Робота присвячена розробці методу збільшення довготривалої міцності литих корпусів парових турбін, що навантаженні парою з надкритичними параметрами. Предметом дослідження є експлуатаційні процеси зношуваності основного металу під дією температурних напружень. Показано, що врахування зусиль затяжки шпильок фланцевого з'єднання має вагомий вплив на пошкоджуваність корпусів. Запропоновано метод зменшення впливу даних зусиль завдяки технологічному управлінню ресурсом

Ключові слова: корпус турбіни, шпильки, затяжка, напружено-деформований стан, довготривала міцність, управління ресурсом

Работа посвящена разработке метода увеличения длительной прочности литых корпусов паровых турбин, нагруженных паром сверхкритических параметров. Предметом исследования являются эксплуатационные процессы износа основного металла под действием температурных напряжений. Показано, что учет влияния затяжки шпилек фланцевого соединения имеет существенное влияние на поврежденность корпусов. Предложен метод уменьшения влияния данных усилий благодаря технологическому управлению ресурсом

Ключевые слова: корпус турбины, шпильки, затяжка, напряженно-деформированное состояние, длительная прочность, управление ресурсом

UDC 621.165.62
DOI: 10.15587/1729-4061.2018.126042

DEVELOPMENT OF A TECHNOLOGICAL APPROACH TO THE CONTROL OF TURBINE CASINGS RESOURCE FOR SUPERCRITICAL STEAM PARAMETERS

O. Chernousenko
Doctor of Technical Sciences, Professor*
E-mail: chernousenko20a@gmail.com
D. Rindyuk
PhD, Associate Professor*
E-mail: rel_dv@ukr.net
V. Peshko
PhD, Assistant*
E-mail: vapeshko@gmail.com
V. Goryazhenko*
E-mail: vgandcohookah@gmail.com
*Department of Cogeneration Installations of Thermal and Nuclear Power Plants
National Technical University of Ukraine «Igor Sikorsky Kyiv Polytechnic Institute»
Peremohy ave., 37, Kyiv, Ukraine, 03056

1. Introduction

Thermal power plants (TPP) play an important role in the generation of electricity in the Integrated power system (IPS) of Ukraine. Maintaining a high level of effective performance is considerably complicated by the fact that most of the power equipment in Ukraine has exhausted its designed and extended park resource. Construction of new energy capacities can solve the problem, but it requires engagement of a large number of fixed assets and is accompanied by significant capital expenses. The experience gained in operation of single-type equipment at various power plants makes it possible to prolong the permissible operation term of turbine equipment beyond the park resource. Given the fact that most parts of the steam-powered units wear out slower than separate highly stressed elements, the entire unit can be renovated only by the replacement of separate components. These operations are performed during extended scheduled maintenance repairs and can completely restore the physical performance of a turbine.

Casing elements of a high-pressure cylinder (HPC) are among the most expensive high-temperature elements of steam turbines on supercritical steam parameters. Ensuring maximum operation terms of such equipment is a strategically important task in today's economic situation in Ukraine. However, this task is complicated by the fact that there are certain technological, structural and mode factors that limit the permissible service life of steam power equipment.

One of these factors is the level of pins' tightening in a flange of a horizontal connector. All pins in the casings of steam turbines are tightened with approximately the same force that corresponds to tightening of the most loaded group of pins. However, their operation conditions may differ considerably due to both a change in pressure of steam medium and a change of the shell diameter for each group of pins.

Thus, the problem of the influence of tightening of pins on the resource indicators of steam turbine casings is relevant and requires detailed studying.

2. Literature review and problem statement

An increase in the share of electricity generation at nuclear power plants leads to the gradual TPP pushing to semi-peak and peak parts of the daily load schedule. This factor requires a more detailed analysis of resource indicators of power equipment for prevention of premature wear [1]. Identification of major aspects of this problem and a decrease in the influence of factors of accelerated completion of service life are at the heart of the problem of resource control of power equipment.

