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DEVELOPMENT OF A SYSTEM FOR ESTIMATING AND FORECASTING THE RATIONAL RESOURCE-SAVING OPERATING MODES OF TPP

Світова енергетична криза та екологічні проблеми спонукали стрімке збільшення долі генерації електроенергії відновлювальними джерелами. Проте, режими роботи таких енергопотужностей є досить нерівномірними протягом доби. Так, для енергетики більшості країн, що розвиваються, та частини розвинених країн такі коливання в загальному балансі енерговиробітку призводять до примусового обмеження потужності обладнання на ТЕС, або й до повної зупинки енергоблоків.

Недостатня кількість маневрових потужностей в загальному енергогенеруючому балансі є характерною рисою енергосистем таких країн як Російська Федерація, Україна, Македонія, Болгарія, Румунія, Аргентина та низки інших. Нестача таких потужностей часто компенсується за рахунок пиловугільних блоків потужністю 200–300 МВт, що залучаються до роботи в напівпікових та пікових режимах. Дане обладнання проектно не пристосовано до такої роботи. Тому для запобігання передчасного зношення генеруючого устаткування ТЕС пропонується розробка режимного методу управління ресурсом.

На базі технічного аудиту експлуатаційної документації генеруючих компаній, запропоновано метод, спрямований на прогнозування раціональних ресурсоощадних режимів роботи високотемпературних елементів енергетичного обладнання шляхом оптимізації дольового відношення числа пусків устаткування з різних теплових станів. Сформульовано задачу оптимізації, яка полягає у визначенні такого розподілу конструктивно-технологічних параметрів процесу, що забезпечують максимальне збереження ресурсу обладнання. Як цільову функцію задачі оптимізації обрано залишковий ресурс. Розроблений метод представлено у вигляді комплексної системи оцінки та прогнозування раціональних режимів експлуатації високотемпературних елементів ТЕС, що дає можливість визначення індивідуальних ресурсних показників на протязі всього часу експлуатації обладнання для усіх можливих майбутніх комбінацій режимів роботи та згенерувати прогнози для тисяч різних варіантів режимної експлуатації енергоблоку, з розрахунком ресурсних показників для кожного з них

Ключові слова: теплова електростанція, енергоблок, пошкоджуваність, залишковий ресурс, прогнозування, оптимізація

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, Senior Lecturer*
E-mail: vapeshko@gmail.com
V. Goryazhenko
Postgraduate Student*
E-mail: vgandcohookah@gmail.com
O. Chernov
Postgraduate Student*
E-mail: wist1706@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

An important issue related to the energy systems of many countries, including parts of Europe, the CIS, Argentina, and South Africa, is the lack of peak capacities in the overall generating energy balance. As a result, there is a need to involve base and semi-base TPP energy units to control power in the grid. However, such equipment is not designed to operate under frequent variable modes. Violating the service regulations, caused by the necessity of excessively frequent launches and stops of power units, leads to a sharp decrease in the lifetime of the specified power units [1].

Therefore, at the current stage of the development of the energy sector in such countries, an acute and priority task is to substantiate the feasibility and possibility to prolong the service life of TPP main equipment of this type. However, a simple extension of the service life will not make it possible to ensure the high excessive operation and is not able to provide sufficient time for the technical modification of energy generation.

It is expedient to apply such methods to manage the service life-time of high-temperature elements that could slow the pace of damage accumulation by the basic metal of power equipment [2].

Consequently, there is a need to devise a methodology for analyzing the impact of the structural, technological, and regime parameters of appropriate equipment on the damageability and residual resource. The purpose is to compile recommendations on the management of a high-temperature elements' resource, both for the power units that have been in operation over a long time and for those newly installed.

There is a need to combine experimental experience and classic empirical dependences, which are conventionally used for project calculations, as well as modern information technologies [3]. The effective implementation of the procedure for analyzing the reliability and durability of the high-temperature elements' operation is largely dependent on considering the correlation between the structural, technological, and regime parameters of a power unit.

Given the significant number of significant factors affecting the damageability and residual resource, there is a need to determine their optimal, or at least rational, distribution. The high efficiency of the implementation of the results from forecasting optimization in power engineering has been proven in studies [4, 5].

The above testifies to the relevance of studies aimed at determining the rational operational regimes for the TPP high-temperature elements.

2. Literature review and problem statement

It is known that in order to ensure stable operation of a power system, it is advisable that the base capacities within a structural balance of energy generating capacity should amount to 50–55 %, half-peaks – to about 30–35 %, and peak – at least to 15 % [6].

The base maneuvering peak capacities in most countries of the world are provided by gas-turbine, hydroelectric power stations (HEPS), and pumped storage power plants (PSPP). However, according to data from WEC (World Energy Council), in some regions of the world, their capacity is not enough to compensate for the fluctuations in power systems. Thus, in the Middle East, their share is only 5 %, whereas in some European countries – more than 20 %.

For example, according to ref. [1], in 2020, as regards the energy-generating structure of Ukraine, they make up about 10 %, in contrast to 15 % required for the steady operation of the power system.

A similar issue relates to maneuvering half-peak capacities. At present, TPP power units with a capacity of 100–150 MW, which, at sufficient efficiency [7], could be used as the half-peak maneuvering ones, constitute about 18 % against the required 30–35 %.

At the same time, the energy engineering in many countries the world is characterized by a rapid increase in the proportion of electricity generation by renewable sources [8],

which is predetermined by both the economic causes [9] and environmental problems [10].

However, it should be noted that the operating modes of such energy facilities are rather uneven over 24 hours. For example, according to the daily schedule of electricity consumption by United Energy System of Ukraine (UESU) as of 07.04.2020 [11], the renewable energy sources (RES) capacity for the period from 10:00 to 16:00 was about 2.5–3.3 GW, while it decreased to 220 MW over the evening-night period. Such a fluctuation in power in the overall balance resulted in the forced equipment power limits at TPPs or their shutdown.

