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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.)

Analysis of the calculation methods of the thermal strength and resource of steam turbine elements

In A. Podgorny Institute of Mechanical Engineering Problems of the National Academy of Sciences of Ukraine methodical ware was developed for conducting calculated estimates of the resource of power machine components, as well as substantiating the possibility of its extension. The causes of damage to power machine components are, mainly, their low-cycle fatigue resulting from a greater number of thermal changes and creep of their high-temperature elements. A technique for a combined solution to the three-dimensional non-stationary problems of thermal conductivity and thermo-mechanics on a single finite element grid in either the Cartesian or cylindrical coordinate system was developed in [1, 2]. A technique for conducting a calculated estimate of the damage from creep and low-cycle fatigue, taking into account the history of the cyclic loading of an object, was developed in [3, 4]. A technique for conducting a calculated estimate of the survivability of cracked components was developed in [5–8].

Determination of a thermo-stressed state is performed, taking into account the dependence of material properties on temperature, deformation of plasticity and creep with material damage, non-stationary boundary conditions of heat exchange, and thermo-contact interaction of various parts [1, 9, 10]. In the thermo-contact interaction of various parts, the problems of thermal conductivity and thermo-mechanics turn out to be connected through unpredetermined contact conditions. The two problems are solved by numerical integration over time in combination with the iterative process. For its convergence, special algorithms are used [11]. Both the presence of gaps or negative allowances between the contact areas, arising from either the manufacturing error or the difference in the temperature expansion of the parts, and the contact conductivity (depending on the contact pressure, state of the contacting surfaces and thermal conductivity of the medium filling the gaps) [1, 12] are taken into account. Calculation of the stress-strain state of the blade locking joints with the disk (and other units) within the thermo-contact problem significantly refines the results, on which the accuracy and correctness of assessing both the long-term strength and resource of turbo-machine elements depend to a large extent [13].

The technique for estimating crack resistance is based on the mechanics of brittle fracture. The multi-mode nature of structural behaviour under static and cyclic loading, cycle asymmetry, change in the geometry of a crack in time, stress relaxation during creep, dependence of the material properties on temperature, presence of a working medium [14, 15], and other factors affecting the kinetics of the crack are taken into account. In the case of a complex stress state, the finite element method is applied at the crack tip and an equivalent stress intensity factor is introduced. Subsurface, or elliptical surface or one-dimensional cracks of uniform depth are considered. Structure survival time is determined until the moment of avalanche-like fracture or crack growth through the part wall. In addition to operational loads, hypothetical emergency loads (for example, rotor sudden acceleration to a certain value, pressure increase above the norm or temperature regime violation) are also taken into account.

Along with the techniques based on theoretical provisions for brittle fracture, both methodical ware and software were developed to calculate the kinetics of cracks under cyclic loading, using the parameters of material scattered damage [8, 16]. In this case, instead of the stress intensity coefficients and kinetic crack growth diagrams requiring that complex tests of the samples with cracks be performed, deformation diagrams and low-cycle fatigue curves of smooth samples are used. A further development of this technique in [17–19] required that the elasto-plastic problems for structures with cracks of different depths be solved by the finite element method, including taking into account crack edge contact. This allowed one to remove both the restrictions on crack tip plastic zone sizes and the asymmetry of cyclic loading.

Although the survivability of cracked rotors is not taken into account in assessing turbine resources [20], it is of considerable interest for determining overhaul control expiry dates and predicting hypothetical crack behaviour in the most stressed places that can be overlooked during inspections.

Inclusion of the scalar and vector parameters of the material damage corresponding to brittle and viscous fracture into solving the creep problem, allowed one to determine the time and place of the initial stage of structural fracture during the assessment of the long-term strength of high-temperature elements [3, 21].

In solving thermo-elasticity problems, reference data on the mechanical and thermo-physical properties of the material are used; for solving the problem of plasticity theory curves of sample deformation are used; for solving the problem of creep theory, creep curves right up to fracture are used; for assessing the long-term strength at low-cycle loading, low-cycle fatigue curves are used; for assessing crack growth resistance, the fracture toughness of material K_{IC}, as well as the kinetic diagrams of the material obtained by testing special cracked samples under static and cyclic loading are used, and in the case of using the parameters of scattered damages, the diagrams of elasto-plastic deformation and the material fatigue curves are used.

