UDC 621.165.62
DOI: 10.15587/1729-4061.2017.112284

RESEARCH ON RESIDUAL SERVICE LIFE OF AUTOMATIC LOCKING VALVE OF TURBINE K-200-130

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Проведено дослідження нестаціонарного теплового і напружено-деформованого стану литого корпусу АСК ЦВТ. При визначенні граничних умов враховані зміни тисків, температур, витрат і швидкостей пара при пусках з різних теплових станів на прикладі парової турбіни К-200-130. Виконана розрахункова оцінка залишкового ресурсу і отримані нові дані по рівню ресурсних характеристик стопорних клапанів ЦВТ парової турбіни К-200-130

Ключові слова: стопорний клапан, напружено-деформований стан, малоциклова втома, пошкоджуваність, залишковий ресурс

Проведено исследование нестационарного теплового и напряженно-деформированного состояния литого корпуса АСК ЦВД. При определении граничных условий учтены изменения давлений, температур, расходов и скоростей пара при пусках из различных тепловых состояний на примере паровой турбины К-200-130. Выполнена расчетная оценка остаточного ресурса и получены новые данные по уровню ресурсных характеристик стопорных клапанов ЦВД паровой турбины К-200-130

Ключевые слова: стопорный клапан, напряженно-деформированное состояние, малоцикловая усталость, повреждаемость, остаточный ресурс

1. Introduction

The problem of provision of reliable operation of power equipment in Ukraine is becoming increasingly relevant, as the aging of equipment outperforms the pace of technical upgrading. Currently, service life of the majority of generating units of thermal power plants in Ukraine with a capacity of 200–300 MW, put into operation in the 60s–80s of the twentieth century, reached 180–320 thousand hours [1]. In addition, basic fleet of equipment of the TPP (generating units with capacity from 160 MW to 300 MW) has become obsolete physically and morally.

To extend the service life of power generating units of 200 MW, it is necessary to generate a conceptual approach to problems of possibility of subsequent operation of TPP. It is also essential to pay attention to replacement of the power equipment, which finished its service life, with the new one [2].

Provision of reliable and long-term operation of steam turbine equipment of the thermal power plant requires determining individual service life of its high-temperature elements. Estimated service time is, to great extent, limited to various technological, constructive or mode factors that were not foreseen or sufficiently studied at the design stage. Accelerated finishing of residual service life of operating equipment under current economic condition is not permissible because the current operation time of the majority of turbine equipment already exceed the fleet one.

Identification of dominating factors and mechanisms of aging, reduction or limitation of their impact on the rate of exhausting of assigned service life of high-temperature elements of steam turbines is a relevant problem both in scientific and practical terms.

2. Literature review and problem statement

Although developed countries do not face the economic problems that exist in Ukraine, they extend previously established service life of the power equipment that finished its fleet service life. In the United States [3], while the estimated service life of elements of TPP is from 30 to 40 years, they are supposed to be in operation within up to 50–80 years. Extension of service life of equipment can be up to 20–30 % of the cost of construction of a new thermal power plant, which allows us to consider service life extension quite profitable from the economic point of view.

The cost of extending service life of TPP (England) is determined by the total sum from 30 to 55 pounds per 1 kW of power. Experience of Dutch power engineers on TPP operation suggests possible usage of it within $3\cdot10^5$ h at 3000 starts. Research of Danish specialists on determining of heat-resistant properties of steel, containing chromium, molybdenum and vanadium, after operation for more than 10^5 h allowed us to assess additional service life of metal with values of up to 10^5 hours. Similar data are true for the TPP at Turow (Poland) with ten generating units with capacity of 200 MW. In Russia, equipment that has been in operation for more than $3\cdot10^5$ h is still used [4].

One of the most important stages in calculation of durability of parts of power equipment, operating under conditions of numerous transitional modes, is the choice of safety factors [5]. It is also important to determine the end of service life in the process of operation. This will eliminate sudden brittle destruction due to crack reaching critical dimensions, hermeticity loss, as well as its premature withdrawal from operation without dangerous damage [6].

