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ASSESSMENT OF RESIDUAL SERVICE LIFE OF CAST BODIES OF CONTROL VALVES OF 220 MW POWER UNITS

Olha Yu. Chernousenko
chernousenko20a@gmail.com
ORCID: 0000-0002-1427-8068

Dmytro V. Ryndiuk
rel_dv@ukr.net
ORCID: 0000-0001-7770-7547

Vitalii A. Peshko
vapeshko@gmail.com
ORCID: 0000-0003-0610-1403

National Technical University of Ukraine "Igor Sikorsky Kyiv Polytechnic Institute",
37, Peremohy Ave., Kyiv,
03056, Ukraine

In the regulatory documents of the Ministry of Energy and Coal Industry of Ukraine, the beyond-design operating life of the high-energy equipment of 220 MW power units is limited to the operating life of 220 thousand hours and 800 start-ups. To date, the high-temperature cast bodies of the control valves for the high- and intermediate-pressure cylinders of the K-200-130 200 MW steam turbines of DTEK Lugansk TPP have operated about 305–330 thousand hours with the total number of start-ups from 1438 to 1704, which exceeded the beyond-design service life characteristics. Therefore, it is necessary to assess the residual operating life of the control valve bodies of the high- and intermediate-pressure cylinders of K-200-130 steam turbines in order to determine the possibility of their further operation. These calculations were carried out on the basis of our earlier studies of the thermal and stress-strain states of cast turbine equipment. This paper establishes the values of stress intensity amplitudes, the values having been reduced to a symmetric loading cycle for the most typical variable operating modes. Using the experimental low-cycle fatigue curves for the 15Kh1M1FL steel, we established the values of the permissible number of start-ups and the cyclic damage accumulated in the base metal. We also determined the value of the static damage accumulated in the course of stationary operating modes according to our previously obtained experimental data on the long-term strength of the 15Kh1M1FL steel. The calculations showed that the total damage to the control valve bodies of the K-200-130 steam turbine of power unit 15 of DTEK Lugansk TPP is 97 and 98%. The residual operating life of the metal of the control valves of high-pressure cylinders is practically exhausted, being equal to 10 thousand hours. The residual life of the control valves of intermediate- pressure cylinders is 7 thousand hours, i.e. it is also practically exhausted, with safety factors for the number of cycles and strains at the level of 5 and 1.5, as well as the permissible 370,000 operating hours of the metal. With an increase in the permissible operating life of the metal to 470 thousand hours, according to experimental studies of Igor Sikorsky KPI, the total damage to the metal of cast valve bodies is reduced to 80%, and the residual metal life increases to 79,000 h and 75,000 h for the control valves of the high- and intermediate-pressure cylinders, respectively.

Keywords: *residual service life, long-term strength, low-cycle fatigue, safety factor, control valve, cast body, steam turbine.*

Introduction

According to the regulatory documents of the Ministry of Energy and Coal Industry of Ukraine, the beyond-design operating life of the high-temperature power equipment of 200 MW power units is limited to the operating life of 220,000 h and 800 start-ups [1]. To date, the high-temperature cast bodies of the control valves (CV) for the high-pressure cylinders (HPC) and intermediate-pressure cylinders (IPC) of 200 MW steam turbines of DTEK Lugansk TPP have operated for about 305,000–330,000 h with a total number of start-ups from 1,438 to 1,704, which exceeded the beyond-design operating life characteristics. A significant excess of design service life indicators carries the danger of emergency equipment failure with serious material costs [2].

A significant shortage of maneuvering capacities in the United Energy System of Ukraine leads to the frequent involvement of 200 MW power units in energy generation regulation. At the same time, the studies carried out [3] show a direct relationship between the number of operational failures of turbine steam distribution bodies and the number of variable operating modes.

The studies carried out [4] have established the most loaded zones of steam turbine CVs where both cracking and fatigue cracks occur. These are the radius round-offs and transitions between the steam inlet or outlet pipes and the steam duct, areas adjacent to the stiffeners inside the steam duct, and the valve seat cage. In these areas, the greatest stresses arise during numerical experiments on the study of the thermally stressed state. At the same time, it has been found that for certain operating conditions, these stresses can exceed the creep limit of valve steel at design metal temperature [5].