Given the above, the energy systems in many European countries have recently been characterized by the displacement of semi-base power units at TPPs towards the half-peak and peak regions in an electric load schedule [12].

This issue was considered in [13], reporting an approach aimed at evaluating the problems related to the maneuverable operation mode of power units, with recommendations on the operation and planning of power plants' exploitation. The research results make it possible to increase the efficiency of maneuverable thermal power plants over variable modes, but the issue of their operation duration and resource-saving was not considered.

Paper [14] estimated the maneuvering possibilities of power generating units. The authors analyzed a series of negative consequences due to the increased dynamism and mobility of TPP power units. They proposed a series of possibilities to improve the maneuverability of power units. However, the issue of reducing the resource indicators of energy equipment was disregarded.

The influence of frequent variable operation modes of the TPP pulverized coal units on the durability of their performance was investigated in paper [15]. However, the authors did not address the optimization of the operating modes of power units to prevent the premature wear of TPP generating equipment under operation at the peak and half-peak parts of load schedule.

It is worth noting the data reported by the authors of scientific work [16]. It is noted that the growing proportion of electrical power from renewable energy sources dictates the irregular operation of heat-energy plants to compensate for the energy-generating instability of renewable sources. As a consequence, due to thermomechanical fatigue, creep, and corrosion there is a reduction in the operational period of power unit nodes. The authors of [16] emphasize that a technique that could predict the residual lifetime of unit operations is necessary for managerial decisions on the operation of power plants and planning their service.

All this allows us to argue that research aimed at creating technology for estimating and forecasting the rational, in terms of prevention of premature wear, operating modes of power units could make it possible to partly compensate for the negative impact of TPP maneuvering operations.

3. The aim and objectives of the study

The aim of this study is to build a system for estimating and forecasting the rational resource-saving operational regimes of the high-temperature elements of energy equipment. This would make it possible to automate the process of data acquisition on the residual resource and to extrapolate the information obtained for making timely decisions regarding the operation of specific power units.

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

– to acquire and to treat statistically the data on the operation of specific energy units at TPP (the number of launches; the number of launches for the most characteristic operating regimes (CS, NCS, HS), operation under a rated mode; overall operation time;

– to determine the allowable number of cycles for different types of launches based on the technological audit, as well as data on the actual operating conditions over the entire operation duration, and the diagnostic control of the main metal;

– to construct a mathematical model for predicting the rational resource-saving regime operational modes and to implement it by software.

4. Materials and methods to study approaches to building an evaluation and forecasting system

Underlying the development of an evaluation and forecasting system (EFS) is the approach based on [17, 18, 20]: «a mathematical model – an intelligent expert system – an automated evaluation and forecasting system», which is schematically shown in Fig. 1. An EFS examines the technological process in the form of a multi-component system of the interrelated examined objects: the elements of power equipment, a heat-carrier, mechanical loads, etc.

Over the period from 2004 to 2019, significant work has been made to accumulate and statistically treat data on the operation duration of specific TPP power units in Ukraine. There is a data array on the number of launches, the number of launches for the most characteristic modes of operation (CS, NCS, HS), the duration of operation under a rated mode, the total equipment operation duration. As an example, Tables 1, 2 give data on the DTEK Vostokenergo Luhansk TPP and the DTEK Vostokenergo Kurakhiv TPP.
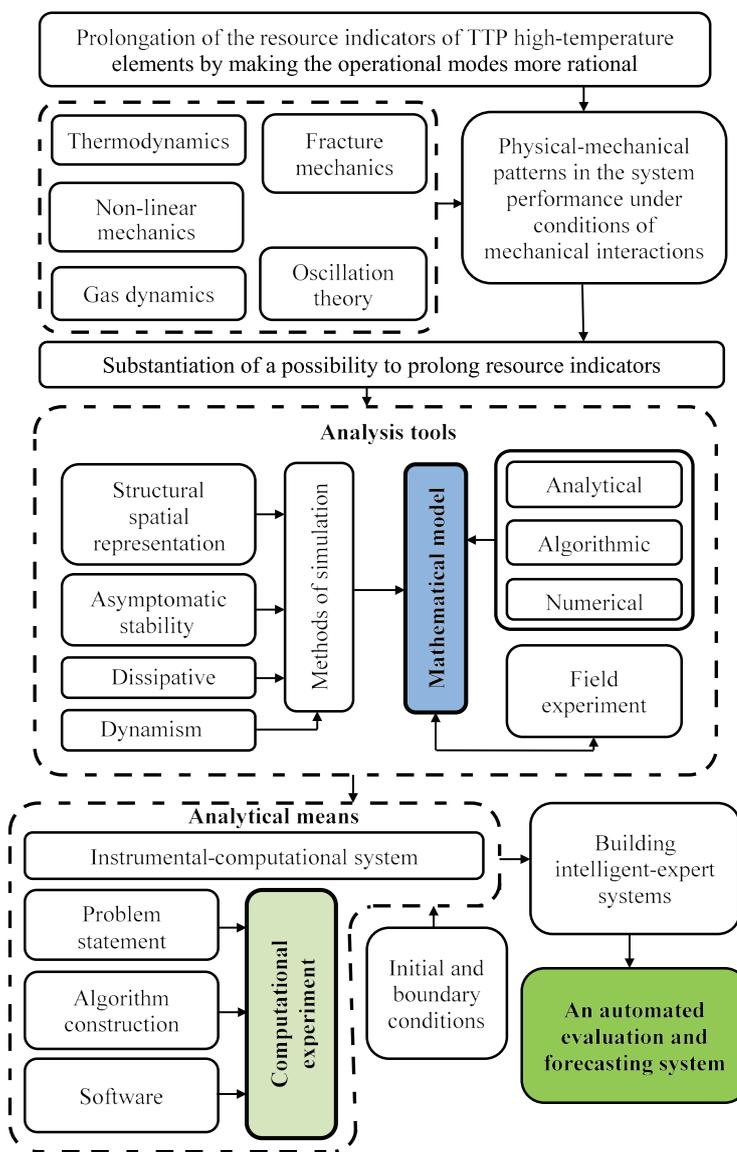