While determining admissibility of extension of service life of power generating units of 200 MW, it is necessary to assess individual service life of each power generating unit after finishing fleet service life by going through the following stages. The first stage includes technical audit of a power generating unit (assessment of actual operating conditions within the whole operation period of power equipment). The second stage involves estimated calculation of individual service life based on calculation of data of thermal and stress-strain state of K-200-130 turbine considering a change in geometry of the basic elements under major repairs and experimental research in the state of metal of rotors and casings that have been in operation for more than 220,000 hours [7]. The third stage involves control of metal (replicas, visual inspection, ultrasonic inspection, X-ray fault detection, Eddy current inspection, magnet and powder fault detection, color fault detection, laboratory studies of metal clippings, etc.). The final stage includes expert conclusion on extension of service life of high-temperature elements of steam turbines [8].

That is why for extension of service life of power units of 200 MW, it is necessary to perform assessment of the individual service life of K-200-13 turbine based on an integrated approach, combining results of destructive and non-destructive testing of metal with verification calculations of strength [9, 10]. At the stage of control of the state of the basis metal of high-temperature elements of the turbine, employed for a long period of time, it is necessary to explore separately the possibilities of optimal selection of safety factors [10], which is possible in experimental study of metal [11–13]. Complex spatial construction of automatic locking valve (ALV) of high-pressure cylinder (HPC) of heavy-duty steam turbines, existing damage during the operation, high cost of ALV of HPC necessitate a more accurate assessment of residual equipment service life for possible extension of its operation.

3. The aim and objectives of the study

The aim of present research is to design recommendations on the extension of service life for heat-power engineering equipment based on estimated calculations of residual service life of locking valves of HPC of steam turbine K-200-130.

To accomplish the set goal, the following problems had to be solved:

– to perform evaluation of stress-strain state of the valve, for this to carry out calculation taking into account combined influence of temperature gradient and operational internal steam pressure in ALV of HPC;

– to perform calculations of low-cycle fatigue and static damage of casing of ALV of HPC of steam turbine K-200-130-3 of power unit No. 4 at DTEK Kurakhove TPP (Ukraine) and to determine total damage of the metal casing of ALV of HPC;

– to design recommendations and a set of measures to improve reliability of elements of the turbine, to decrease thermal loads and improve operation quality.

4. Materials and methods of research

The research methods include numerical modeling of thermal state (TS), stress-strain state (SSS), as well as individual service life of high-temperature elements of the steam turbine K-200-130 of generating power unit No. 4 at DTEK Kurakhove TPP. In the course of modeling, we applied the software package Solidworks Simulation [14] based on the finite element method.

Simulation of thermal and stress-strain state of automatic locking valve of HPC was carried out in a three-dimensional setting, taking into account the lids of valves. Characteristic points of maximum stress intensities are shown in Fig. 1.

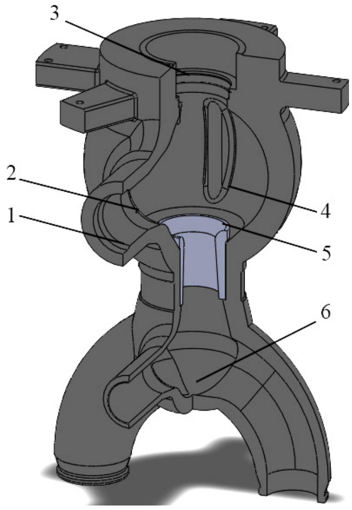


Fig. 1. Calculation model locking valve of HPC with characteristic points of maximum stress intensities: 1 — inlet steam pipeline from steam generator; 2 — inlet steam pipeline into casing of ALV of HPC; 3 — lid of ALV of HPC; 4 — stiffener of ALV of HPC; 5 — seat of ALV of HPC; 6 — outlet steam pipelines from ALV to regulating valves of HPC

Mathematical model for estimation of residual service life of casings of ALV of HPC is given in detail in [8].

A set of works on numerical research on residual service life of casing parts of ALV of HPC of steam turbines with capacity of 200 MW was developed. The studies are based on approximated procedure of assessment of permissible number of cycles before appearance of cracks, total damage, total permissible operating time and residual service time of casing parts.