Resource control is a complex of measures, aimed at ensuring a high level of resource indicators of power equipment through the influence on certain aspects of its operation. Thus, changing the mode of start, stop or shut down cooling, it is possible to influence the level of amplitudes of stress intensity, thereby reducing the damage by the mechanism of low-cycle fatigue [2]. For equipment with high operation time, it is possible to decrease the temperature of heated steam by 10–20 °C, thereby improving long-term strength of the basic metal [3]. It was determined experimentally that through an active influence on the surface layer of metal, it is possible to significantly change mechanical characteristics of material, including resistance to short-term, low-cycle or static stress. Periodic removal of the damaged surface layer is one of the methods of resource control [4]. The use of new schematic solutions, such as preliminary warming up the rotor in the end seals area can improve the stressed state of rotating elements of steam-power plants [5]. It is possible to achieve a decrease in the general level of stress intensity of both the casings of regulating valves, and a steam distributing box of the HPC casing by changing the scheme of steam feed drainage [6]. The structural methods of resource control, aimed at a decrease in the number of geometric stress hubs are effective. For example, a change in the design of end seals of the labyrinthine type for straight flow or cellular one improves stressed-strained state (SSS) of turbines' rotors in all operation modes [7].

The specified resource control methods have proven to be effective in practice for ensuring long-term operation of steam turbines. However, along with it, the problem of development of new resource control methods is relevant.

Steam density of steam turbine casings is provided with the help of high clamping force of pins in a flange joint. Depending on pressure of steam medium, the level of these forces can reach very high values [8]. As a result, there is a significant influence of clamping forces of pins on stressed-strained state of casing elements during operation in the elastic range of loads [9]. Similarly, the influence of high-temperature casing elements on stressed-strained state in the plastic statement of the problem was studied in paper [10].

Thus, a change in forces of pins' tightening can be considered as a method of technological resource control of steam turbine casings. When selecting tightening forces at the level that is sufficient to ensure steam density of casings and taking into account necessary reserve coefficients, it is possible to achieve the improvement of long-term strength.

3. The aim and objectives of the study

The aim of present research is to develop a technological approach to resource control of casing elements of steam turbines with hot steam pressure of 24 MPa with the help of a change of pins' tightening force in the flange joint.

To accomplish the aim, the following tasks have been set:

– to perform calculation assessment of stressed-strained state of the casing of a high pressure cylinder (HPC) of the turbine K-800-240-2, taking into consideration temperature stresses and forces of steam medium pressure;

– to assess the impact of taking into consideration real tightening forces on SSS of casing elements;

– to perform estimated assessment of SSS of the casing taking into account forces of pins' tightening at a certain technological level according to the calculation technique;

– to compare resource indicators of the casing of HPC of the turbine K-800-240-2 of block 7 of the Slaviansk thermal power plant (Ukraine) for the specified three calculation options and to offer recommendations.

4. Materials and methods of research

The methods of research include numeric studies of thermal state (TS) and stressed-strained state of the casing elements of HPC of the turbine K-800-240-2 with the use of modern methods of mathematical modeling. These methods are based on the main provisions of the theory of non-stationary thermal conductivity and mechanics of solids. The numerical methods for solution of the problems of mathematical physics and calculation methods of engineering analysis, based on the finite element method, were used.

The geometric model of the calculation object is performed in three-dimensional statement due to the absence of an axis-symmetric geometry, the presence of flanges of a horizontal connector, nozzles of steam feed and removal and other structural complications (Fig. 1).

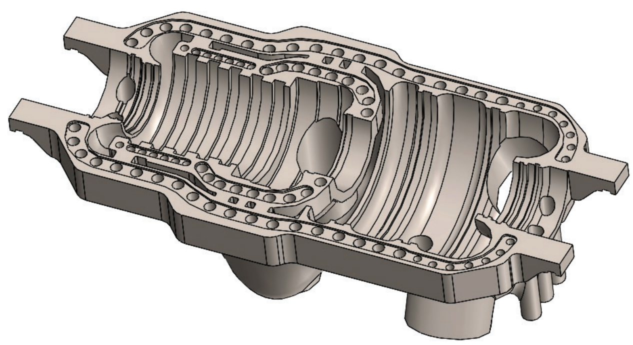


Fig. 1. Geometric model of the lower part of double-walled casing of HPC of turbine K-800-240-2

A high pressure cylinder of the turbine K-800-240-2 is cast and double-walled. After the first six stages of the internal casing, there is a reversal of steam flow to the following six stages of the external casing. The internal casing is made of steel 15C11MVB and consists of two parts, connected by flanges. The external casing of the HPC is made of steel 15C1M1V. The internal casing is put in the external casing with special lugs and centered by guiding keys.

