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THERMAL AND STRESS-STRAIN STATE OF CAST BODIES OF CONTROL VALVES OF 200 MW POWER UNITS

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200 MW steam turbines of DTEK Lugansk TPP units have operated for about 305–330 thousand hours with a total number of starts from 1.438 to 1,704, as of the end of 2019. The term for extending the operation of high-temperature power equipment between scheduled preventive maintenances has expired. When extending the operation of cylinder bodies and rotors, one should also pay attention to steam distribution elements. A peculiarity of the re-extension of the operation of a 200 MW power unit is the beyond-design operating time of power equipment of more than 250 thousand hours and the operation of equipment in maneuverable modes (more than 1,700 starts from various thermal states), with covering peaks of the electrical load with the excess of the number of starts for certain types of equipment by two to three times. Such a significant number of variable operating modes negatively affects the life cycle of equipment and requires studying the influence of the main damage mechanisms on the metal of cast components. The paper presents a calculated study of the thermal and stress-strain states of high- pressure (HP) and intermediate-pressure (IP) control valves of a K-200-130 turbine. The calculations were carried out using three-dimensional geometric models, as well as taking into account real operating conditions. The geometric model of HP control-valve bodies was constructed taking into account the complex geometry during the transition from the inlet nozzles to the valve vapor volume with a subsequent narrowing of the outlet nozzle section to the control stage of the HP cylinder. Similarly, the geometric model of IP control-valve bodies was constructed taking into account the complex spatial geometry according to the drawings provided by the operating organization. A numerical study of the thermal and stress-strain states was carried out for typical operating modes, using the finite element method. Start-up modes were investigated in a non-stationary setting, while constant ones – in a stationary setting. The thermal states of HP and IP control valves were calculated for three variants of startup modes: cold-startup mode at an initial metal temperature of 100 °C, warm-startup mode at an initial metal temperature of 250 °C, and hot-startup mode at an initial metal temperature of 410 °C. The boundary conditions for thermal state calculations were determined using real and most representative startup schedules provided by the power plant. When calculating thermal states for different startup modes, the dynamics of changes in temperature gradients was taken into consideration. During the stress-strain state studies, the main zones of stress concentration in control valves of a K-200-130 steam turbine were established.

Keywords: *control valve, K-200-130 steam turbine, thermal state, temperature gradients, stress-strain state.*

Introduction

Steam turbines of LMP K-200-130 type were designed for the temperature of live steam and steam after intermediate superheating of 565 °C with a guaranteed service life of 100 thousand hours for high-temperature elements. However, due to the difficulties encountered in adjusting steam generating units to their design parameters, the units had actually operated until 1970 at a steam temperature of 540–565 °C, and since 1971 they operated at a temperature of 530–545 °C. This temperature regime somewhat improved the useful life characteristics of high-temperature elements of steam turbines [1]. The design life of the power equipment of 200 MW power units is 220 thousand hours with the number of starts of 800 according to the regulatory documents of the Ministry of Energy and Coal Industry of Ukraine [2, 3]. In 2005–2009 Igor Sikorsky KPI carried out works to assess the remaining useful life of the high-temperature power equipment of 200 MW power units No. 11, 13–15 of Lugansk TPP, power units Nos. 3–9 of Kurakhovskaya TPP and power unit No. 10 of Starobeshevskaya TPP. Based on the results of those works, the operation of power equipment was extended by 50 thousand hours and 400 starts for each power unit.

As of the end of 2019, 200 MW steam turbines of units No. 9, 11, 13, 14, 15 of DTEK Lugansk TPP had operated for about 305–330 thousand hours with a total number of starts from 1,438 to 1,704. The term of extending the operation of high-temperature power equipment between scheduled preventive maintenance overhauls (50 thousand hours) has expired. According to the recommendations [2], it is necessary to reassess the individual useful life of the HP and IP control valve bodies of a 200 MW K-200-130 steam turbine in order to determine the possibility of a further extension of operation [4].