In the process of estimation of residual service life, the authors took into consideration repair-restoration activities based on the results of non-destructive testing in the planned preventive repairs, conducted during operation extension. Changes in properties of metal of elements of the steam turbine during long operation were also take into account. A number of experimental studies on samples, cut from high-temperature elements, were carried out in order to determine safety factors of steel that have been in operation for more than 220 thousand hours.

When evaluating damageability of individual elements of the turbine in estimated three-dimensional models of locking valves of HPC, some changes in geometry were made. In places of appearance of cracks and cracking zones, metal sampling was made according to the data of last visual inspection of metal of cast casings of valves of turbine K-200-130 in power generating unit No. 4 at DTEK Kurakhove TPP. This enabled us to consider the influence of actual operation on service life characteristics of high-temperature elements of the steam turbine.

5. Results of research on estimation of the residual service life of ALV of HPC

5. 1. Estimated studies of thermal and stress-strain state of ALV of HPC

Estimated studies of thermal and stress-strain state of ALV of HPC of turbine K-200-130 were conducted for proposed by customer operation modes, which are the most characteristic in the practice of operation of thermal power plants, the characteristic of which is given in Table 1. Steam temperature and pressure, as well as electrical loads are taken from the diagrams, provided by the adjustment department at Kurakhove TPP and correspondent to the selected modes.

The data on schedule of starts were taken for high-pressure cylinders. The turbine was put into operation in 1973, by the beginning of 2006, the number of its starts had amounted to 1,611 and operation time was 204,886 hours over the period of the previous estimated study. By 01.02.2017, the number of starts was 2,475, operation time was 261,773 hours.

Table 1

Characteristic of starting modes of power unit No. 4 at DTEK of Kurakhove TPP

Start mode	Temperature of casings of ALV of HPC before starting, °C	Duration of rotor's turn from jolt to synchronization, min	Duration of loading, min
Start from cold state (CS)	100	75	285
Start from non-cooled state (NCS-1)	240	25	180
Start from non-cooled state (NCS-2)	410	15	70

According to data from the Kurakhove TPP, statistics of starts of generating power unit No. 4 from different thermal states over the period from 01.02.1993 to 01.02.2006 is the following: 296 starts after 6–10 hours of downtime, 43 starts after 15–20 hours of downtime, 58 starts after 30–35 hours of downtime, 77 starts after 50–60 hours of downtime and 132 starts from cold state. A total of 606 starts were made from different thermal states.

There is no complete statistics on the types of starting modes at the moment. Based on the data for the period from 01.02.1993 to 01.02.2006, percentage ratio by starting types was calculated. There were 296 (48.8 %) starts by NCS-2 type, 178 (29.4 %) starts by NCS-1 type and respectively, 132 (21.8 %) from CS, and this operation mode continues till the present time. In other words, there were 1,209 (48.8 %) starts by NCS-2 type, 727 (29.4 %) starts by NCS-1 type and, respectively, 539 (21.8 %) starts from CS, in total, there were 2,475 starts from different thermal states.

In geometric modeling, results of control of the parts of turbine K-200-130 of power generating unit No. 4 at DTEK Kurakhovo TPP were taken into account. According to the results of non-destructive testing of the state of metal of casings of ALV of HPC, cracks were found in the upper part of the stiffener of the casing of ALV of HPC. On the lateral surface of the valve, cracking zones and a few cracks of different orientation were detected. Cracks were sampled up to the depth of 20 mm. To account for the impact of these samples in the estimated 3D model of ALV of HPC, the geometry was modified.

Heat transfer boundary conditions for ALV of HPC during the start from non-cooled states NCS-2, NCS-1 and CS correspond to the operation modes (Table 1). Calculation of stress-strain state of the valve for the start mode from non-cooled state by NCS-2, NCS-1 and cold state was conducted from original temperature conditions (Table 1). For estimation of stress-strain state of the valve, calculations were conducted under combined influence of the temperature gradient and the operational internal vapor pressure in ALV of HPC under alternating operation modes.

According to conducted calculations of TS and SSS of the casing of ALV of HPC, the overall level of summary stresses during operation time increased by 5–8 %, which did not have any significant influence on durability of ALV of HPC.