The damage to the external casing of the HPC was taking into consideration in the process of creation of the geometric model through organization of samples of metal in the places of emerging of cracking. It was performed according to the requirements of the regulation document

SOU-N MEV 40.1-21677681-52:2011 «Determining the estimated resource and evaluation of survivability of rotors, and turbine casing parts». Dimensions and the depth of such samples are accepted according to visual control data of metal of cast casing parts. In the estimated model of HPC casing, a longitudinal sample of dimension of 120×85×25 mm and 100×70×20 mm was simulated in the external casing of HPC.

The mathematical model of evaluation of residual resource of power equipment is shown in [11].

5. Results of studying residual resource of casings at various forces of pins' tightening

5. 1. Calculation study of TP and SSS of HPC casing without taking into consideration forces of pins' tightening

Boundary conditions of I–IV kind on different heat exchange surfaces were calculated in order to conduct the numerical study of thermal condition of casing elements. Thus, boundary conditions of kind I were assigned at known temperature in specific nodes of the casing at the initial moments of turbo-plant start. The absence of the heat flow for isolated external surfaces of the external casing was assigned for boundary conditions of kind II. Regularities of heat exchange between steam and the casing elements of the flow part and ends seals were accepted for those of kind III. Boundary conditions of kind IV corresponded to the ideal contact between the bores in the casing and diaphragm races on the touch at the same temperatures and heat flows.

Numerical study of temperature condition was performed for all typical modes of operation, including starts from the hot, non-cooled and cold states, as well as the nominal operating mode. An example of a TS in the stationary operation mode is shown in Fig. 2, *a*. The resulting distribution of temperatures is the input data for studying SSS of the casing. Pressure of steam medium, as well as reaction of the supports, was additionally taken into account (Fig. 2, *b*).

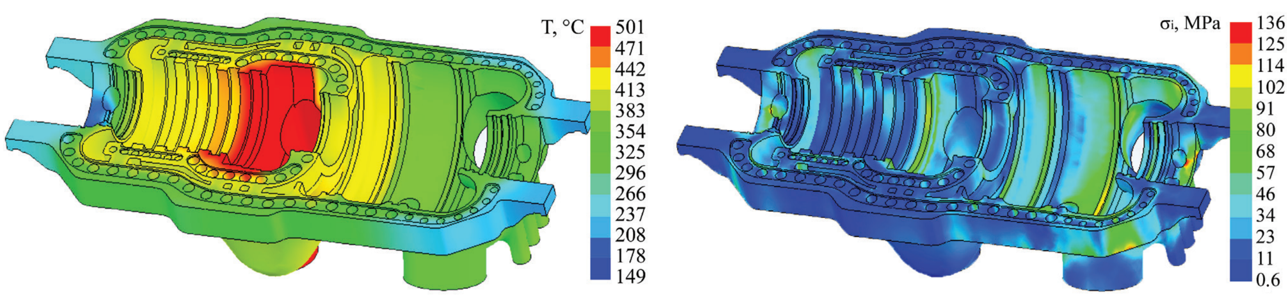
Analyzing stressed-strained state, it should be noted that most loaded areas are zones of end seals (σ_i=110–136 MPa), as well as the area of bores for mounting diaphragm of nozzle blades (σ_i=80–115 MPa).

Similar data were obtained for other operation modes. Fig. 3 shows the graph of changing stress intensity σ_i during the start from the non-cooled state. It should be noted that most loaded moment of the start is the beginning of turbo-aggregate loading up to the power of 800 MW after keeping at the power of 360 MW (τ=26,100 s). However, the level of stresses at this time does not exceed 300 MPa.

In general, due to high duration of starting modes and uniform heating of the flow part, amplitudes of stresses intensity reach not very high values. That is why we can conclude about low damage of metal by the mechanism of low-cycle fatigue.

5. 2. SSS of HPC casing taking into account clamping force of flange joint pins

As it was already noted above, steam density of casing elements in the horizontal plane is provided by high clamping force of flange joint pins. For steam turbines of JSC «Leningrad metal plant» (JSC «LMP», Russia) with initial steam pressure of 23.6 MPa, we used pins, made of the alloyed steel 25C2M1V. Current force of tightening each group of pins depends on their diameter and is about Q_z=3–4 MN. SSS of HPC casing of a turbine K-800-240-2, taking into account these forces, is shown in Fig. 4.



a *b*

Fig. 2. Results of calculation of nominal operation mode without taking into account forces of pins' tightening: *a* — thermal state; *b* — stressed-strained state