The computational studies of the service life indicators of the locking and protective valves of the K-200-130 steam turbine have shown a significant effect on the durability of their operation not only of static, but also of cyclic mechanisms of destruction [6].

Taking into account the above, the problem of assessing the residual service life of the CV bodies of the HPC and IPC of the K-200-130 steam turbine is relevant, and must be solved when justifying the possibility of further operation of this equipment.

Purpose and Objectives of the Study

The purpose of this paper is a calculated assessment of service life indicators and justification of the admissibility of extending the operation of the CVs of the HPC and IPC of the K-200-130 steam turbine of power unit No. 15 of DTEK Lugansk TPP.

To achieve this purpose, we performed:

– a calculation of the amplitudes of the strain intensity in cast CVs and the permissible number of cycles for the most typical operating modes of a 200 MW power unit;

– an assessment of the resistance of valve base metal to the exhaustion of long-term strength and a calculation of the static damage of valve bodies for stationary operating modes;

– a calculated assessment of the residual service life of the CV bodies in the HPC and IPC of the K-200-130 turbine and justification of the possibility of extending their operation.

Assessment of Low-cycle Fatigue of the Control Valves of the HPC and IPC of the K-200-130 Steam Turbine of Unit 15 of DTEK Lugansk TPP

The verification calculation for the low-cycle fatigue of the CVs of the HPC and IPC of the K-200-130 steam turbine of unit No. 15 of DTEK Lugansk TPP was carried out on the basis of the analysis of the acting loads and temperature fields at typical start-up conditions, which we obtained earlier [7]. The obtained maximum and minimum values of stress intensities for stationary and transient operating modes of the turbine are taken into account. The damageability of the bodies of the HPC CVs and IPC CVs is taken into account according to the data of visual inspection, etching, magnetic particle diagnostics, and determination of the mechanical properties of the metal. The calculations were carried out using the amplitudes of elastic strains, since the values of the intensities of elastic strains satisfied the condition [8]. The calculation method for low-cycle fatigue, as well as a mathematical model for calculating the service life indicators of steam turbine equipment is presented in [9].

When performing the calculation for low-cycle fatigue of the body of the CV of the HPC (Fig. 1) of the K-200-130-3 steam turbine, characteristic control points were considered (Fig. 1, a), in which the ranges of intensities of conditional elastic stresses were determined for all the periods of starts from different thermal states (Fig. 1, b, 2). The maximum stress intensities at start-up from the hot thermal state are observed in the steam box at the moment the rotor jerks (estimated time τ=920 s) and amount to 100 MPa. At other times, the stress values do not exceed 90 MPa.

At start-up from the cold thermal state (Fig. 2), the maximum stress intensity σ_i=120 MPa is observed in the seat cage throat of the HPC CV after 5 minutes from the beginning of the preliminary heating of steam lines (estimated time τ=300 s). When the nominal operating mode is reached, all the stresses in the regions under study acquire a tensile nature and amount to 35–70 MPa.

Similar studies were carried out for the IPC CV (Fig. 3, 4). The maximum stress intensities during the hot start-up occur at a time instant of 2,400 s (the turbine is loaded up to 100 MW of electrical power) and is 152 MPa in the area of the welded joint of the steam inlet pipe and the steam duct. Also, high 102 MPa stresses are observed at the same moment in the area of the steam inlet from the side of the automatic protective valve (Fig. 3, b).

At start-up from the cold state (Fig. 4), the most loaded time points for the IPC CV are τ=100 s (2 minutes after the start of the heating of steam lines), τ=2,700 s (rotor jerk) and τ=9,300 s (the beginning of turbine loading after synchronization with the power line). The values of the maximum stresses at these time points are 103, 150, and 139 MPa, respectively.