A feature of the repeated extension of the operation of a power unit is the beyond-design operating time of its power equipment of more than 250 thousand hours. The equipment operates in maneuverable modes (more than 1,700 starts from various thermal states), with covering peaks of the electrical load with the excess of the number of starts for certain types of equipment by two to three times. Such a significant number of variable operating modes negatively affects the life cycle of the equipment and requires studying the influence of the main damage mechanisms on the metal of cast components [5, 6].

Considering, that in practice, cracks are detected after several years of operation, it is of considerable interest to solve the problem with account taken of possible imperfections and defects in valve-body castings, as well as low-cycle fatigue of the material in non-stationary modes [7].

Purpose and Objectives of the Study

The purpose of this paper is a computational study of the thermal and stress-strain states of the HP and IP control valve bodies of the K-200-130 steam turbine of power unit No. 15 of DTEK Lugansk TPP.

To achieve this purpose, we performed:

– an audit of the technical documentation regarding the operating modes of the K-200-130 steam turbine, as well as the results of diagnosing damage to HP and IP control-valve bodies in scheduled preventive maintenance overhauls;

– a computational study of the boundary conditions of heat exchange of HP and IP control-valve bodies in startup and stationary operating modes;

– a computational study of the thermal and stress-strain states of HP and IP control-valve bodies and determination of the most loaded areas.

Research Objects and Features of Geometric Models

The steam distribution system of a K-200-130 steam turbine largely determines its economical and reliable operation. Fresh steam is supplied to the turbine through two steam pipelines with a diameter of 325×38 mm via the main steam valves with a diameter of 250 mm. After them, the steam goes to two automatic check valves with a flow section of 225 mm. Further, through four bypass pipes with a diameter of 273×32 mm, the steam goes to four control valves.

The HP control valves are of unbalanced type, except for valve No. 2. The diameters of valves No. 2, 3, 4 are 150 mm, the diameter of valve No. 1 is 125 mm, the diameter of the overload relief valve is 75 mm.

Once reheated, the steam goes to the IP cylinder through two steam pipelines with a diameter of 630×25 mm via two automatic protective valves of unbalanced type with a diameter of 420 mm.

After the automatic safety valve, the steam goes through four bypass pipes with a diameter of 426×16 mm to the four IP control valves. All IP control valves are of balanced type. The main valve diameters are 325 mm, and the balanced-valve diameters are 105 mm.

The material of HP and IP control-valve bodies is the 15Kh1M1FL alloy steel.

Structurally, the housings of HP and IP control valves are complex technical objects with a developed system of steam inlet and outlet pipes. The design features of HP and IP control-valve bodies make it necessary to model these objects in a three-dimensional setting.

The geometric model of HP control-valve bodies is constructed taking into account the complex geometry during the transition from the inlet nozzles to the vapor volume of the valve with a subsequent narrowing of the outlet nozzle section to the HP-cylinder control stage. Similarly, the geometric model of IP control-valve bodies is constructed taking into account the complex spatial geometry according to the drawings provided by the operating organization.

Regulatory documents [2, 3] in the study of the useful life indicators of the operating power equipment presuppose the obligatory consideration of changes in the structure of the object under consideration during scheduled preventive maintenance overhauls.

In 2018, during the overhaul period of power unit No. 15 of DTEK Lugansk TPP, four HP and four IP control valves were inspected visually, as well as with magnetic particle and dye penetration tests. At the same time, no defects were found on the outer and inner surfaces of the control valves. Therefore, no changes were made to the design structure.

The models used to calculate the thermal and stress-strain states are shown in Fig. 1.

Design Study of the Thermal and Stress-Strain States of HP and IP Control-Valve Bodies for the K-200-130 Steam Turbine of Power Unit No. 15 of DTEK Lugansk TPP

Computational studies of the thermal state of HP and IP control valves were carried out both in a non-stationary setting for variable operating modes and in a stationary setting for constant modes. In this case, the finite element method was used to discretize the computational domain. When creating a computational mesh, tetrahedral elements were used, the size of which decreased closer to the boundary of solids, and especially in the areas of presumptive stress concentrators. The total number of finite elements for an HP control valve is over 370 thousand, while for an IP control valve it is over 580 thousand.