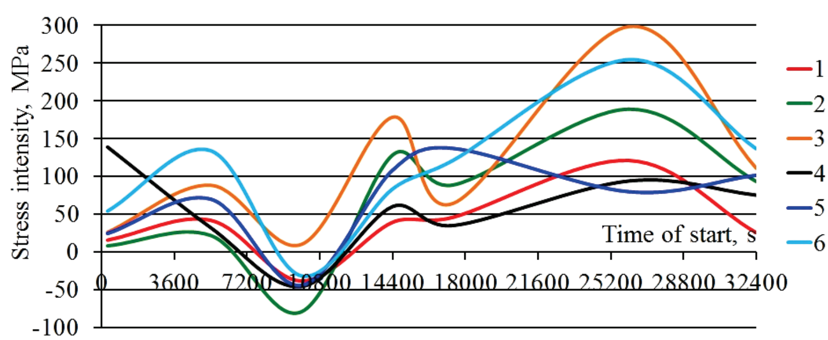


Fig. 3. Graph of change in stresses intensity σ_i in specific areas at start from non-cooled state: 1 — steam feed zone, 2 — bore for mounting nozzle blades of grade 2, 3 — second chamber of front end seals, 4 — bore of the first diaphragm of nozzle blades (grades 7–9), 5 — bore of second diaphragm of nozzle blades (grades 10–12), 6 — third chamber of rear end seals

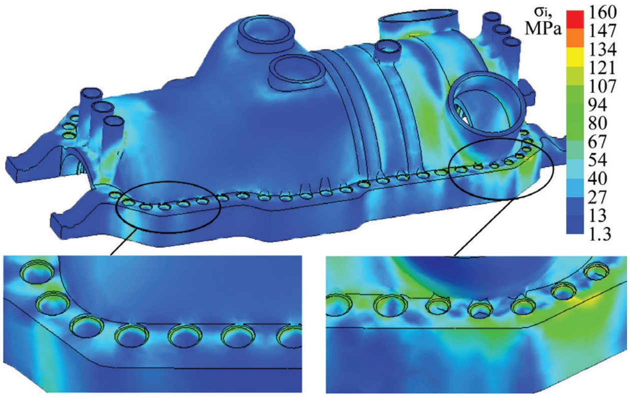


Fig. 4. SSS of HPC casing (external surface) taking into account forces of pins' tightening in nominal operation mode

Taking into consideration forces of pins' tightening caused an increase in maximum stresses intensity from value σ_i=136.4 MPa to σ_i=160.6 MPa (by 17.7 %), in this case, rear end seals remain the area of maximum stresses in the stationary mode. An insignificant increase (2–4 %) in local stresses is observed for the rest of the areas of the flow part. For the external surface of the casing, taking into account forces of pins' tightening caused an increase in values of stresses intensity in the areas of adjoining of exhaust nozzles by 14–16 %. Intensity increased by 70–80 % directly in the flange joint due to appearance of contact stresses of metal of flanges with nuts of pins.

5. 3. Numerical study of SSS of casing elements in calculation forces of pins' tightening

An increase in maximum intensity of stresses, caused by forces of pins' tightening, will significantly accelerate the rate of accumulation of static damageability and destruction of basic metal of casing elements due to deterioration of long-term strength. That is why the possibility of decreasing the values of stresses intensity due to a decrease in influence of forces of pins' tightening at provision of steam density is able to improve resource indicators of the casing and is the problem of residual resource control.

Minimum necessary force of tightening of a pins' group for ensuring steam density is calculated from formula [12]:

$$Q_{\min} = 0{,}5 \cdot p \cdot d \cdot l(1+3c)/(2a-b), \quad (1)$$

where p is the steam pressure in the area of the studied pins' group; d is the internal diameter of the casing in the area of the studied pins' group; l is the average distance between neighboring pins; a, b, c are the geometric parameters that characterize the position of a pin in a flange.

Taking into consideration forces of pins' tightening at the level that is minimally necessary to ensure steam density is insufficient because at the initial stages of operation (operation period) pins are exposed to the most intense relaxation. The level of clamping force after 10^5 s of work is called current and already corresponds to the normal operation mode of pins. Subsequently, deformation of pins will continue, so will stresses relaxation, though not so intensively. Usually, stresses relaxation during the entire operation time of a pin does not exceed 30 %.

Given this fact and accepting reserve coefficient for the details of this type n=1.2, current force of tightening a group of pins is accepted:

$$Q_z = 1{,}5 \cdot Q_{\min}. \quad (2)$$

Calculated values of tightening forces for groups of pins of HPC casing of turbine K-800-240-2 are shown in Fig. 5.