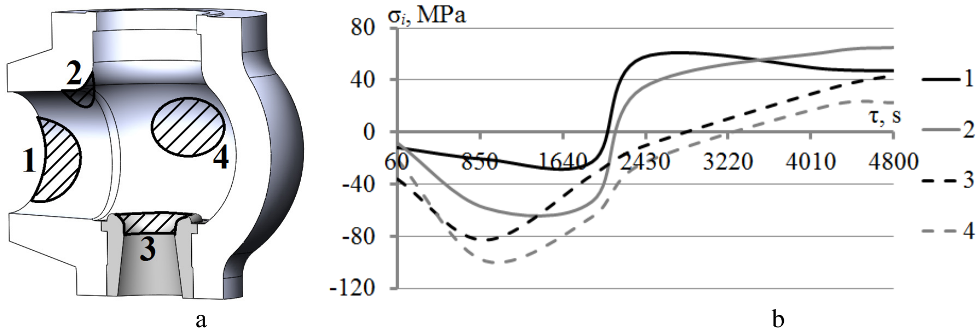

Fig. 1. Dynamics of changes in stress intensity in the HPC CV at start-up from the hot thermal state:
a – characteristic areas of study (1 – steam inlet pipe area, 2 – the radius transition from the steam inlet pipe to the steam box, 3 – valve seat throat, 4 – steam box); b – stress intensity in time

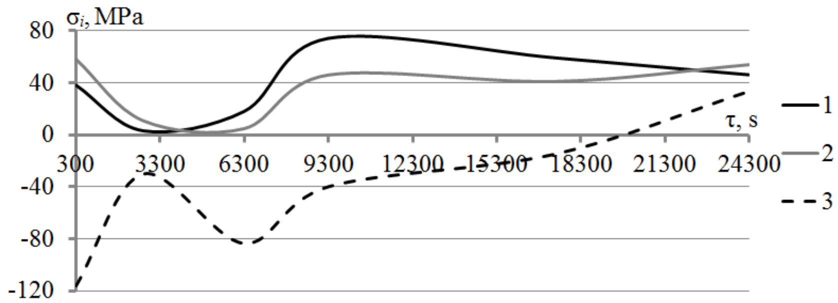

Fig. 2. Dynamics of changes in stress intensity in the HPC CV at start-up from the cold thermal state

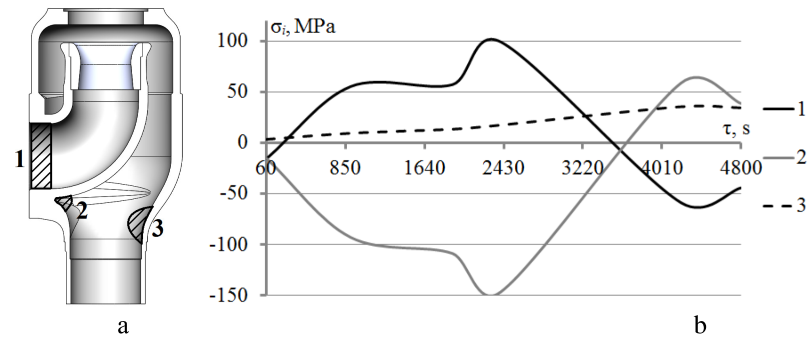

Fig. 3. Dynamics of changes in stress intensity in the IPC CV at start-up from the hot thermal state:
a – characteristic areas of study (1 – steam inlet pipe area, 2 – weld zone of the steam inlet pipe and steam box, 3 – steam box area at the exhaust pipe); b – stress intensity in time

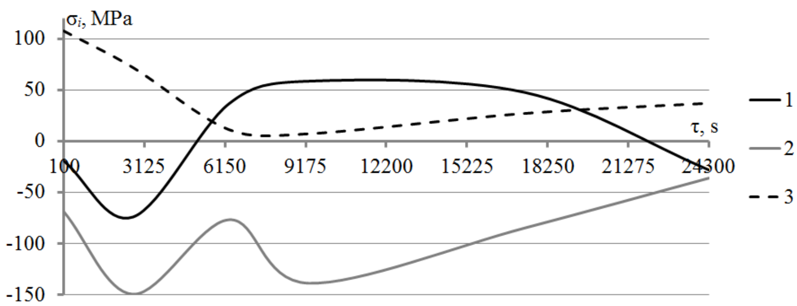

Fig. 4. Dynamics of changes in stress intensity in the IPC CV at start-up from the cold thermal state

Since the maximum stress intensities for all the investigated modes did not exceed the yield stress of the 15Kh1M1FL steel at a temperature of 540 ºC, which is 168 MPa, the plasticity problem was not considered. It should also be noted that the low stress level is explained by the start-up technology at power unit No. 15 of Lugansk TPP, according to which all the start-up modes are performed with fully open CVs, except for the start-up from the hot thermal state, during which the IPC CV changes its flow area (the HPC CV is fully open).