The thermal states of HP and IP control valves were calculated for three variants of startup modes: cold startup mode at an initial metal temperature of $t_{0м}$=100 °C, warm startup mode at an initial metal temperature of $t_{0м}$=250 °C, and hot startup mode at an initial metal temperature of $t_{0м}$=410 °C [8]. The boundary conditions for thermal state calculations were determined using real and most representative start-up schedules provided by the power plant.

According to the start-up technology used at power unit No. 15 of DTEK Lugansk TPP, the rotor jerk, spin-up and power ascension are carried out with fully open control valves, which greatly simplifies the calculation of the boundary conditions of heat transfer for start-up operating modes.

For all valve surfaces, the second- and third-type boundary conditions were calculated and set. So, for the outer valve surfaces, second-type boundary conditions q=0 W/m^2 were set. For the upper section, where the valve cover is seated, the non-stationary heat flux was calculated for the entire start-up term.

The inner valve surface was divided into several characteristic areas, for which third-type boundary conditions were calculated based on the thermodynamic calculation of variable operating modes. The heat transfer coefficients were determined according to the classical criterion equation of the form

$$\mathrm{Nu}=0.021\cdot\mathrm{Re}^{0.8}\cdot\mathrm{Pr}^{0.43}.$$

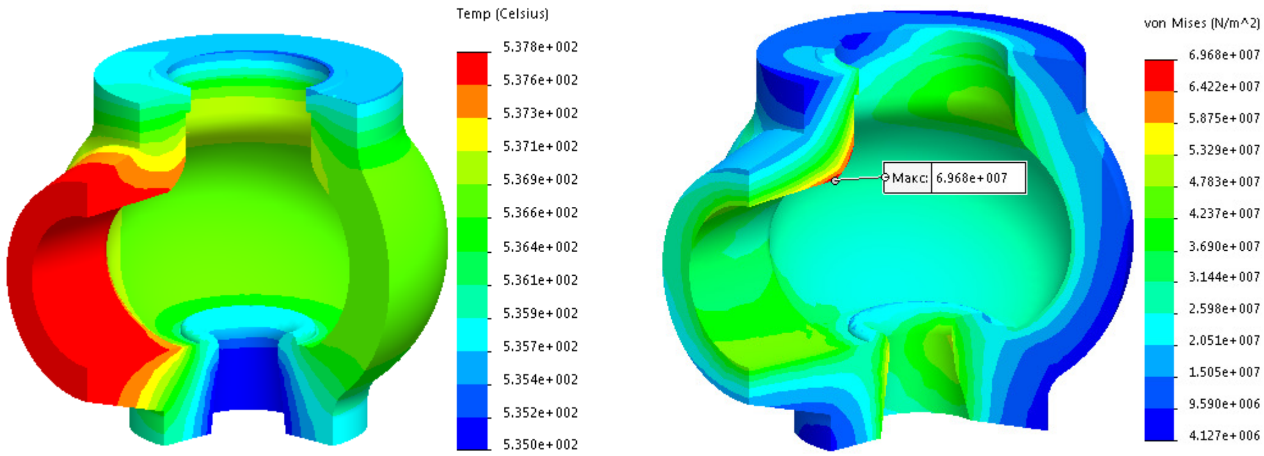
The determining sizes and velocities for each area were selected separately.

Based on the obtained thermal states of the control valves, the stress-strain state was also calculated. The main stresses that formed the stress-strain state of the valves were: temperature, stress from uneven temperature fields and from the pressure of the vapor medium. A detailed description of the used algorithm for calculating the thermal and stress-strain states of high-temperature TPP elements is given in [8–10]. Below are the results of calculating the HP and IP control valves of the K-200-130 steam turbine of power unit No. 15 of DTEK Lugansk TPP.