As an example, we show below the temperature fields and corresponding to them distributions of stress intensities under different start modes for moments of time of maximum stresses (Fig. 2–4). Maximum stresses occur at starts from CS and NCS-1. They reach 345 MPa at loading of up to 50 MW and at start from of NCS-1 in the valve lid area, and 274 MPa at the beginning of loading to up to 5–7 MW at start from CS in the area of the valve seat.

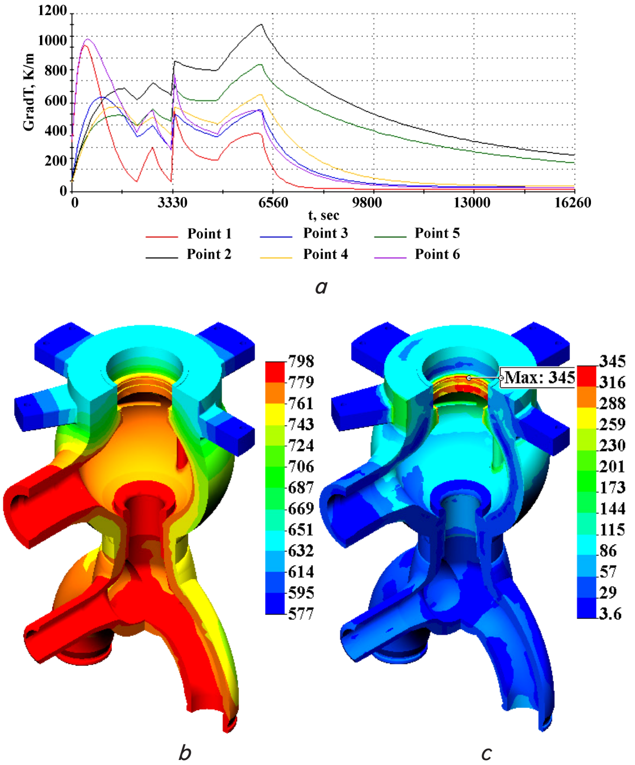


Fig. 2. Thermal and stress-strain state of ALV of HPC at the start from non-cooled state (NS-1): *a* — temperature gradients at the start from NCS-1, K/m; *b* — TS at moment of time 6,100 s; *c* — SSS at the moment of time of 6,100 s, MPa

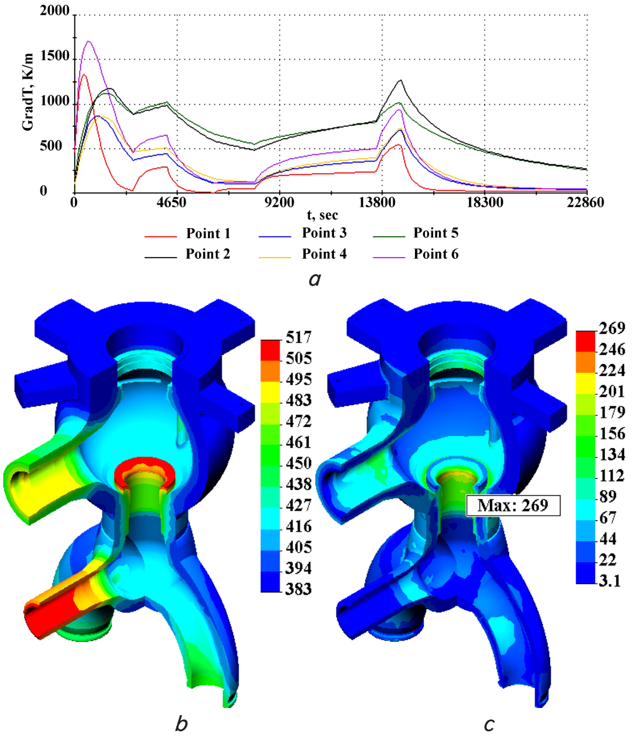


Fig. 3. Thermal and stress-strain state of ALV of HPC at the start from cold state (CS): *a* – temperature gradients at start from CS K/m; *b* – TS at moment of time of 500 s, K; *c* – SSS at the moment of time of 500 s, MPa