Fig. 1. EFS principal diagram

Table 1

Indicators of damageability and the residual resource of power units at the Luhansk TPP as of 2015 for various operating regimes

Resource indicator		Unit No. 9	Unit No. 10	Unit No. 11	Unit No. 13	Unit No. 14	Unit No. 15
Year of unit introduction into operation		1962	1962	1963	1967	1968	1968
Unit operation duration as of 01.10.15		322,672	308,281	317,571	284,658	280,930	292,226
Number of unit's launches as of 01.10.15		1,617	1,813	1,811	1,896	1,729	1,327
Damageability over the entire time at normal operation	static	0.403	0.385	0.397	0.356	0.198	0.183
	cyclic	0.591	0.554	0.589	0.471	0.809	0.783
	total	0.994	0.939	0.986	0.827	1.006	0.966
Damageability over one year at daily start-stop	cyclic	0.220	0.225	0.243	0.061	0.228	0.225
	total	1.214	1.164	1.230	0.888	1.234	1.191
Residual resource, hour	Normal operation	3,096	34,027	7,429	104,530	−2,208	12,755
	Daily start−stop	264	2,675	579	29,604	−23,524	1,163

Table 2

Indicators of damageability and the residual resource of power units at the Kurakhiv TPP
as of 2015 for various operating regimes

Resource indicator		Unit No. 3	Unit No. 4	Unit No. 5	Unit No. 6	Unit No. 7	Unit No. 8	Unit No. 9
Year of unit introduction into operation		1972	1973	1973	1973	1974	1974	1975
Unit operation duration as of 01.10.15		279,723	254,623	239,615	234,531	247,278	244,695	239,208
Number of unit's launches as of 01.10.15		1,424	2,352	2,862	2,655	2,186	2,381	1,691
Damageability over the entire time at normal operation	static	0.350	0.318	0.300	0.188	0.309	0.198	0.183
	cyclic	0.616	0.653	0.683	0.433	0.660	0.442	0.426
	total	0.966	0.971	0.983	0.621	0.969	0.640	0.609
Damageability over one year at daily start-stop	cyclic	0.073	0.122	0.060	0.159	0.122	0.122	0.106
	total	1.039	1.092	1.043	0.779	1.091	0.762	0.715
Residual resource, hour	Normal operation	15,626	11,388	6,044	205,412	11,430	199,123	219,552
	Daily start-stop	4,807	2,164	2,364	19,127	2,221	25,545	31,583

Based on the concluded agreements with DTEK Vosto-kenergo, we conducted a set of estimation studies on determining the acceptable number of cycles for different types of launches. The studies were based on data about the actual operational conditions over the entire period of work, as well as the results of technical auditing and diagnostic control of the main metal, conducted at the Laboratory of Metals and Welding of the separate enterprise Luhansk TPP from DTEK Vostokenergo.

Calculations of the total projected and existing damageability (static, cyclic), as well as a residual resource, were carried out for the protocols of equipment operating under the basic modes of operation and under the potentially most difficult maneuvering regime (daily start-stop). The calculation studies and their results are described in detail in papers [15, 21, 22].

It should be noted that the greatest proportion of the damage to the rotors and casings of steam turbines belongs to launches from the hot (HS) and cold (CS) states. The smallest proportion to rotors damage belongs to launches from the non-cooled state (NCS) at a metal temperature at the launch onset of 250 °C. As an example, Tables 3, 4 give the estimated damageability and residual resource of the high-pressure (HPR) and intermediate-pressure rotors (IPR) for certain power units.

Our analysis of data from Tables 1–4 indicates that at the current level of operation duration (222,438–322,672 hours) and the number of launches (1,424–2,978), even at the reduced coefficients of strength, the damageability of power units is within 0.67–0.85. This testifies to the very limited capability of power units with a capacity of 200 MW to control load in the grid. When operating these units under maneuvering modes, and especially under a mode of daily launch-stop, their residual resource would decrease considerably. Further operation under such conditions requires the optimization of the number of launches from various thermal states.

Table 3

Estimated damageability and residual resource of HPR and IPR of power units No. 4, 5 at the Kurakhiv TPP
at the repeated extended operation in 2018

Resource indicator		HPR No. 4		IPR No. 4		HPR No. 5		IPR No. 5	
Total number of launches		2,475		2,475		2,978		1,742	
Total operation duration, hour		261,773		261,773		243,785		241,544	
Strength resource coefficient		5\1.5	3\1.25	5\1.5	3\1.25	5\1.5	3\1.25	5\1.5	3\1.25
Allowable number of cycles for various types of launches	$[N_{pl}]_{HS}$	7,500	>10,000	3,900	6,400	7,500	>10,000	3,900	6,400
	$[N_{pl}]_{NCS}$	6,200	9,300	5,800	8,000	6,200	9,300	5,800	8,000
	$[N_{pl}]_{CS}$	5,200	8,200	2,500	4,170	5,200	8,200	2,500	4,170
Cyclic damageability		38.21	26.48	65.10	40.90	45.74	31.8	46.37	29.01
Allowable operation time, hour		$3.7 \cdot 10^5$	$5.6 \cdot 10^5$	$3.7 \cdot 10^5$	$5.6 \cdot 10^5$	$3.7 \cdot 10^5$	$5.6 \cdot 10^5$	$3.7 \cdot 10^5$	$5.6 \cdot 10^5$
Static damageability		70.75	46.75	70.75	44.52	65.89	43.53	65.28	41.08
Total damageability		108.96	73.23	135.85	85.42	111.68	75.33	111.65	70.09
Residual resource, hour		<0	95,714	<0	44,667	<0	79,820	<0	103,088