According to the results of the calculation of the thermal and stress-strain states of the HP control valve (Fig. 1) at the rated turbine power (200 MW), it was found that due to the simplicity of the design and full opening of the control valve, the temperature field is uniform. The maximum metal temperature $t_м$=538 ºC is observed in the area of the steam inlet pipe, which gradually decreases closer to the exhaust pipe. The highest stress intensity at the nominal operating mode σ_i=69.7 MPa is located in the area of the upper radius rounding between the steam inlet pipe and the valve steam duct.

Likewise, for the IP control valve (Fig. 2), the temperature field at the nominal operating mode is uniform. The highest metal temperature $t_м$=539 ºC is typical for the valve throat and the exhaust pipe (Fig. 2, a). A lower temperature is observed in the area of the control-valve cover and its support brackets $t_м$=489–515 ºC.

The stress level (Fig. 2, b) is also rather low. The maximum stress intensity is manifested in the area of the welded joint of the steam inlet pipe and the valve steam duct σ_i=36.4 MPa.



a b

Fig. 1. Computational study of the HP control valve in a stationary operating mode:
a – thermal state; b – stress-strain state

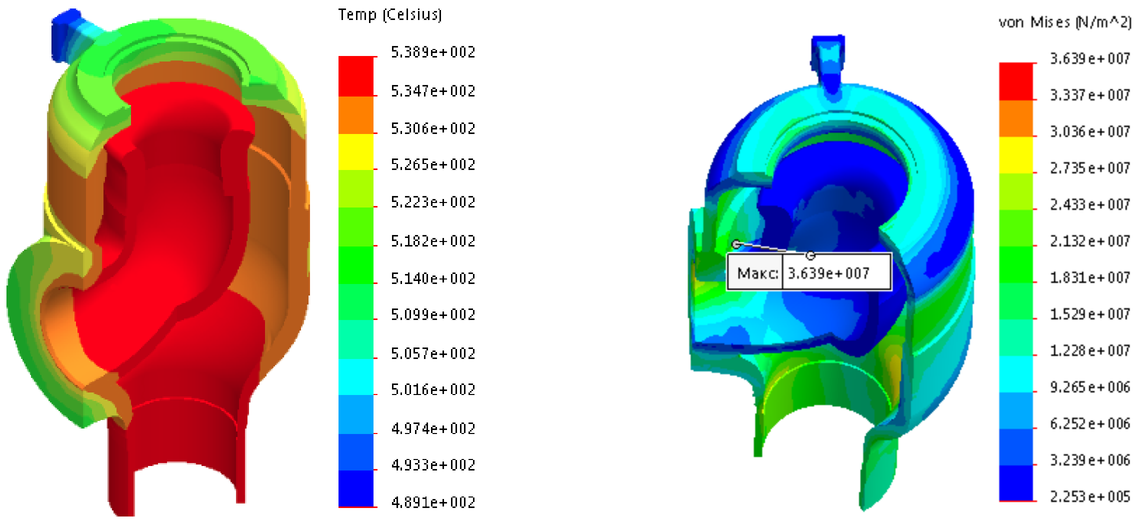


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Fig. 2. Computational study of the IP control valve in the stationary operating mode:
a – thermal state; b – stress-strain state

As noted earlier, the variable operating modes were studied in a non-stationary setting. Of particular interest for startup operating modes is the dynamics of temperature gradients, which makes it possible to establish those points in time at which the forces from the unevenness of temperature fields will have the highest effect on the stress-strain state.

Temperature gradients for the cold start-up are shown in Fig. 3 for some characteristic areas of the valve (denoted by figures in Fig. 3, a). Zones for investigating the uneven heating of: 1 – steam inlet pipe, 2 – radial rounding of the steam inlet pipe and valve steam duct, 3 – cover zone, 4 – valve steam duct, 5 – upper part of the seat cage, 6 – seat cage throat. In value, the temperature gradients are small, which indicates a uniform heating of the metal of the HP control valve during the cold start-up. The largest temperature gradient grad T=1186 K/m is observed for the upper part of the seat cage at time 6300 sec. This time corresponds to the beginning of the rotor spin-up after the delay at a frequency of 600 rpm.