The stressed-strained state of casing elements with regard to calculation current tightening forces of group of pins (Fig. 5) during working in the stationary operation mode is presented in Fig. 6.

Maximum intensity of stresses decreased by 9.3 % (σ_i= =145.7 MPa), which will have a positive impact on damageability accumulation rate of metal of HPC casing. There is also a decrease in total level of flange joint stresses by 11–41 %.

A decrease in the forces that occur in the flange joint will also have an impact on SSS of casing elements of HPC at starts from various thermal states, therefore, on the rates of cyclic damageability accumulation.

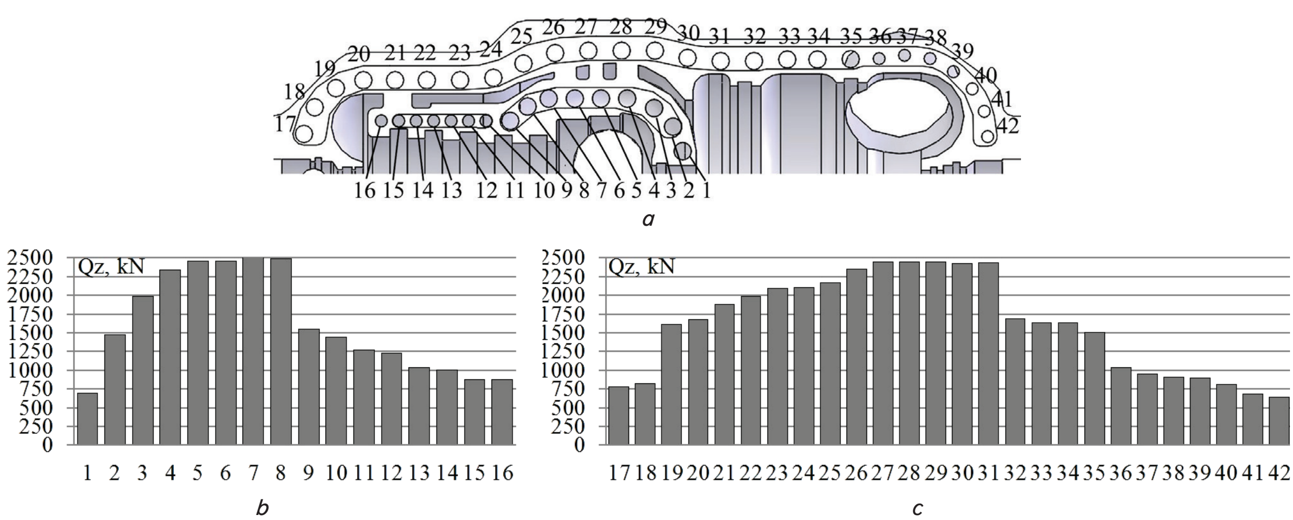


Fig. 5. Calculation of current clamping forces of groups of pins: *a* – numbers of groups of pins; *b* – current forces for internal casing; *c* – for external casing

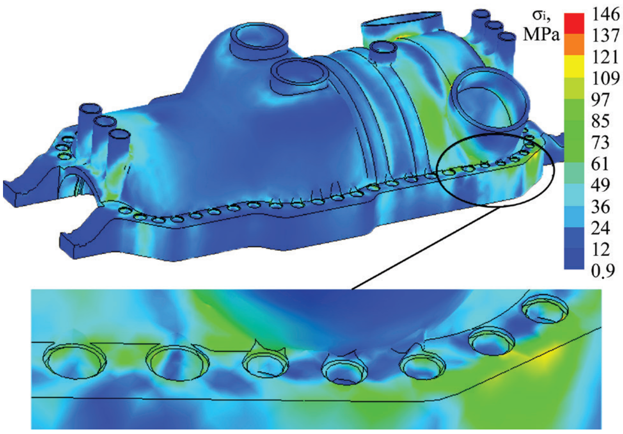


Fig. 6. SSS of casing elements taking into account forces of pins' tightening under nominal operation mode

5. 4. Comparative evaluation of resource indicators of HPC casing at various tightening forces of groups of pins

Assessment of the influence of a change in forces of tightening of flange joint pins on resource indicators of casing elements was conducted for HPC of the turbine K-800-240-2 of unit 7 of Slaviansk TPP, according to the technique, which is described in detail in paper [11]. In accordance with power plant data, operation time of power unit is T=291,811 h at the number of starts from different thermal states n=500. The results of comparative evaluation are given in Table 1.