The developed software allowed one to solve the following important problems of thermal strength and resource of turbine units:

– to assess the resource of the high-temperature high and medium pressure rotors of the K-300-240-2 HTGZ and T-250 / 300-240 UTMZ turbines, subjected to creep and low-cycle fatigue [1, 22, 23];

– to assess the long-term strength of the high-temperature zones of steam turbine integral forged rotors [3, 24, 25];

– to analyze the thermo-stressed state of the blade locking joints of various steam and gas turbines, taking into account the thermo-contact interactions under creep conditions [11, 13];

– to calculate the curvature of steam turbine rotors due to the inhomogeneity of material creep and plasticity in the circumferential direction under axisymmetric loading [1];

– to calculate the curvature of steam turbine rotors in the case of non-axisymmetric overheating due to seizures in labyrinth seals [26];

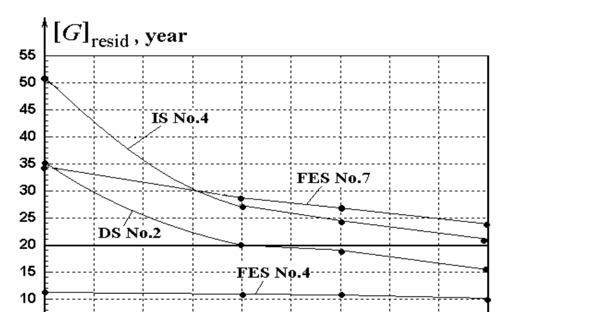
– to determine the destructive numbers of NPP rotor revolutions in the case of sudden acceleration, taking into account and without taking into account blade separation [27, 28];

– to analyze the kinetics of cracks in steam turbine rotors and high-temperature locking joints of steam and gas turbines [1, 29, 30];

– to calculate steam turbine casing deformation when the cylinder is opened after long-term operation under creep conditions [31];

– to investigate both the stressed state of the blade row and the steam turbine axial stiffness diaphragm by the multi-grid finite element method (FEM), taking into account contact phenomena in leaning and defects in the places where the guide vanes are connected with the disk rims [32, 33].

As an example of the influence of the transient load-unload regimes caused by the energy market conditions on turbine element resources, the T-250 / 300-240 turbine (Kharkiv TPP-5) high-pressure rotor residual resource was considered at different load rejection and increase rates [1]. Fourteen variants of transient regimes were analyzed. The history of the turbine operation at the time of the resource assessment was studied, boundary conditions for heat exchange, thermo-stressed state and damageability at various operating modes were determined. The most stressed and damageable areas of the rotor were identified: the grooves of the front end seal, second stage diaphragm seal, and internal seal. The residual resource for the subsequent operational period was predicted provided the average annual operating modes of the power unit under the energy market conditions are maintained. The considered variants of transient unload-load regimes differed in rate and duration. The predicted residual resource of different rotor zones in years, depending on the unload-load rate, can be determined from the curves shown in figure, where the points denote the calculated values of the residual resource $[G]_{\text{resid}}$.



Predicted residual resource of the high-pressure rotor depending on the unload-load rate:
IS – internal seal, DS – diaphragm seal, FES – front end seal

The calculated studies showed that the predicted residual resource of the turbine high-pressure rotor is limited by thermal groove No. 4 of the front end seal. The main contribution to the resource wear-out in the front end seal zone is made by start-stop regimes, especially the starts from the hot state and the short-term stops without vacuum breakdowns, whereas the contribution of the transient unload-load regimes is insignificant. The reason for the accelerated wear-out of the residual resource in the rotor front end seal, when the rotor is stopped without vacuum breakdown and started from the hot state, is the seal cooling by the seal collector vapor.

In the first stage zone and those adjacent to it (second-stage diaphragm seal, internal seal), the influence of the transient unload-load regimes is more significant.

From the results obtained (figure) it follows that, with the accepted predicted average annual operating mode, the rotor residual resource in the second-stage diaphragm seal zone with its daily unload from 300 to 140 MW and load rate of 15 MW/min is 15 years, and that with the load rate of 10 MW / min is 20 years.

With the capacity change rate of 6 MW/min regulated by the appropriate instruction, the predicted residual resource of the high-pressure rotor is 11 years (thermal groove No. 4 of the front end seal).

The high-pressure rotor residual resource can be increased to 20 years at the unload-load rate of 10 MW/min, if the number of starts from the hot state is reduced by half (from 5 to 2.5 per year) or measures are taken to reduce their effect on the damage to the front end seal (for example, the seal collector vapor temperature is increased).