Table 4

Estimated damageability and residual resource of HPR and IPR of power unit No. 9 at the Luhansk TPP at the repeated extended operation in 2018

Resource indicator		HPR		IPR	
Total number of launches		2,475		2,475	
Total operation duration, hour		222,438		144,596	
Strength resource coefficient		3\1.25	5\1.5	3\1.25	5\1.5
Allowable number of cycles for various types of launches	$[N_{pl}]_{HS}$	$>10^4$	6,800	3,000	1,800
	$[N_{pl}]_{NCS}$	$>10^4$	7,100	7,500	4,800
	$[N_{pl}]_{CS}$	2,700	1,800	2,600	1,450
Cyclic damageability		0.172	0.453	0.2789	0.4698
Allowable operation time		$3.7 \cdot 10^5$	$3.7 \cdot 10^5$	$3.7 \cdot 10^5$	$3.7 \cdot 10^5$
Static damageability		0.601	0.601	0.391	0.391
Total damageability		0.7739	1.0549	0.6697	0.8606
Residual resource, hour		85,699	<0	64,562	23,419

5. Constructing a mathematical model for an evaluation and forecasting system

In analogy to work [17], a procedure for constructing a mathematical model can be represented by a sequence of the following steps [18]:

1. Define the analytical dependences containing parameters that describe the estimated pattern of the examined object. These ratios should take the form of a closed system of equations describing the behavior of the object of study in real spatially-temporal coordinates (the boundary problem of mathematical physics).

2. Solve the stated problem and develop a sequence of actions (algorithm) for the conversion of input parameters to the output parameters.

3. Implement the constructed algorithm in the form of software aimed at enabling the automation of computational experiments.

Each of the above stages is a separate, sometimes a rather complicated, problem. The result of each stage would be the construction, accordingly, of three interconnected models – analytical, algorithmic, and digital.

Thus, a mathematical model implies a theoretical construct in the form of analytical, algorithmic, and digital models. It reflects all the properties of the examined object within the created estimated scheme and enables its automation for practical application by using computer technologies.

An analytical model defines the properties of the examined object and the problematic aspect of the set problem [19].

The structure of an analytical model is as follows:

1. Description of the patterns necessary for the comprehensive assessment of the residual energy equipment resource.

The boundary problem of the non-stationary thermal conductivity:

$$\text{div}\left[\lambda(T)\text{grad}\,T\right] = c(T)\gamma(T)\frac{\partial T}{\partial \tau}, \tag{1}$$

where λ, c, γ are the functions of temperature and coordinates at the initial conditions $T_0 = T(x,y,z,0) = f_0(x,y,z)$ and boundary conditions of the I, II, III, or IV kind.

In solving the problem on thermal conductivity, it is necessary to specify the non-stationary boundary condition of the I–IV kind:

– I kind – when the temperature of an object's surface is known at a certain time:

$$T_s = f_1(x,y,z,\tau); \tag{2}$$

– II kind – at the isolated surfaces, the boundary conditions are set by a heat flow:

$$q_s = -\lambda\left(\frac{dT}{dn}\right) = f_2(x,y,z,\tau); \tag{3}$$

– III kind – the regularities of heat exchange between a hot heat-carrier and the equipment metal:

$$-\lambda\left(\frac{dT}{dn}\right) = \alpha(T_m - T_s); \tag{4}$$

– IV kind – corresponds to the perfect contact of solids, in the cases when both bodies at the interface of their contact have the same temperature and heat flows:

$$\begin{cases} T_{s1} = T_{s2}, \\ -\lambda_1\left(\frac{dT}{dn}\right)_1 = -\lambda_2\left(\frac{dT}{dn}\right)_2. \end{cases} \tag{5}$$

The stressed-strained state of power equipment was calculated when solving the equilibrium equations jointly, which, in a tensor form, take the following form:

$$\{\sigma_{il}\}_j + \rho X_i = 0; \quad i,j = 1,2,3, \quad p_i = f(x,y,z,0), \tag{6}$$

where σ_i are the normal and tangent stresses in equipment elements, X_i is the mass force operating in the elements, p_i are the external distributed stresses, ρ_i is the density of an element's material.

We also added the equations characterizing the simultaneous action of deformations and the elasticity law, which, in a matrix form, take the following form:

$$\{\varepsilon_{ij}\} = [a]\{\sigma_{ij}\} + \{\beta \cdot \Delta T\}, \tag{7}$$

where $\{\varepsilon_{ij}\}$ is the vector of deformations; $[a]$ is the matrix of elastic coefficients; $\{\sigma_{ij}\}$ is the vector of stresses; $\{\beta \cdot \Delta T\}$ is the vector of temperature deformations, β is the coefficient of linear expansion; ΔT is the change in temperature during operation.

A Neuber's method was used to account for the patterns of influence of the stressed-deformed state of TPP high-temperature elements on the accumulated damage. The calculation followed the mechanism of low-cycle fatigue and long-term durability based on the amplitudes of the intensity of the local elastic-plastic deformations at the estimated temperature in this region.

The amplitude of deformations was determined based on the values of strain intensity over a load cycle (initial state – loading – rated mode – unloading – initial state) according to:

$$\varepsilon_a = \frac{1}{2}(\varepsilon_{i\max} - \varepsilon_{i\min}), \tag{8}$$

where $\varepsilon_{i\max}$, $\varepsilon_{i\min}$ are the maximal and minimum value of deformation intensity per cycle.

