dimensional, and a complex deformation pattern is observed;

– in general, the level of stresses in the walls of the casing is small, but there are zones of increased stresses both on the external surface in the area where the toroidal part of the casing mates with the horizontal connector flange and on the internal surface in the area where the steam inlet mates with the cylindrical part of the casing;

– maximum deformations are experienced by the toroidal part of the casings in the area of the bridge between the steam supply pipes in the radial direction;

– zones of increased design stresses correspond to the places of concentrated defects that are detected during the operation of turbines, which indirectly indicates the cause of these defects.

The solution to the problem in a three-dimensional setting made it possible to assess the degree of influence of various geometric stress concentrators, such as steam pipes and horizontal connector flanges, and note that there is a pronounced difference in the nature of the distribution of the equivalent stresses in the region of transition of the cylindrical part of the casing to the toroidal one.

Comparison of the results obtained by the FEM for the three-dimensional model with the data for two-dimensional models indicates that the results of calculating the SSS at some distance from the area where the main casing part intersects the steam supply pipes and flanges of the horizontal connector are consistent with each other, in other areas there is a significant difference in stress levels.

The results obtained indicate the feasibility of solving the problem in a three-dimensional setting, taking into account a number of operational factors: temperature fields, stud compliance, thermo-contact interaction of elements, effect of plasticity, creep, etc.

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Пружно-напружений стан елементів внутрішнього корпуса циліндра високого тиску парової турбіни

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Оцінюється пружно-напружений стан внутрішніх корпусів циліндрів високого тиску (ЦВТ) парових турбін потужністю 300 і 500 МВт з використанням тривимірної розрахункової моделі конструкції. Внутрішні литі корпуси ЦВТ, що мають складну просторову форму і працюють в умовах складного силового і теплового навантаження, є одними з найбільш відповідальних і дорогих елементів парових турбін, що лімітують їх ресурс. Спрощені розрахункові моделі, що застосовувалися в інженерній практиці, не дозволяли оцінити ряд факторів, що *визначають особливості напруженого стану. Для уточнення розподілу напружень по конструкції внутрішніх корпусів розв'язується задача напружено-деформованого стану (НДС) в тривимірній постановці з урахуванням умов експлуатації і контактної взаємодії фланців. Щоб визначити ступінь впливу окремих факторів на НДС, їх урахування проводиться послідовно. На даному етапі задача про НДС внутрішнього корпусу розв'язується в пружній постановці, без урахування впливу температурних напружень і деформацій. Розв'язок контактної задачі у фланцевих з'єднаннях внутрішніх корпусів базується на застосуванні моделі контактного шару. Зони передбачуваної контактної взаємодії зображаються контактними елементами, механічна взаємодія поверхонь контакту визначається величиною їх взаємного проникнення. Задача визначення НДС внутрішніх корпусів ЦВТ турбін К-325-23.5 і К-540-23.5 у тривимірній постановці розв'язується за використанням методу скінченних елементів, загальне число елементів – 19553 і 1780141 відповідно. В створених скінченноелементних моделях враховано контактну взаємодію фланців двох половин корпуса в області горизонтального роз'єму. У зонах контакту здійснюється згущення сітки. Наводяться результати оцінки напруженого стану внутрішніх корпусів ЦВТ парових турбін потужністю 300 і 500 МВт при пружному деформуванні з урахуванням впливу навантажень, що виникають в процесі монтажу і експлуатації турбін.*

Ключові слова: *турбіна, фланцеве з'єднання, горизонтальний роз'єм, внутрішній корпус, циліндр високого тиску, напружений стан, перепад тиску, граничні умови, розрахункова оцінка, площина роз'єму.*

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