The obtained dynamics of the change in stress intensity makes it possible to establish the strain intensity amplitude value and bring it to a symmetric loading cycle, using the Neuber method [8].

The permissible number of cycles for each start-up mode was determined from the experimental curves of low-cycle fatigue for the 15Kh1M1FL steel for the specified temperature (Tables 1, 2).

For the HPC CV (Table 1), the strain intensity amplitude (reduced to the symmetric loading cycle) for the considered start-up modes is 0.032–0.037%, which corresponds to the permissible number of cycles to destruction, exceeding 10,000. This fact demonstrates that the low-cycle fatigue influences the damage of cast HPC CVs insignificantly, which is associated with favorable conditions for the start-up technology at this TPP.

When carrying out a computational assessment of the low-cycle fatigue of the metal of the K-200-130 turbine IPC CV body (Table 2), the maximum valve wall temperature did not exceed 536–540 ºC. The low level of reduced strain at start-up from the cold thermal state (0.048%) also determines the permissible number of cycles over 10,000. Only at start-up from the hot thermal state, due to a high level of stress amplitude (103 MPa), does the strain amplitude value turn out to be 0.069%. The permissible number of start-ups from the hot thermal state for the IPC CV is 9300.

Table 1. Calculated assessment of the low-cycle fatigue of the HPC CV body metal

Start-up type	Calculated temperature t_{max}, ºC	Stress intensity amplitude in a cycle σ_a, MPa	Reduced strain $\varepsilon_{a\,r}$, %	Permissible number of start-ups N_p at safety factors n_N=5, n_ε=1.5
HS	538	63.50	0.0315	$>1\cdot10^4$
CS	536	74.45	0.0369	$>1\cdot10^4$

Table 2. Calculated assessment of the low-cycle fatigue of the IPC CV body metal

Start-up type	Calculated temperature t_{max}, ºC	Stress intensity amplitude in a cycle σ_a, MPa	Reduced strain $\varepsilon_{a\,r}$, %	Permissible number of start-ups N_p at safety factors n_N=5, n_ε=1.5
HS	540	103.0	0.0692	9300
CS	536	74.9	0.0484	$>1\cdot10^4$

Calculation of the Service Life Indicators of the CVs of the HPC and of IPC the K-200-130 Steam Turbine of Unit No. 15 of DTEK Lugansk TPP and Justification of the Possibility of Extending Their Operation

Taking into account the data on the intensities of conditional elastic stresses during start-ups from various thermal states, as well as the assessment of the low-cycle fatigue of the metal of the CVs of the HPC and IPC of the K-300-130 steam turbine, the calculated assessment of their damage and individual residual lives is presented in Table 3. According to the operation organization, the total number of start-ups is 438 and the total operating time of the power unit for the entire operating period is 305,303 h. The safety factors in the number of cycles n_N=5 and strains n_ε=1.5 were taken according to the recommendations in [8]. According to the calculations, the cyclic damage of the cast body of the HPC CV was 14.4%, and that of the cast body of the IPC CV, 15.3%.

With regard to static damage, it should be noted that for the CV metal, it is 82.5% in the case when the permissible operating time of the CV metal is taken to be 370,000 h. With the admissible operating time of the metal of 470,000 h, according to the data in [6], the static damage of the cast bodies of the CVs of the HPC and IPC decreased to 65%.

Thus, the total damage to the metal of the CV bodies of the HPC and IPC is 97% and 98% with a permissible metal operating time of 370,000 h, and the residual service life is almost completely exhausted, which does not allow the possibility of extending the operation of this equipment.