The number of loading cycles until the occurrence of cracks was determined based on the experimental curves of low-cycle fatigue, obtained from testing the samples for stretching-compression under a severe symmetrical cycle and at a constant temperature. The allowable number of cycles at the estimated temperatures below 480 °C for heat-resistant steel, below 420 °C for alloyed steel, and below 350 °C for carbon steel, was selected based on the experimental curves of low-cycle fatigue by adopting the least of the two values:

$$N_p = \min\left\{\frac{N_1}{n_N}; N_2\right\}, \tag{9}$$

where N_1, N_2 is the number of cycles that correspond in the curve of fatigue to the amplitudes $\varepsilon_{a.r.}$ and $n_\varepsilon \cdot \varepsilon_{a.r.}$; n_N, n_ε are the strength reserve coefficients for the number of cycles and deformation; $\varepsilon_{a.r.}$ is the amplitude of deformation intensity reduced to the symmetric cycle of loading, taking into consideration the effective coefficient of stress concentration $\bar{K}_T$.

The amplitude of deformation intensity, reduced to the symmetric loading cycle, was calculated as follows:

$$\varepsilon_{a.r} = \frac{1+\nu}{1.5E}\left(C\sigma_a + \sigma_{-1} - \sigma_N\right), \tag{10}$$

where ν is the Poisson ratio; E is the elasticity module of steel; C is the coefficient of the current number of cycles:

$$C = \begin{cases} 1, \text{ if } N \le 10^4; \\ \dfrac{\bar{K}_T}{K_T}, \text{ if } N\big|_{C=1} > 10^4; \end{cases} \tag{11}$$

σ_a is the amplitude of stress intensity:

$$\sigma_a = \frac{\left(\sigma_{\max} + \sigma_{\min}\right)}{2}, \tag{12}$$

σ_{-1} is the limit of fatigue under a symmetrical loading cycle; σ_N is the limit of fatigue under an asymmetrical loading cycle:

$$\sigma_N = \frac{\sigma_{-1}}{1 + \dfrac{\sigma_{-1}}{\sigma_B}\dfrac{1+r}{1-r}}, \tag{13}$$

σ_B is the tensile strength of steel; r is the coefficient of loading cycle asymmetry; $\bar{K}_T$ is the effective coefficient of stress concentration:

$$\bar{K}_T = 1 + p\left(K_T - 1\right), \tag{14}$$

where p is the coefficient of steel sensitivity to the concentration of stresses.

At elevated temperatures, when there occurs the creep of material under the rated mode of operation, the number of cycles was determined as follows:

$$N_p = \left[1 - \left|\frac{1.25\sigma^A}{\sigma_{l.s.}}\right|^q\right]\min\left\{\frac{N_1}{n_N}; N_2\right\}, \tag{15}$$

where σ^c is the intensity of stresses at a particular point of the component in the state of steady creep; $\sigma_{l.s.}$ is the limit of the prolonged strength of a material at the time point determined by the predefined technical conditions; q is the power indicator in the equation of long-term strength:

$$t = B \cdot \sigma^q. \tag{16}$$

The amplitude of deformation intensity reduced to the symmetric isothermal loading cycle at the estimated temperature:

$$\varepsilon_{a.r} = \frac{1+\nu}{1.5}\left(C\sigma_a + \min\{\sigma_{-1}; \sigma_{l.s.}\} - \min\{\sigma_N; \sigma_N^c\}\right), \tag{17}$$

$$\sigma_N^c = \begin{cases} \min\left\{\dfrac{\sigma_a\sigma_{l.s.}(T_1)}{|\sigma_{\max}|}; \dfrac{\sigma_a\sigma_{l.s.}(T_2)}{|\sigma_{\max} - 2\sigma_a|}\right\}, \text{ if } \sigma_a < \bar{\sigma}_{0.2}^c; \\ \min\left\{\sigma_{l.s.}(T_1); \sigma_{l.s.}(T_2)\right\}, \text{ if } \sigma_a > \bar{\sigma}_{0.2}^c, \end{cases} \tag{18}$$

where σ_a is the amplitude of stress intensity at the estimated point; $\sigma_{l.s.}(T_1)$, $\sigma_{l.s.}(T_2)$ are the long-term strength limits over a service life corresponding to the temperature T_1 and T_2; $\sigma_{\max}$ is the maximum stress per cycle.

The total damage D', accumulated in the metal exposed to the joint effect of creep at various steady modes of the q' types and cyclic loads at different variable modes of the k' types:

$$D' = D'_{st} + D'_c = \sum_{j=1}^{q'}\frac{t'_j}{t'_{pj}} + \sum_{l=1}^{k'}\frac{n'_l}{N'_{pl}}, \tag{19}$$

where Π'_{st}, Π'_c are the static and cyclic damages accumulated in the test zone of the component, at the time of estimating a possibility to prolong the service life duration; t'_j is the time of operation under the j-th steady mode at the appropriate temperature of metal and equivalent local creep stresses $(\sigma'_{ej})_{\max}$; t'_{pj} is the time before entering a boundary state under the action of equivalent stresses $(\sigma'_{ej})_{\max}$; at temperatures T'_j; n'_l is the number of cycles of type 1; N'_{pl} is the number of cycles before the emergence of fatigue cracks under the influence of the cyclic loads of the i-th type only; q' is the number of different types of steady regimes at the time of evaluation with temperature T'_j and the fixed equivalent local creep stresses $(\sigma'_{ej})_{\max}$; k' is the number of different types of cycles at the time of evaluation with different amplitudes of the reduced stresses $\Delta\sigma'_l$ or amplitude of deformations ε'_{dl}.

The residual operation duration before the emergence of a crack $[\tau]_{res}$ (in years):

$$[\tau]_{res} = \frac{1-D'}{D''_{pred}}, \tag{20}$$

where Π''_{pred} is the averaged annual damage projected for the period of operation following the estimation.

