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ROTOR HEATING CONDITIONS INFLUENCE ON THE THERMOSTRUCTURAL STATE AND LIFETIME OF THE 325 MW STEAM TURBINE DURING START-UPS

Виконано розрахункове дослідження теплового і термонапруженого стану ротора циліндра високого тиску парової турбіни потужністю 325 МВт на етапах прогріву і пуску із холодного стану. Для визначення нестаціонарного теплового стану, розроблена методика, що дозволяє визначити граничні умови теплообміну з високою точністю завдяки врахуванню процесу конденсації пари на поверхнях ротора і ступеня дискретизації теплових зон для призначення граничних умов. Врахування процесу конденсації у міжкорпусному просторі дозволило точніше визначити параметри пара на елементах ущільнень ротора. Базуючись на результатах дослідження, запропоновано зміну конструкції і умов прогріву ротора в області переднього кінцевого ущільнення на етапі підготовки до пуску з холодного стану. Показана можливість зниження рівня термічних напружень і вплив умов прогріву на ресурс турбіни.

Ключові слова: парова турбіна, термоміцнісний розрахунок, малоциклова втома, теплопередача, конденсація.

Выполнено расчетное исследование теплового и термонапряженного состояния ротора цилиндра высокого давления паровой турбины мощностью 325 МВт на этапах прогрева и пуска из холодного состояния. Для определения нестационарного теплового состояния, разработана методика, позволяющая определить граничные условия теплообмена с высокой точностью благодаря учету процесса конденсации пара на поверхностях ротора и степени дискретизации тепловых зон для назначения граничных условий. Учет процесса конденсации в межкорпусном пространстве позволил более точно определить параметры пара на элементах уплотнений ротора. Базируясь на результатах исследования, предложено изменение конструкции и условий прогрева ротора в области переднего концевого уплотнения на этапе подготовки к пуску из холодного состояния. Показана возможность снижения уровня термических напряжений и влияние условий прогрева на ресурс турбины.

Ключевые слова: паровая турбина, термопрочностной расчет, малоцикловая усталость, теплопередача, конденсация.

Thermal and thermostructural study for the 325 MW steam turbine high pressure cylinder rotor during pre-warming phase and cold start-up has been performed. To determine rotor transient thermal state with highest accuracy, the improved methodology was developed. According the approach, steam characteristics in rotor flow path and end seals regions have been calculated taking into the account leakages through drainages and specificity of turbine heating through exhaust hood. The highest accuracy of the method was provided by realistic prediction of the condensation process on rotor surfaces and simulation of the convection heating conditions taking to the account condensation influence. Based on the study, the front-end seals design changes and pre-warming process modification have been proposed. The thermo-structural and lifetime analyses results for the baseline and modified designs have been presented and discussed in the article.

Key words: steam turbine, thermo-structural analysis, low cycle fatigue, heat transfer, condensation.

Introduction. The lack of peaking power generating units in the energy sector of Ukraine compel the power plants operators to perform more frequent start-up events for 200-300 MW steam turbines [1]. These actions result in much higher levels of a lifetime consumption for primary turbine components.

The exploitation experience shows that for significant number of units with power 150-300 MW, which were in operation more than 50 k hours, circumferential cracks were observed in the high temperature rotors at the front-end seals zones and seals behind the control stage [2]. In all cases cracks were the result of high thermal stresses in the regions of stress concentrators, such as small fillets, thermo-compensation slots, grooves, etc.

The main factor that limits the number of turbine start-upsis high thermal stresses at the transient operation which results in low cycle fatigue(LCF) of components material. Thermal stresses occur in the turbine rotor and casing high-temperaturecomponents (high pressureHP and intermediate pressure IP cylinders). Steam turbine component transient thermal state directly influence on structural and lifetime analyses result and depend on the accuracy of calculated thermal boundary conditions (BC).

One of the factors that can accelerate LCF life consumption is condensation process, which usually takes place during the turbine pre-heating phase and at the initial phase of cold start-up (CS) and continues until the rotor surface temperature becomes higher than the surrounding steam saturation temperature.

Convection BCsimulation accuracy and, especially, the effect of steam condensation during CS, are the key factors to realistically predict turbine unit thermal state during transients.

A large number of studies have been devoted to the thermal and thermostructural analysis of the steam turbine elements [3, 4, 5]. Widely used practice for steam turbine component convection conditions determination is to apply correlations based on the Dittus-Boelter equation for turbulent pipe flow to calculate heat transfer coefficients (HTC) [1, 5, 6]. Due to complexity and uncertainties for 'condensation' conditions simulation, in most cases researchers ignore this effect, decreasing the accuracy of the results. Some information for the 'condensation' conditions simulation in steam turbine components is presented in monographs 0 and 0.