The thermal and stress-strain states of the HP control valve for the same time is shown in Fig. 4. The highest metal temperature $t_м$=275 °C is characteristic just of the upper part of the valve seat cage, while the stresses in this area are about 63 MPa. The greatest stresses at this time, σ_i=83.4 MPa, are in the area of the valve throat.

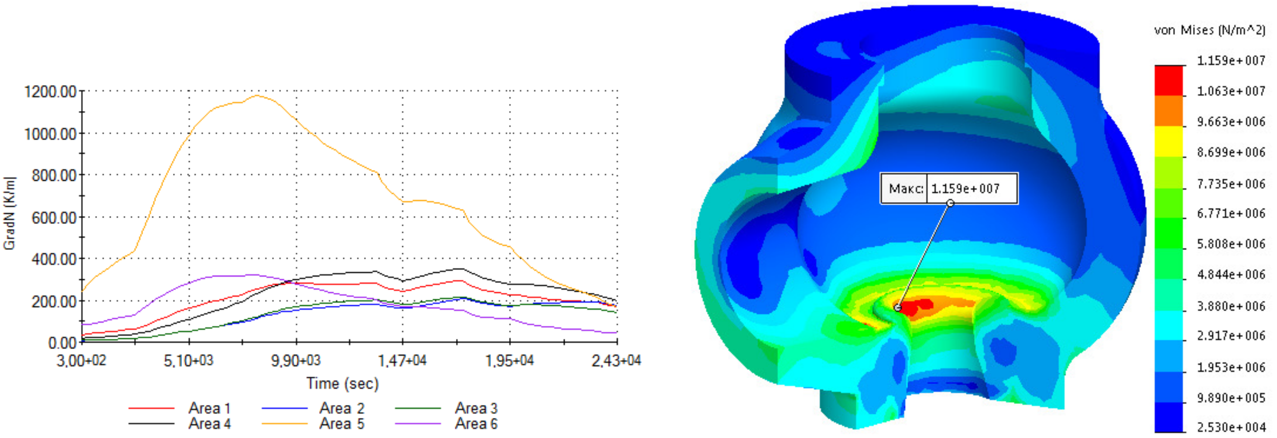

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Fig. 3. Results of calculating the HP control valve during the cold start:
a – temperature gradients; b – stress-strain state at time 300 sec