2. Constructing an analytical pattern between the reduced deformation ε_a^{red} and the acceptable number of cycles N_p based on the mathematical-statistical analysis of experimental data.

It should be noted that significant difficulties in calculating the damage and residual operation duration of the TPP high-temperature elements, operation duration are caused by the inaccuracy or complete lack of information in reference literature on the behavior of special heat-resistant alloyed steels (brands 25Cr1Mo1V, 20Cr3MoWV, 15Cr1Mo1V, etc.) at the high operating temperatures of 400–550 °C. Similarly, there are no experimental data on the low-cycle fatigue of the above materials.

To solve this problem, we conducted a series of experimental studies into the prolonged strength and degradation

in the static and cyclic strength of these steels after long-term exploitation in order to clarify the coefficients of strength reserve and determine the residual resource.

Experimental studies were carried out at the Pisarenko Institute for Problems of Strength of the National Academy of Sciences of Ukraine, using the laboratory installation AIMA-5-2, which is designed for the testing of metals for creep and long-term durability at constant temperature and load. The tests [23] aimed to establish a dependence between stress and time before destruction at the predefined constant temperature. The initial experimental results from studying the creep and prolonged strength of steels were analyzed based on a basic charting method. The basic charting method is based on a clear specification of the features of separate experimental sections and design diagrams of prolonged durability. Two problems are solved within the framework of this method: experimental data are analyzed; based on the analysis results, forecasting is implemented.

Based on data from the experimental studies and by using, as the base approximation function, the modified Steinhart-Hart equation, we derived the dependence between the reduced deformation ε_a^{red} and the allowable number of cycles N_p in the range of operating temperature of 400–550 °C, which, in a general case, takes the following form:

$$N_p = \frac{t\left(1+t+\varepsilon_a^{red}\right)}{1+\ln\varepsilon_a^{red}+\ln^3\left(\varepsilon_a^{red}\right)}. \qquad (21)$$

A detailed methodology of experimental research and the results obtained are described in detail in [23].

3. Stating a problem on the optimal distribution of the technological (mode) parameters for the operation of energy equipment based on the mathematical programming methods.

For the adopted structurally-technological scheme of a power unit, it is possible to distinguish the following basic parameters defining the course of the process: the geometric sizes of main nodes and parts of equipment, the thermal and aerodynamic parameters of a heat-carrier, as well as the mode starting parameters.

We propose solving the optimization problem, which implies determining such a distribution of the structurally-technological process parameters that would ensure maximum preservation of the equipment resource. Residual resource G was chosen as the objective function of the optimization problem:

$$G(\vec{x}) \to \max_{\vec{x}\in\bar{X}} G(\vec{x}).$$

The solution to the set optimization problem is such a point $x^{opt}\in X$ that $G(\vec{x}^{opt})\geq G(\vec{x})$ for all $x\in X$, that is

$$G(\vec{x}^{opt}) = \max_{\vec{x}\in\bar{X}} G(\vec{x}),$$

$$N_{X\min} \leq \left|\bar{X}\right| \leq N_{X\max},$$

where G is the objective function; $\vec{x}$ is the vector of the structural-technological parameters that affect G; $\bar{X}$ is the area of the existence of vector $\vec{x}$; $N_{X(\min)}$, $N_{X(\max)}$ are the boundaries of the existence of the vector $\vec{x}$ components.

Thus, the problem of maximizing the residual resource G requires finding such combinations of values of the vector $\vec{x}$, components whose implementation produces the extreme value of the objective function G.

For a given case, we have:

$$G(t,NS) \to \max_{\vec{x}\in\bar{X}} G(t,NS),$$

$$G(t,NS) =$$

$$= \cfrac{(1-P_{sum})\cdot\chi}{\cfrac{t}{T}+\left[\cfrac{(n_{\min}-n_{\max})\cdot(t-t_{\min})}{t_{\max}-t_{\min}}+n_{\max}\right]\cdot\left[\begin{array}{c}\cfrac{HS}{N_{hs}}+\cfrac{1-HS}{N_{ns}\cdot NS^{-1}}+\\+\cfrac{1-HS}{N_{gs}\cdot(1-NS)^{-1}}\end{array}\right]},$$

$$\vec{x}=\begin{cases}t_{\min} \leq t \leq t_{\max}\\n_{\min} \leq n \leq n_{\max}\\hs_{\min} \leq hs \leq hs_{\max}\end{cases},$$

$$HS = (t-t_{\min})\cdot\frac{hs_{\max}-hs_{\min}}{t_{\max}-t_{\min}}+hs_{\max},$$

where $t_{\min}$, $t_{\max}$ are the minimum and maximum number of hours of power unit operation per year for the projected period; $n_{\min}$, $n_{\max}$ are the minimum and maximum number of total annual launches of a power unit; $hs_{\min}$, $hs_{\max}$ are the minimum and maximum values of the share of the number of launches from the cold state (CS); HS is the proportion of the number of launches from the cold state; NS is the share of launches from the non-cooled state within the proportion of the launches from the hot state; N_{hs}, N_{ns}, N_{gs} is the allowable number of launches from the respective states (CS, NCS, HS); χ is the average annual operation duration according to the energy auditing.

4. Algorithmic model.

In a general form, the algorithmic model consists of the following main parts.

Preprocessor unit:

– a power unit operation duration;

– the number of launches of a power unit;

– the percentage ratio of launch types from different thermal states;

– the results of the estimated assessment of SSS in a non-stationary statement.

Solver unit:

– the functional dependence of the allowable number of cycles N_p on the reduced deformation ε_a^{red} and the temperature of the metal;

– patterns in the SSS influence on the accumulated damage in line with the mechanism of low-cycle fatigue and long-term strength;

– the gradient (by Newton abo Levenberg-Marquardt) algorithms to search for extreme values.