The purpose of the present study is to increase the start-up number for 325 MW steam turbine by design improvement. To reach the goal, following tasks will be solved in this study:

1) Improve the methodology for steam turbine thermo-structural analysis at start-up regimes to increase the accuracy by

(a) ‘Condensation’ effect simulation (determination of start and end time of condensation process, ‘condensation’ conditions calculation utilization in thermal analysis);

(b)Account the effect of jet flow for regions with anticipated high level of stresses (front-end seal zone) by refining corresponding zones for convection conditions simulation;

(c) Flow parameters determination in seal chambers taking into the account inter-casing space condensation;

2) Calculate thermo-stress state for base line design and reveal critical zones with regards to LCF;

Suggest heating conditions and design changes;

3) Estimate the influence of the proposed design on the steam turbine LCF life.

Background. About 50 % of all steam turbines, which are used in fossil power plants in Ukraine today, are the models K-300-240 and K-300-240-2 (PJSC ‘Turboatom‘). All these turbines are in operation approximately200-290 k hours which exceedthe design life.K-325-23,5supercritical parameters steam turbine (fig. 1) was developed by PJSC ‘Turboatom‘ to replace old work off machines and increase the efficiency and reliability of the power plants.

For similar steam turbines, as shown in [2], the most critical region with regards to LCF cracking is HP rotor front-end seal zone. To estimate rotor LCF lifetime, thermal and thermo-structural analysis for the component has been performed and discussed in this article.

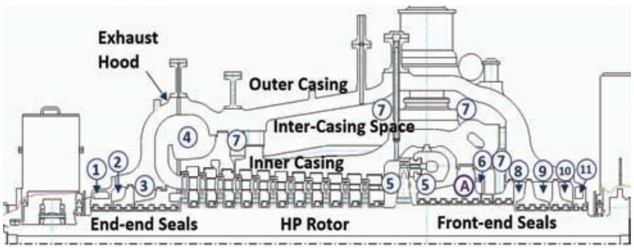


Figure 1 – 325 MW Steam Turbine HP Cylinder Cross Section

Thermo-structural Analysis. Cold start-up (including turbine pre-warming phase) and shut down will be considered in this study. Start-up diagrams, recommended by OEM for K-325-23,5 steam turbine cold start-up,are presented in the fig. 2.

Cold start-up process for the steam turbine can be divided into 3 phases. At first phase (reaching the vacuum, 0 – 90 min) the steam with the temperature of 180 ^{o}Cand pressure of 130 kPa comes to the end seals chambers#2 and #10 (fig. 1). The seal'sejector is activated and the pressure in chambers #1 and #11 becomes of 97 kPa.

At the second period of start-up (90 – 180 min), the steam with the temperature of 190 ^{o}C flows from the boiler through the cold reheater steam pipes to exhaust hood. During 15 min steam temperature increases up to 290 ^{o}C. The steam from exhaust hood goes through 9th chamber ring slot to inter-casing space and then to the front-end seal chamber #7. In this case a portion of the steam flows from exhaust hood through the turbine flow path to the front-end seals. Because of this the pressures from both sides of the carrier ‘A’ are almost the same, which result in negligible steam flow between 5th and 6th front end seals chambers and lack of rotor pre-heating in this region during whole pre-warming phase. As a result, at further steps of cold start-up the HP rotor zone under carrier ‘A’ may be overstressed.

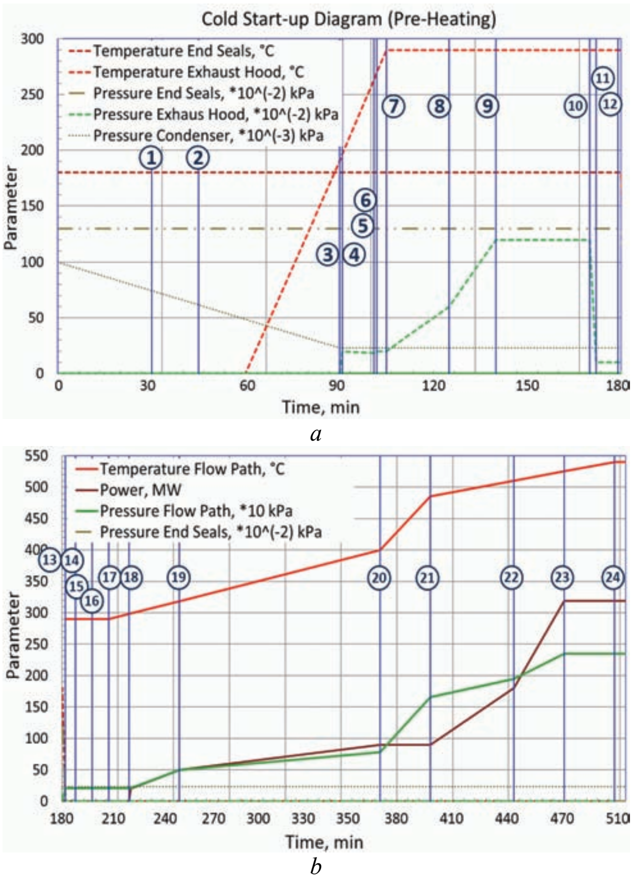


Figure 2 – Cold Start-up Diagrams with Simulation Time Steps: *a* – Pre-warming Phase, *b* – Cold Start-up

At the third phase of cold start-up: main steam goes into the flow path, rotor starts to spin and rotation speed increases. Next steps are ramping-up to the idle mode, synchronization and reaching the nominal power (see fig. 2, *b*).