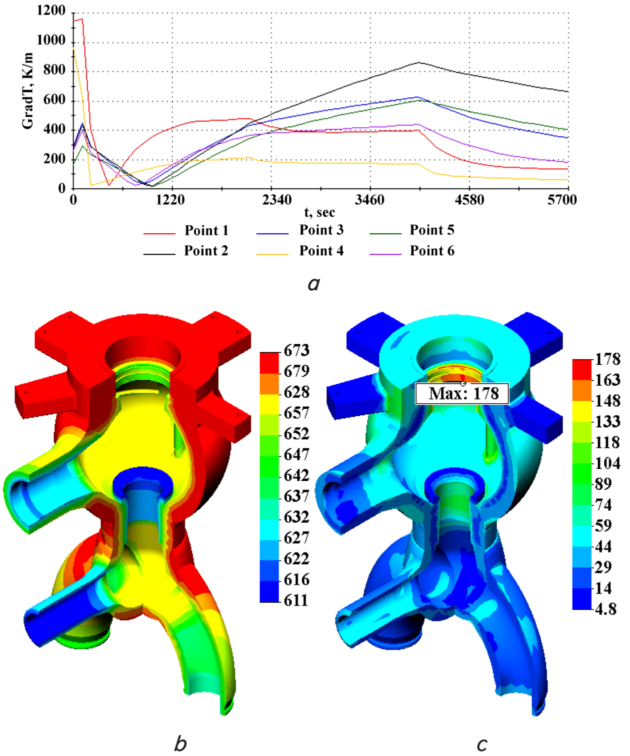


Fig. 4. Thermal and stress-strain state of ALV of HPC at start from non-cooled state (NCS-2): *a* – temperature gradients at start from NCS-2 K/m; *b* – TS at moment of time of 4,000 s, K; *c* – SSS at moment of time of 4,000 s, MPa

The total level of stresses in the casing of ALV of HPC is at the level of 76 205 MPa at starts from CS, 105–230 MPA at starts from of NCS-1, and 54–137 MPa at starts from NCS-2, which does not exceed permissible strength characteristics for this material.

5. 2. Estimated studies of damageability and residual service life of casings of locking valve (ALV of HPC)

Verification calculation of low-cycle fatigue of ALV of HPC of the steam turbine K-200-130 of power generating unit No. 4 of DTEK the Kurakhovo TPP was performed based of analysis of existing loads and temperature fields in valves of HPC of a turbine under typical starting modes. Obtained minimum and maximum values of stress intensities under stationary and transient operation modes of the turbine were taken into account. Damageability of casings of ALV of HPCS according to results of visual inspection, etching, magnetic-powder flaw detection and determining of mechanical properties of the metal of cast parts of the steam turbine was taken into account according to the data of non-destructive testing. Thickness of valves' wall was 84–110 mm, hardness of valves' metal was 154–166 HB.

Calculation was performed by amplitudes of elastic deformations, because values of intensities of elastic deformations met condition [10]. Mathematical model of verification calculation of thermal, stress-strain state and estimation of residual service life of casings of ALV of HPC of steam turbines is shown in detail in [8].

Results of estimation of low-cycle fatigue of metal of casings of ALV of HPC are given in Table 2.

Table 2

Estimation of low-cycle fatigue of metal of casing of ALV of HPC of turbine K-200-130-3 of power generating unit No. 4 at DTEK Kurakhove TPP