Postprocessor unit:

– a unit to display values of the residual resource in the form of three-dimensional surfaces;

– a unit to display the rational range of values for the mode-operational parameters;

– optimal distribution of the mode-operational parameters.

6. Results of evaluating the residual resource of power units' elements

Using the above system of estimating and forecasting the rational operating regimes of high-temperature elements,

we studied certain typical equipment at TPP. The study involved the equipment for a power unit with a capacity of 200 MW, which exhausted its projected resource of 220,000 hours. The number of launches of the equipment corresponds to a park value of 800, of which 50 % are the launches from the hot state of the metal, 20 % – non-cooled, 30 % – cold. The obtained results in the form of contour charts are shown in Fig. 2–4.

For the intermediate-pressure rotor of the turbine K-200-130, the most rational mode of operation that could provide the highest durability and resource-saving is a semi-basic mode (Fig. 2). The rational values of the operating parameters are: the number of hours of work per year is 3,000–4,400 h, the number of launches-stops over a year is 48–64, with the following distribution for different types: CS – 28–52 %, NCS – 0–20 %, HS – 28–48 %. In this case, there is an evident optimum distribution of mode parameters: 3,660 hours of work per year at 57 launches, of which 40 % – from the cold state, 60 % – from the hot state.

For some equipment, there is a clear region of the irrational operating parameters. Thus, for hot intermediate overheating steam pipelines, when increasing the number of hours per year, the residual resource decreases (Fig. 3). That is, for such equipment, the rational mode of operation in the peak part of an electrical load diagram is: 2,000 hours of work per year, 75 launches during the year, 90 % of which are the launches from the hot state, 10 % – cold. This is due to that the exhaustion of long-term strength for such equipment has a dominant effect on the rate of decrease in the residual resource.

Specific equipment has several ranges in the rational operation modes. This is typical for equipment, which is equally damaged both by the mechanism of exhaustion of long-term strength and due to the accumulation of low-cycle fatigue. For example, a drum in the boiler TP-109 has two rational regions of mode parameters (Fig. 4).

Fig. 3. The chart of residual resource depending on operating parameters for steam pipelines of hot intermediate overheating in the turbine K-200-130, which exhausted their park resource

Fig. 4. The chart of residual resource depending on operating parameters for a drum in the boiler TP-109, which exhausted its park resource
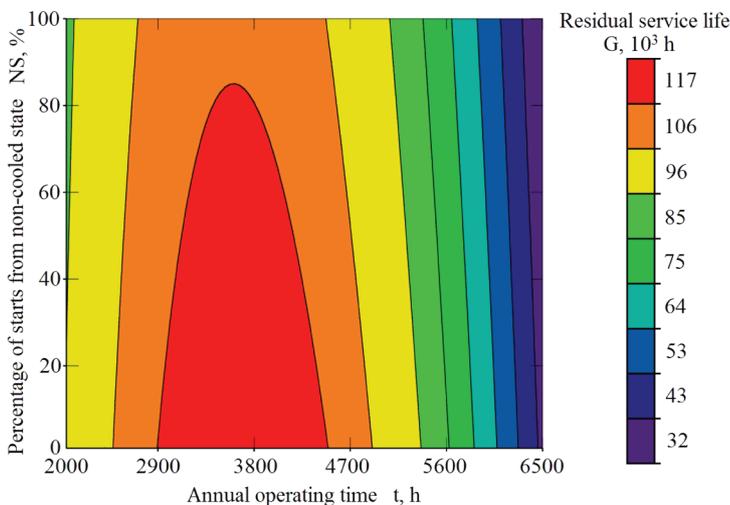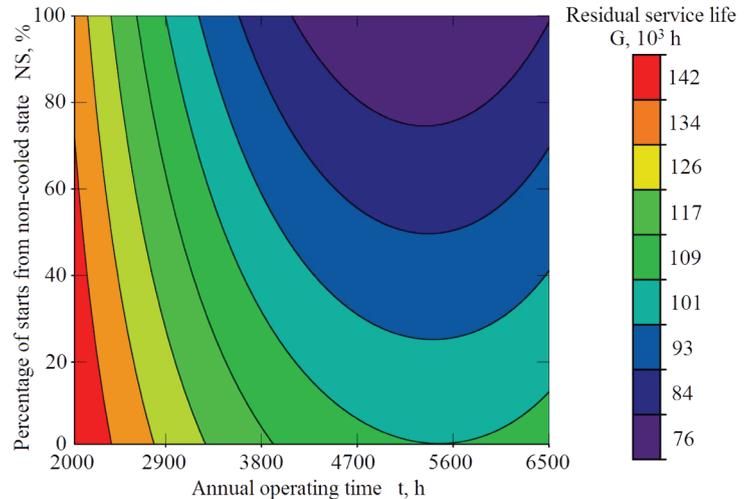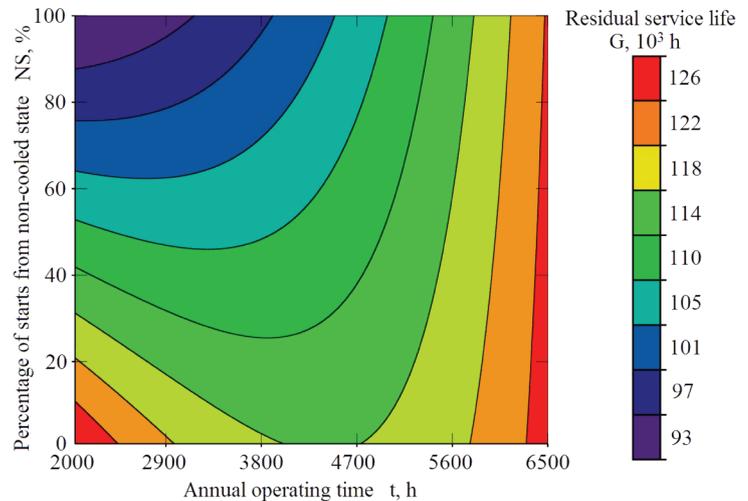

Fig. 2. The chart of the residual resource depending on operating parameters for the intermediate-pressure rotor in the turbine K-200-130, which exhausted its park resource

The first region of rational values is the basic mode involving 6,100–6,500 hours of work per year at the minimum number of launches (25–32) per year, 90 % of which are launches from the cold state, the rest – from the hot and non-cooled states. The second region is the peak mode implying 2,000 hours of work per year and the number of launches of 70–75, of which 67–90 % – launches from HS, 0–15 % – NCS, 10–18 % – CS.