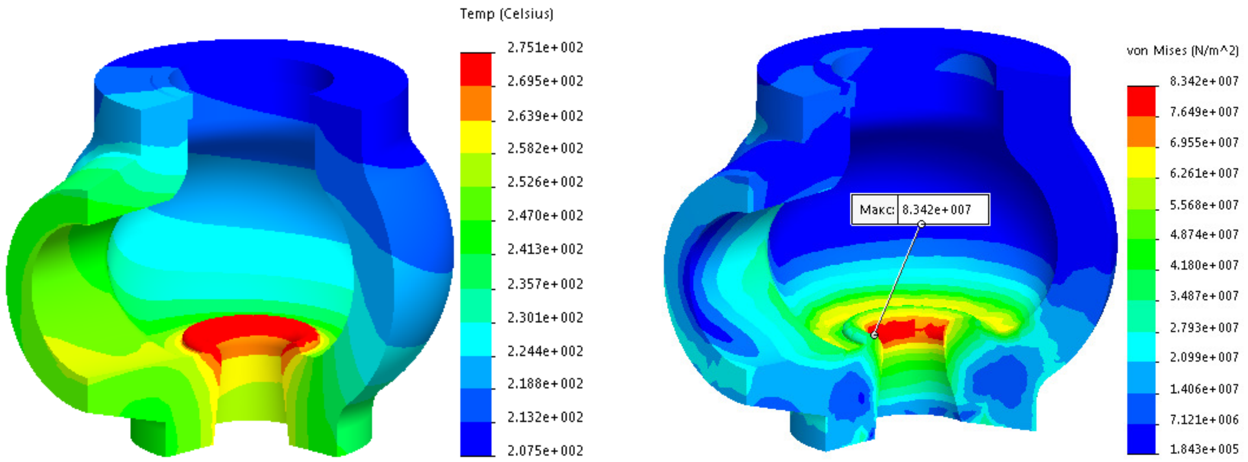

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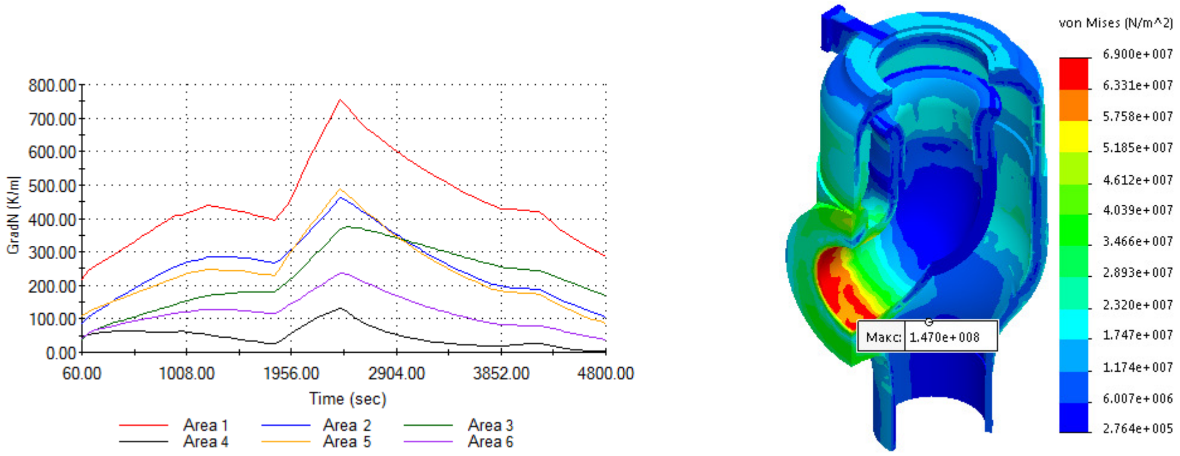
Fig. 4. Results of calculating the HP control valve during the cold start at time 6300 sec:
a – thermal state, b – stress-strain state

The maximum stresses in the HP control valve during the cold start-up are observed at time 300 sec. This time corresponds to an increase in steam consumption for heating the steam pipelines and a more significant opening of the main steam valve. The valve-throat stress intensity σ_i=115.9 MPa.

Calculations were carried out in a similar way for other typical operating modes.

Fig. 5 shows the temperature gradients for the IP control valve during the start from the hot metal state. Typical areas of research were (Fig. 5, a): 1 – steam inlet pipe, 2 – welded seam of steam inlet and exhaust pipes, 3 – cover zone, 4 – seat cage throat, 5 – inner chamfer of the valve steam duct, 6 – valve steam duct. The values of the temperature gradients of IP control valves, as well as HP control valves, are relatively small. The peak value grad T=753 K/m occurs at time 2,400 sec, which corresponds to the beginning of turbine loading up to 100 MW and the admission of the nominal amount of steam.

At the same time, the maximum stress intensities σ_i=147 MPa appear for the entire hot start-up cycle (Fig. 5, b). The zone of occurrence of the maximum stress is the weld between the steam inlet and exhaust pipes. The value of stresses in the region of occurrence of the maximum temperature gradient σ_i=91.1 MPa for the given time.



a b

Fig. 5. Results of calculating the IP control valve during the hot start:
a – temperature gradients; b – stress-strain state at time 2400 sec

Similar data were obtained for all typical operating modes. Since the maximum stress intensities for all 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.

The performed computational studies of the thermal and stress-strain states of HP and IP control valves make it possible to assess their remaining useful life and make a decision about the admissibility of extending the operation of the cast bodies of the K-200-130 steam turbine of power unit No. 15 of DTEK Lugansk TPP.