In the calculation of the permissible operating time of the metal, using the experimental curves of the long-term strength of the 15Kh1M1FL steel [6], the total damage to the CV metal is reduced to 79% and 80%, and the residual life is 79,510 h and 75,200 h for the HPC CV and IPC CV, respectively.

Table 3. Estimated assessment of the service life indicators for the bodies of the CVs of the HPC and IPC of the K-200-300 steam turbine of power unit 15 of DTEK Lugansk TPP

Name	Formula	HPC CV body		IPC CV body	
Total number of start-ups	n_{total}	1438		1438	
Total operating time	τ_{total}, h	305,303		305,303	
Safety factors in the number of cycles/in strains	n_N / n_ε	5 / 1.5		5 / 1.5	
Permissible number of cycles for different types of start-ups	N_{HS}=935	>10,000		9,300	
	N_{WS}=259	>10,000		9,300	
	N_{CS}=244	>10,000		>10,000	
Cyclic damage	$П_{cyclic}=\sum n_1 / N_{pl}$, %	14.4		15.3	
Permissible metal operation time	t_{pl}, h	3.7×10^5	4.7×10^5	3.7×10^5	4.7×10^5
Static damage	$П_{static}=\sum\tau_{total} / t_{pl}$, %	82.5	65.0	82.5	65.0
Total damage	$П_\Sigma=П_{static}+П_{cyclic}$, %	96.9	79.4	97.8	80.3
Individual residual service life	$T_{residual}=G\times\tau_{annual}$, h	9,786	79,510	6,890	75,200

If the expert commission, consisting, according to [1], of representatives of the power plant, manufacturer, specialized and other organizations, can accept the permissible metal operating time at a level of 470,000 h, then the individual residual metal life for the body of the CV of the HPC of the K-200-130 steam turbine is 79,510 h, and that for the body of the CV of the IPC is 75,200 h. This allows us to extend the operation of the bodies of the CVs of the HPC and IPC by 50,000 h with the number of start-ups equal to half of the beyond-design number, i.e. 400 start-ups.

Conclusions

1. The performed calculation for the low-cycle fatigue of the bodies of the CVs of the HPC and IPC showed that the highest value of the amplitude of the stress intensity for the HPC CV is observed during the start-up from the cold thermal state and is 74.5 MPa. For the IPC CV, the highest stress amplitude (103 MPa) is characteristic of the start-up from the hot thermal state. A relatively small strain intensity amplitude value during start-up conditions sets a high permissible number of cycles for the HPC CV (10,000) and IPC CV (9,300).

2. The total damage accumulated in the base metal of the CV bodies for 305,000 h of operation is 79.4% for the HPC and 80.3% for the IPC, with the safety factors for the number of cycles and deformations n_N=5 and n_ε=1.5, respectively, as well as the permissible 470,000 h operating time of the metal.

3. The estimated value of the individual residual life of the cast bodies of the CVs of the HPC and IPC of the K-200-130 turbine is 79,510 h and 75,200 h, respectively. This makes it possible to extend the operation of the bodies of the CVs of the HPC and HPC by 50,000 h, with the residual number of start-ups not exceeding half of the beyond-design number.

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Оцінка залишкового ресурсу литих корпусів регулюючих клапанів енергоблоків потужністю 200 МВт

О. Ю. Черноусенко, Д. В. Риндюк, В. А. Пешко

Національний технічний університет України
«Київський політехнічний інститут імені Ігоря Сікорського»,
03056, Україна, м. Київ, пр. Перемоги, 37