Taking into account the results of the research, a normative document of the Ministry of Energy and Coal Industry of Ukraine was developed and put into effect [20], dealing with the calculated assessment of the resource of the high-temperature rotors and basic parts of TPS and TPP steam turbines. It offers updated calculation schemes, models and methods for determining thermo-stressed states, material damage, resource assessment and recommendations for specifying them. New, less conservative, reserve factors are introduced, and survivability criteria for cracked structures are revised.

A computerized system for diagnosing the thermo-stressed state and assessing resource wear-out due to low-cycle fatigue and creep (resource counter) in the hazardous areas of the T-250 / 300-240 turbine high-pressure rotors was created [34–36].

The operation of the resource counter consists in the automated assessment of the turbo unit operating modes by the archived parameters of an automatic control system of technological processes (ACS TP) and the numerical modeling of the thermal and thermo-stressed state of the rotor during its entire period of operation.

The actual operating conditions of the turbo-unit are determined by the following parameters of ACS TP: rotor speed, temperature, pressure and live steam rate in front of the stop valves, active generator power, steam temperature and pressure in the station collector, and pressure in the condenser.

The algorithm proposed in the resource counter determines the material damage in the diagnostic zones as the loading cycles and half-cycles are formed in accordance with the rain method. The number, time and incremental damage per cycle or half-cycle is recorded in electronic journals. The resource counter allows one to take into account the actual operating conditions of the turbine unit. To organize its work, no additional equipment is required. The graphical interface allows one to analyze the changes in the ACS TP parameters, temperatures, and equivalent voltages in the diagnostic zones for the specified time. With the help of the system, the transient moderate regimes of the turbine unit can be determined from the predicted indices of various operating modes [37]. The approbation of the resource counter was carried out at the T-250/300-240 turbine unit of Kharkiv TPP-5.

One of the causes of breakdowns, emergency stops and destruction of turbine unit rotors can be the accumulation of fatigue damage due to intense torsional vibrations of the shaft line, which are most often caused by the generator. Both the methodical ware and the software for assessing the strength and resource in the most dangerous sections of turbine unit shaft lines in the case of two-phase and three-phase short circuits was developed [38].

Conclusions

The resource assessment of steam turbine components includes calculations of the long-term strength under cyclic loading, high-temperature creep and crack growth resistance of the material, taking into account the influence of non-stationary temperature fields. Calculated prediction of thermal strength and resource plays an essential role in ensuring the safe operation of power equipment.

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Розрахункове прогнозування термоміцності та ресурсу елементів парових турбін

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Ефективна і надійна робота енергетичних агрегатів тісно пов'язана із забезпеченням термоміцності й довговічності їх елементів і вузлів. Потреби сучасного енергоринку призводять до експлуатації обладнання на змінних режимах, що викликає прискорене спрацювання його ресурсу. Проблема продовження ресурсу енергомашин набуває все більшого значення у зв'язку з тим, що процеси старіння обладнання випереджають темпи його заміни. Тому для забепечення надійної експлуатації енергетичних агрегатів важливе значення має розрахункова оцінка термоміцності й довговічності їхніх елементів ,що грунтується на застосуванні нових методик і розрахункових моделей з урахуванням ряду важливих факторів (пошкоджуваність, неоднорідність властивостей матеріалу, контактність взаємодій, наявність тріщин, вплив нестаціонарних температурних полів і т.д.). У роботі наведено огляд методичного і програмного забезпечення та результатів розрахункових досліджень термоміцності, ресурсу й тріщиностійкості елементів парових турбін, які виконані в Інституті проблем машинобудування ім. А. М. Підгорного НАН України протягом останніх 15 років. Розрахункова оцінка ресурсу елементів і вузлів енергомашин та обґрунтування можливості його продовження проводилися в рамках розробленого авторами нормативного документа для визначення розрахункового ресурсу й живучості роторів і корпусних деталей турбін з більш обґрунтованими коефіцієнтами запасу. Розроблене методичне забезпечення дозволило провести розрахунки елементів парових турбін у нових уточнених постановках з урахуванням особливостей реальних умов експлуатації. Розроблена комп'ютеризована система діагностування термонапруженого стану та спрацювання ресурсу високотемпературних роторів парових турбін, враховуючи реальні режими роботи турбоагрегатів, одержані на основі параметрів автоматичної системи керування технологічними процесами, дозволяє більш точно оцінити час їхньої безаварійної експлуатації. Наведено постановки та короткий аналіз результатів розглянутих задач термоміцності й ресурсу елементів турбін.

Ключові слова: *розрахункове прогнозування, термоміцність, ресурс, тріщиностійкість, елементи парових турбін.*

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