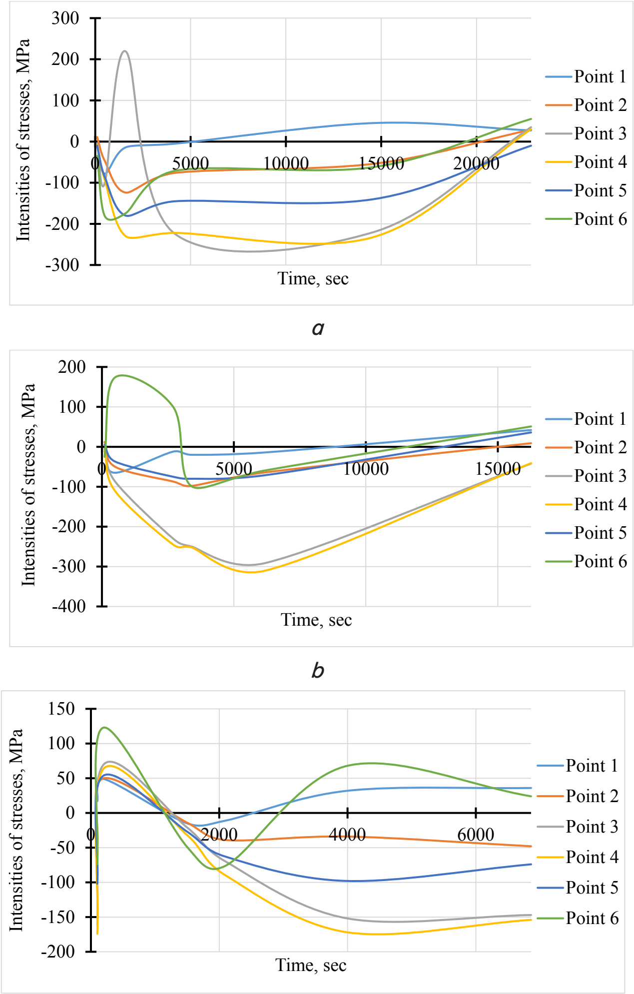
ALV of HPC	Temperature by thickness of valve's wall t_{max}, °C	Intensity of stresses, σ_i, MPa	Reduced deformation, $\varepsilon_{a\ red}$, %	Permissible number of starts, N_{pl}	
				n_N=5 and n_ε=1,5	n_N=3, n_ε=1,25
NCS-2	540	119	0.05803	$>1\cdot10^4$	$>1\cdot10^4$
NCS-1	540	137	0.07637	$>1\cdot10^4$	$>1\cdot10^4$
CS	540	222	0.10825	6,100	9,800

For casing of ALV of HPC of the steam turbine K-200-130-3 of power unit No. 4 at DTEK Kurakhovo TPP, the spans of intensities of stresses for all periods of starts from different thermal conditions were determined by calculation (Fig. 5).

At maximum amplitude of stress intensities, the authors determined intensity of deformations and the permissible number of starts N_{pl} from different thermal states according to regulations of RTM [8].

At heat impacts at the initial stages of starts and at moisture getting into the hot valve, intensities of conditional elastic stresses may increase up to 590–630 MPa. In such cases, permissible number of cycles decreases significantly and could reach a magnitude of order of 2,000–1,900.

Given low-cycle metal fatigue of casings of ALV of HPC of the steam turbine K-300-130-3 (Table 2), estimation of damage and residual service life of casings of ALV of HPC of the steam turbine K-200-130 of power generating unit No. 4 at DTEK Kurakhove TPP is given in Table 3.



a

b

c

Fig. 5. Intensities of stresses in calculation of low-cycle fatigue for the whole period of starts for starting modes of ALV of HPC: *a* – start from CS; *b* – start from NCS-1; *c* – start from NCS-2

Table 3

Estimation of damageability, residual operating time in years and residual service life of casings of ALV of HPC of steam turbine K-200-130 of power unit No. 4 at DTEK Kurakhovo TPP

Entry	Name	Formula	Casing of ALV of HPC	
1	Total number of starts	N_{tot}	2,475	
2	Total operating time	τ_{tot}, h	261,773	
3	Safety factors by cycles/deformations	$n_N \backslash n_\varepsilon$	5\1,5	3\1,25
4	Permissible number of cycles by different types of starts	$[N_{pl}]\ n_{\mathrm{NCS-2}}=1209$	39,000	66,000
		$[N_{pl}]\ n_{\mathrm{NCS-1}}=727$	23,000	40,000
		$[N_{pl}]\ n_{\mathrm{CS}}=539$	6,100	9,800
5	Cyclic damage	$[D_c]=\sum n_l/[N_{pl}]$, %	18.08	10.97
6	Permissible operation time	$[t_{pl}]$, h	3.7×10^5	5.0×10^5
7	Static damage	$[D_{st}]=\sum\tau_{tot}/[t_{pl}]$, %	65.89	48.76
8	Total damage	$[D_\Sigma]=[D_{st}]+[D_c]$, %	83.97	59.73
9	Individual residual service life	$T_{res}=G\cdot\tau_y$, h	46,543	164,383

The total damage of metal of casings of ALV of HPC of the steam turbine K-200-130 of power unit No. 4 at DTEK Kurakhove TPP is 84 %. The estimated residual service life of metal of ALV of HPC is 46,543 h with safety factors by number of cycles and deformations of 5 and 1.5, as well as permissible operation time of metal of 370 thousand hours.