7. Discussion of results of developing a system of estimating and forecasting the rational modes of operation and its application

The reported system for estimating and forecasting the rational resource-saving regimes of operation of the TPP high-temperature elements makes it possible to determine the individual resource indicators over the entire time of equipment operation for all possible combinations of operation modes.

Numerous studies of the resource indicators of Ukraine's TPP power equipment performed earlier have been summarized and treated statistically. That has made it possible to detect the most typical modes of power units' operation, as well as to determine the main mechanisms for the accumulation of damage by the main metal of the equipment, as well as the factors leading to its destruction. This has allowed us to establish regularities in the influence exerted by each of the typical modes of operation on the rate of exhaustion of the residual resource of the equipment, in order to determine the dominant factors of TPP exhaustion.

The established analytical dependence (21) of the low-cycle fatigue of heat-resistant turbine steels makes it possible to automate the estimation process while studying the residual resource of energy equipment. An issue related to such calculations is that when forecasting residual operation duration, cyclic damage of the metal is estimated based on experimental curves of low-cycle fatigue for a particular combination of operating modes. When a different distribution of regimes is involved, it is necessary to «manually» recalculate. Therefore, typically, when forecasting the residual resource, the condition was accepted that the power unit would continue to operate in the same mode as at the time of calculation. The derived analytical dependence makes it possible to automate the estimation of a metal cyclic damage for many different combinations of TPP operation modes.

The constructed estimating and forecasting system makes it possible to consider all possible intermediate modes of operation of power units within two diametrically opposite variants. Namely, a fully basic one (under which annual operation duration approaches maximum $T{\rightarrow}max$ while the number of launches per year is minimum $n{\rightarrow}min$), as well as a full peak one ($T{\rightarrow}min$, $n{\rightarrow}max$). Additionally, different ratios of the number of launches from the typical thermal state conditions (CS, NCS, HS) are considered. At the same time, certain logical conditions of operations are taken into consideration. For example, for a variant with a large annual operation duration, most of the launches must be from the hot state as, in this case, the downtime is small and the equipment would not have time to cool down to the non-cooled or cold states.

Thus, the EFS makes it possible to build forecasts for thousands of different variants of the power unit operation, with the calculation of resource indicators for each of them. This makes it possible to choose a convenient mode of operation from the region of rational values, thereby providing for the sufficient durability of the equipment operation. This information is useful for generating companies when planning a strategy for their operations in the power system.

At the current stage, the key drawback of a given estimating and forecasting system is that it can provide information about the rational mode of operation for a particular type of equipment, not the entire power unit. Fig. 2–4 show that, for various equipment of the same unit with a capacity of 200 MW, the regions of rational operating modes differ. This is due to that each piece of equipment is not equally sensitive to certain mechanisms of damage; therefore, the influence of different combinations of operating modes varies.

In the future, we plan to construct an integrated system for predicting rational modes of operation, which would be able to provide recommendations for the entire power unit. They would be established on the basis of the partial distributions of optimum operating modes taking into account the range of change in the residual resource for the specified equipment, its cost, the complexity of repair, consequences of emergency failure, etc.

The ultimate implementation of the further advancement of the reported EFS is to consider its integration into a single complex with registration instruments (sensors) of basic parameters, with a controller, a computer of appropriate power, and, directly, a power unit. That would enable dynamic tracking of change in the resource parameters; in other words, the creation of a power unit resource counter.

8. Conclusions

1. We have accumulated and treated statistically the data on the operation duration of specific power units at TPPs (the number of launches, the number of launches for the most characteristic modes of operation (CS, NCS, HS); operation under a rated mode; overall operation duration, hours).

2. Based on the mathematical-statistical analysis of experimental data, we have established a pattern between the reduced deformation ε_a^{red} and the acceptable number of cycles N_p for special heat-resistant alloyed steels (brands 25Cr1Mo1V, 20Cr3MoWV, 15Cr1Mo1V, etc.); the chosen basic approximation function was the modified Steinhart-Hart equation. The results of experimental studies into the creep and prolonged strength of the steels were analyzed on the basis of a basic charting method. The data were acquired at high operating temperatures (400–550 °C) of the metal.

3. An estimating and forecasting system has been proposed for the rational resource-saving regimes of operation of the high-temperature elements in TPP power equipment. For the EFS, we have determined an acceptable number of cycles of the power plants' energy equipment for different types of launches. Our study was based on data on the actual operating conditions over the entire period of work, as well as the results from technical auditing and diagnostic control of the principal metal in the high-temperature elements of power units. A mathematical model has also been constructed to forecast the rational resource-saving regimes of TPP power units' operation; it has been implemented as software. The reported estimating and forecasting system of the rational modes of operation of the TPP high-temperature elements makes it possible to provide individual (separately for each node in a specific power generating unit at a specific TPP) recommendations on the appropriate operation modes of equipment in order to ensure the maximum residual operation duration of a power unit. An increase in the residual operation duration when using the above-described EFS could reach 30 % depending on the level of accumulated damage and the type of energy equipment.

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