Table 1

Calculation estimation of damageability and residual resource of casing of HPC of power unit 7 of Slaviansk TPP at various forces of pins tightening

No	Name	Designation	Disregarding	Actual forces	Calculation
1	Stress intensity in nominal mode	$\sigma_{i\,max}$, MPa	136.4	160.6	145.7
2	Static damageability	$[D_{st}]$	0.663	0.7887	0.7116
3	Permissible number of cycles at various kinds of starts	$[N_{pl}]\ n_{ncs}^{HPC}=303$	5,600	5,430	5,500
		$[N_{pl}]\ n_{cs}^{HPC}=46$	3,640	3,570	3,610
		$[N_{pl}]\ n_{hs}^{HPC}=151$	4,420	4,340	4,400
4	Cyclic damageability	$[D_c]$	0.101	0.1035	0.1022
5	Total damageability	$[D_{tot}]$	0.764	0.8922	0.8139
6	Current operation time	T, h	291,811		
7	Individual residual resource	T_{res}, h	90,083	35,274	66,730

A decrease in forces of tightening of pins' groups can significantly decrease the level of static damageability accumulation. Maintenance of tightening forces at the level of Q_z=3–4 MN sets static damageability $[D_{st}]$=78.9 %, at calculation forces, static damageability is $[D_{st}]$=71.2 % (66.3 % without taking forces into account). In this case, as it was noted earlier, the impact on the rate of accumulation of cyclic damageability is quite insignificant 10.4 % vs. 10.2 % at calculation values, which is primarily associated with the operation of the unit in the basic mode. Residual resource of casing elements of HPC of the turbine K-800-240-2 No. 7 of Slaviansk TPP is 35,274 h at actual forces of pins tightening and 66,730 h – at calculation values.

6. Discussion of results of the study of resource indicators of the casing at various forces of pins' tightening

Calculation estimation of SSS of the casing elements showed a significant influence of clamping force of pins' tightening on resource indicators of the turbine on supercritical steam parameters. Thus, when taking into account these forces, the level of maximum stresses increased by 17 % and individual resource of the casing decreased by 14.3 %. Thus, forces of pins' tightening must be taken into consideration by all means in subsequent research of resource indicators of casings of steam turbines for supercritical steam parameters.

When taking into account current forces of pins' tightening at the level that exceed by one and a half times the minimum required level, individual resource of the casing of HPC of unit 7 of Slaviansk TPP increases by 10 % (by 31,456 hours). The maximum intensity of stresses in the casing decreases by 7–9 % for all operation modes.

The basic metal of casings of steam turbines is sensitive to an increase in the level of stress intensity in stationary operation modes. The fact that certain groups of pins are tightened with a force that is by many times greater than the minimum required force for steam density allows considering a change in forces of pins' tightening as a technological resource control method. Performed calculations showed that when taking into account reserve coefficients and relaxation phenomenon, the necessary tightening force for 30 groups of pins is by 1.5–4 times smaller than that, required for tightening the pins at TPP.

However, there is a need for more detailed study of the impact of relaxation phenomenon, taking into consideration its changes over operation time, as in literature, the problems of this type are classically considered in the quasi-stationary statement. It would be also worthwhile conducting a complex of physical experiments, aimed at refining accepted strength reserve coefficients. Thus, these issues must be examined in detail in the future.

The subsequent papers can be devoted to a more detailed exploration of thermal stressed state, taking into consideration contact interaction of casing details and the history of pins' relaxation development. It is also of great interest to study a dynamic change of tightening forces of pins from the beginning of the turbo-plant operation to gaining its nominal load with subsequent attaining the stationary mode of operation.

In general, selection of tightening effort of pins is the optimization problem of steam turbines resource control, as it is necessary to ensure the balance between the long operation term and sufficient steam density, and therefore reliability of the equipment operation.

7. Conclusions

1. Calculation estimation of TS and SSS of casing elements of HPC of the turbine K-800-240-2 for all basic operation modes was performed. Taking into account the main temperature forces and steam medium pressure sets stress intensity in the nominal operation mode $\sigma_i = 136.4$ MPa.