Conclusions

1. For the control valves of the K-200-130 steam turbine, numerical studies of the thermal and stress-strain states have been carried out on the basis of three-dimensional analogs. Typical operating modes have been considered, including stationary operation, starts-ups from cold, warm and hot states.

2. The results of the study of temperature gradients and fields in a non-stationary setting make it possible to assert a fairly uniform heating of control valves for all types of start-ups. The stress intensity values for all variable operating modes do not exceed the yield strength of the 15Kh1M1FL steel at a temperature of 540 ºC, which is 168 MPa.

3. The highest stress intensities are observed in the areas of the valve seat, steam inlet pipe, as well as welded joints and radius roundings of the steam inlet pipe and valve steam duct.

4. In the nominal operating mode, the maximum stress intensity for the HP control valve is σ_i=69.7 MPa and for the IP control valve, σ_i=36.4 MPa.

5. The performed computational studies of the thermal and stress-strain states of HP and IP control valves allow us to assess their remaining useful life and make a decision on the admissibility of extending the operation of the cast bodies of the K-200-130 steam turbine at power unit No. 15 of DTEK Lugansk TPP.

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Тепловий і напружено-деформований стан литих корпусів регулюючих клапанів енергоблоків потужністю 200 МВт

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Парові турбіни потужністю 200 МВт енергоблоків ДТЕК «Луганська ТЕС» відпрацювали близько 305–330 тисяч годин за загального числа пусків від 1438 до 1704 станом на кінець 2019 року. Термін продовження експлуатації високотемпературного енергетичного обладнання між планово-попереджувальними ремонтами закінчився. Продовжуючи експлуатацію корпусів циліндрів і роторів, слід приділити увагу й органам паророзподілу. Особливістю повторного продовження експлуатації енергоблоку потужністю 200 МВт є понадпаркове напрацювання енергетичного обладнання більше 250 тисяч годин і робота обладнання в маневрених режимах (понад 1700 пусків з різних теплових станів) під час покриття піків електричного навантаження з перевищенням кількості пусків для окремих типів обладнання в два-три рази. Таке значне число змінних режимів роботи негативно впливає на довговічність роботи обладнання і вимагає вивчення впливу основних механізмів пошкоджуваності на метал литих деталей. В роботі наведено розрахункове дослідження теплового і напружено-деформованого стану регулюючих клапанів циліндрів високого (ЦВТ) і середнього тиску (ЦСТ) турбіни К-200-130. Розрахунки проведені з використанням тривимірних геометричних моделей, а також з урахуванням реальних умов експлуатації. Геометрична модель корпусів регулюючих клапанів ЦВТ побудована з урахуванням складної геометрії під час переходу від підвідних патрубків до парового об'єму клапана з подальшим звуженням перерізу відвідного патрубка до регулюючого ступеня ЦВТ. Аналогічно геометрична модель корпусів регулюючих клапанів ЦСТ побудована з урахуванням складної просторової геометрії згідно з кресленнями, наданими експлуатуючою організацією. Чисельне дослідження теплового і напру-

жено-деформованого стану проведено для типових режимів експлуатації з використанням методу скінченних елементів. Пускові режими досліджувалися в нестаціонарній постановці, постійні режими – в стаціонарній. Тепловий стан регулюючих клапанів ЦВТ і ЦСТ розраховувався для трьох варіантів пускових режимів: пуск з холодного стану за початкової температури металу 100 °С, з неостиглого стану за початкової температури металу 250 °С і з гарячого стану за початкової температури металу 410 °С. Граничні умови для розрахунку теплового стану визначалися з використанням реальних і найбільш характерних пускових графіків, наданих електростанцією. За розрахунків теплового стану для різних пускових режимів розглянуто динаміку зміни градієнтів температур. В ході дослідження напружено-деформованого стану встановлено основні зони концентрації напружень в регулюючих клапанах парової турбіни К-200-130.

***Ключові слова**: регулюючий клапан, парова турбіна, К-200-130, тепловий стан, градієнти температур, напружено-деформований стан.*

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