6. Discussion of results of research on residual service life of locking valve's casings (ALV of HPC)

Estimation of individual residual service life of the casings of automatic locking valve of HPC of the turbine K-200-130 showed that this equipment had finished fleet service life of 220 thousand hours. Residual service life of ALV of HPC is 46,543 h, which is less than 50,000 h between planning and preventive repairs of power equipment, standardized by regulations. Therefore, extension of service life of such equipment is not permitted.

On the other hand, visual inspections and non-destructive testing indicate satisfactory state of metal of locking valves. If during the pilot study of valves' metal aging it is possible to allow an increase in safety factors compared with design coefficients, it is possible to extend service life of equipment and to save money. Experimental research in metal of cast casing parts, previously conducted by the authors [5, 8], allowed us to decrease safety factors.

At safety factors by the number of cycles and by deformations at the level of 3 and 1.25, as well as at permissible operation time of metal of 500 thousand h, total damage of metal of casings of ALV of HPC decreases up to 60 %. The estimated residual service life of metal is 164,383 h. This allows further operation of power equipment.

In practice of operation of power equipment, they apply the concept of fleet service life and permissible number of starts that make up 200–220 thousand hours and 600–800 starts for power equipment of the steam turbine plant according to regulations. Estimation of residual service life of ALV of HPC, which was in operation for more than 260 thousand hours and had 2450 starts under operating conditions, made it possible to extend operation time. This increase in service life characteristics can be attributed to excessive safety factors, accepted at the design stage, and a more accurate assessment of residual service life.

The benefits of this study should be considered to include 3D modeling of the researched object, taking into account operational damage in the form of cracks, gullies, cracking zones in modeling, considering variable parameters under starting modes. The results of the study can be extended to the cast casings of automatic locking and safety valves for steam turbines with capacity of 250, 300, 500, 800 MW.

7. Conclusions

1. Calculations of TS and SSS of casing of ALV of HPC under combined effect of temperature gradient and operational of internal steam pressure were performed. In geometric modeling, the valve lid was taken into consideration. The general level of total stresses during operation increased by 5–8 %. Taking the lid into account did not have a significant impact on durability of ALV of HPC.

2. Calculations of low-cycle fatigue and static damage of casings of ALV of HPC of the steam turbine K-200-130-3

of power generating unit No. 4 at DTEK Kurakhovo TPP showed that total damage of metal of casings of ALV of HPC is 84 %. The Expert Commission consisting of representatives of the electric power plant, specialized and other organizations should allow a decrease in safety factor by the number of cycles and by deformations at the level of 3\1.25, as well as accept permissible operation time of metal of the casing at the level of 500 thousand hours. Then the estimated residual service life of metal of casing of ALV of HPC of the turbine K-200-130 of power unit No. 4 at DTEK Kurakhovo TPP will be 164,383 hours. This will make it possible to extend operation of casings of ALV of HPC by 50 thousand hours at the number of starts, equal to half the fleet number, that is 400 starts.

3. To increase reliability of the elements of the turbine, to decrease thermal loads and improve the quality of operation, it is necessary to optimize the number of starts from cold state in direction of a decrease. It is necessary to refine safety factor of metal strength of casings of ALV of HPC by deformations n_ε, the number of cycles n_N, limits of fluidity n_f and safety by nominal stresses n_{ns}. To do this, it is necessary to conduct studies on the impact of ageing on changes in physical-mechanical properties of constructional alloy steels under operational and elevated temperatures.

The results of the performed research can be used by implementing the developed recommendations in large-scale and small-scale power industry.

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