2. Taking into consideration actual forces of pins' tightening (Q_z=3–4 MN) showed a significant influence on the stressed-strained state of the casing elements. The maximum stress intensity increased by 17.7 %, it increased by 2–4 % for areas of the flowing part, for the external surface – by 14–16 %, for flanges of the horizontal connector – by 70–80 %.

3. It was proposed to decrease forces of pins' tightening up to a certain calculation level in order to improve long-term strength of basic metal. When taking into account the calculation tightening forces (Q_z=0.65–2.5 MN), maximum stress intensity decreased by 9.3 %, while the stress level in the flange joint decreased by 11–41 %.

4. Conducted numerical studies prove efficiency of application of calculation forces of pins' tightening as a technological method of resource control of the casing elements of the turbine on supercritical parameters (individual resource increased by 10 %). However, along with substantiation of expediency of a decrease in tightening forces, it is necessary to organize regular control of steam density of flanges, as well as the level of relaxation of pins' stress during scheduled maintenance repairs.

References

1. Chernousenko O. Y., Peshko V. A. Influence of the operation of the power units of thermal power plants in the maneuvering mode on the aging rate of power equipment // NTU «KhPI» Bulletin: Power and heat engineering processes and equipment. 2016. Issue 10 (1182). P. 6–16. doi: 10.20998/2078-774x.2016.10.01
2. Nazolin A. L., Polyakov V. I. Nadezhnost' elektroenergetiki. Povyshenie zhivuchesti i prodlenie sroka sluzhby turbogeneratorov metodami rezhimnoy optimizacii // Elektricheskie stancii. 2013. Issue 10. P. 8–12.
3. Georgievskaya E. V., Gavrilov S. N. Osobennosti prodleniya sroka sluzhby parovyh turbin pri narabotkah, znachitel'no prevyshayushchih parkoviy resurs // Visnyk NTU «KhPI». Seriya: Enerhetychni ta teplotekhnichni protsesy y ustatkuvannia. 2013. Issue 12 (986). P. 107–113.
4. Investigation on experimental load spectrum for high and low cycle combined fatigue test / Wang R., Wei J., Hu D., Shen X., Fan J. // Propulsion and Power Research. 2013. Vol. 2, Issue 3. P. 235–242. doi: 10.1016/j.jppr.2013.11.004
5. Remaining life assessment of a high pressure turbine casing in creep and low cycle service regime / Bakic G., Sijacki-Zeravcic V., Djukic M., Rajicic B., Tasic M. // Thermal Science. 2014. Vol. 18. P. 127–138. doi: 10.2298/tsci121219179b
6. The optimization of the start-up scheduling for a 320 MW steam turbine / Ji D.-M., Sun J.-Q., Dui Y., Ren J.-X. // Energy. 2017. Vol. 125. P. 345–355. doi: 10.1016/j.energy.2017.02.139
7. Kostyuk A. G. Selection of labyrinth seals in steam turbines // Thermal Engineering. 2014. Vol. 62, Issue 1. P. 14–18. doi: 10.1134/s0040601515010061
8. Naik D., Kumar K. Contact Pressure Analysis of Steam Turbine Casing // International Research Journal of Engineering and Technology. 2017. Vol. 04, Issue 06. P. 909–913.
9. Mechanical Behavior Study of Steam Turbine Casing Bolts Under In-Service Conditions / Zhao N., Wang W., Hong H., Adjei R. A., Liu Y. // Volume 7A: Structures and Dynamics. 2016. doi: 10.1115/gt2016-56723
10. Grishin N. N., Gubskiy A. N., Pal'kov S. A. Modelirovanie vliyaniya yavleniy polzuchesti na napryazhenno-deformirovannoe sostoyanie vysokonapryazhennyh elementov parovyh turbin // Visnyk NTU «KhPI». Seriya: Enerhetychni ta teplotekhnichni protsesy y ustatkuvannia. 2014. Issue 12 (1055). P. 98–103.
11. Comprehensive rotor service life study for high & intermediate pressure cylinders of high power steam turbines / Peshko V., Chernousenko O., Nikulenkova T., Nikulenkov A. // Propulsion and Power Research. 2016. Vol. 5, Issue 4. P. 302–309. doi: 10.1016/j.jppr.2016.11.008
12. Parovye i gazovye turbiny: uchebnik / Trubilov M. A., Arsen'ev G. V., Frolov V. V. et. al.; A. G. Kostyuk, V. V. Frolov (Eds.). Moscow: Energoatomizdat, 1985. 352 p.