В нормативних документах Міністерства енергетики та вугільної промисловості України парковий ресурс високотемпературного енергетичного обладнання енергоблоків 200 МВт обмежений напрацюванням 220 тис. годин та числом пусків 800. На сьогодні високотемпературні литі корпуси регулюючих клапанів циліндрів високого та середнього тиску парових турбін потужністю 200 МВт енергоблоків ДТЕК Луганська ТЕС відпрацювали близько 305–330 тис. годин за загальної кількості пусків від 1438 до 1704, що перевищує паркові значення. Тому необхідно провести оцінку залишкового ресурсу корпусів регулюючих клапанів циліндрів високого і середнього тиску парової турбіни К-200-130, щоб визначати можливість її подальшої експлуатації. Дані розрахунки виконані на базі дослідження теплового і напружено-деформованого станів литого устаткування турбіни, що виконані авторами раніше. В роботі встановлено значення приведених до симетричного циклу навантаження амплітуд інтенсивності деформацій для найбільш типових змінних режимів роботи. Використовуючи експериментальні криві малоциклової втоми сталі 15Х1М1ФЛ, були встановлені значення допустимого числа пусків і накопичена в основному металі циклічна пошкоджуваність. Значення накопиченої в ході стаціонарних режимів роботи статична пошкоджуваність визначалась згідно з отриманими авторами раніше експериментальними даними щодо довготривалої міцності сталі 15Х1М1ФЛ. Проведені розрахунки показали, що сумарна пошкоджуваність корпусів регулюючих клапанів парової турбіни К-200-130 блока № 15 ДТЕК Луганська ТЕС складає 97 і 98%. Залишковий ресурс металу регулюючих клапанів циліндрів високого тиску практично вичерпаний і становить 10 тис. годин. Залишкове напрацювання регулюючих клапанів циліндрів середнього тиску складає 7 тис. годин, тобто також майже вичерпане, за коефіцієнтів запасу міцності за числом циклів і за деформаціями на рівні 5 і 1,5, відповідно, а також допустимого часу роботи металу 370 тис. годин. При збільшенні допустимого часу роботи металу до 470 тис. годин відповідно до експериментальних досліджень КПІ ім. Ігоря Сікорського сумарна пошкоджуваність металу корпусів клапанів зменшується до 80 %, а залишковий ресурс збільшується до 79 і 75 тис годин для клапанів циліндрів високого і середнього тиску відповідно.

***Ключові слова**: залишковий ресурс, довготривала міцність, малоциклова втома, запас міцності, регулюючий клапан, литий корпус, парова турбіна.*

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STRESS-STRAIN STATE OF STEAM TURBINE LOCK JOINT UNDER PLASTIC DEFORMATION

[1] **Ihor A. Palkov**
igorpalkov1987@gmail.com
ORCID: 0000-0002-4639-6595

[2] **Mykola H. Shulzhenko**
mklshulzhenko@gmail.com
ORCID: 0000-0002-1386-0988

[1] JSC "Turboatom"
199, Moskovskyi Ave.,
Kharkiv, 61037, Ukraine

[2] A. Pidhornyi Institute of Mechanical Engineering Problems of NASU,
2/10, Pozharskyi St.,
Kharkiv, 61046, Ukraine

The stress-strain state problem for the lock joint of the rotor blades of the first stage of the medium-pressure cylinder under plastic deformation is solved. When solving the problem, the theory of elastic-plastic deformations is used. The problem is solved using two different approaches to specifying plastic deformation curves. The applicability of using a simpler bilinear approximation instead of the classical multilinear one is estimated. Based on the example of solving this problem, the time required to perform the calculation with the use of the bilinear and multilinear approximations is shown. Comparison of the results obtained in the form of the distribution of plastic deformations, equivalent stresses, and contact stresses over support pads made it possible to assess the difference when the two types of approximation are used. The obtained result error value when using the bilinear approximation made it possible to draw conclusions about the applicability of this approach to the processing of plastic deformation curves for solving problems of this kind. The problem is solved using the finite element method. To objectively assess the effect of plastic deformation on the redistribution of loads in the lock joint, a finite element model is used, obtained when solving the problem of the thermally stressed state of the rotor blade lock joint. The distribution of contact stresses in the lock joint is shown. The results are compared with those obtained earlier when solving the problem of thermoelasticity. Significant differences in the level of contact stresses are noted. Results of the computational assessment of the stress-strain state of the lock joint of the rotor blades of the first stage of the medium-pressure cylinder of a steam turbine are presented, which allow characterizing the degree of relaxation and redistribution of stresses in the structure in comparison with the results obtained earlier when solving the problem of thermoelasticity. Conclusions are made about the economic viability of using the calculation methods presented.

Keywords*: turbine, lock joint, rotor blade, stress state, deformation curve, yield point.*