To simulate transient heating process start-up sequence was divided into time steps. For each time step (see fig. 2), ***steamflow parameters*** in the flow path and rotor gland seals/chambers were determined utilizing methodology developed by authors and described in [9].

The methodology allows to calculate steam parameters and flow characteristics in the end seals and accounts for steam leakages in each chamber (see fig. 1). End seals chambers pressure was determined, taking into account the hydraulic resistance of the drainage system elements, bypass steam pipes, and inter-casing space.

To simulate flow characteristics in end seals chambers for the period of heating from exhaust hood, described above, the special approach was developed. The approach allows to calculate heating conditions in inter-casing space and estimate the amount of condensed steam in inter-casing space before the steam reach the chamber #7 to predict the flow characteristics in the chamber with high accuracy.

To simulate ***heat convection conditions***, rotor surface was split into thermal zones with convection conditions identical or very close within each zone – see fig. 3.

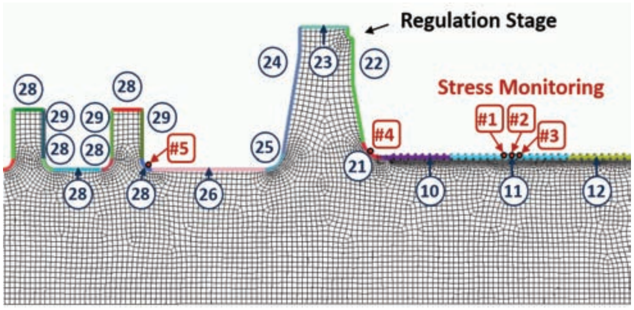


Figure 3 – FE Model Fragment and Heat Convection Zones

The BCs of the third kind (HTC and steam temperature) for the cases of single-phase flow and flow with condensation have been calculated following [9] for all rotor surfaces. Convection conditions for HP rotor sealing zones (sealing groves) for the single-phase flow are calculated taking into the account jet flow and turbulent pulsation of working fluid velocity [10].

Finite element (FE) method was used to simulate thermal and thermo-structural state. 2D axisymmetric FE model based on 8-node quadrilateral plane elements (with axisymmetric option) has been developed for transient analyses. Mesh refinements were done in the regions of potential stress concentration, such as fillets, groves at sealing zones, etc. (see fig. 3).

To predict steam condensation during turbine heating, a special algorithm for transient ***thermal analysis*** has been developed. According to the methodology, for each local thermal zone (fig. 3) at each time during start-up, the temperature of the rotor surface was monitored and compared against saturation temperature of the steam surrounding this zone. If local saturation temperature for any zone is higher than that of local rotor metal temperature, the condensation process was assumed and 'condensation' HTC and steam saturation temperature are applied to this particular zone as a thermal BCs. In other case, when rotor surface temperature is higher than steam saturation temperature, HTCs were calculated with the assumption of single-phase flow and the superheated steam temperature is used for convection BCs.

Figure 3 shows calculated HP rotor temperature distribution for baseline model during pre-warming, CS, and steady state operation. It can be observed that at front-end seals region high-temperature gradients take place at time 105, 140 and 182 min. from the beginning of the turbine start-up. Another peculiarity of the baseline turbine design and start-up sequence is that a rotor portion between chambers 5 and 7 (see fig. 1) remains cold up to the time 180 min, when the rotor starts to spin.

Design Modification. To improve heating conditions for the HP rotor and overcome potential problems with high stresses, the design changes in the region of front end seals (see fig. 5) and modified start-up process have been proposed. Modified design (fig. 5b) contains three insertions in the inner carrier 'A', which forms chambers 12 – 14. The slot from chamber 7 has been made instead of chamber 6 slot. Carrier under chamber 7 contains three seal rings.

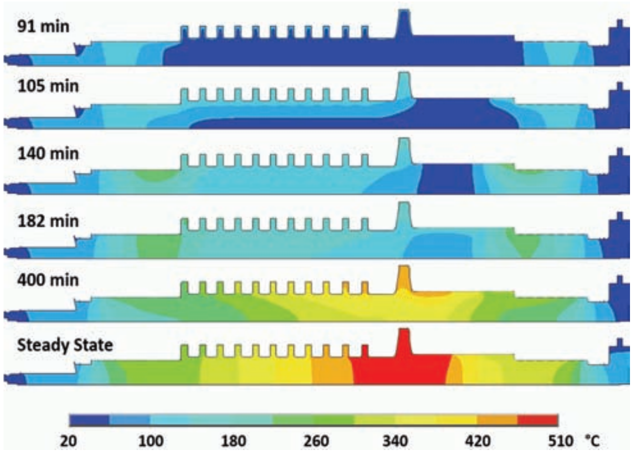
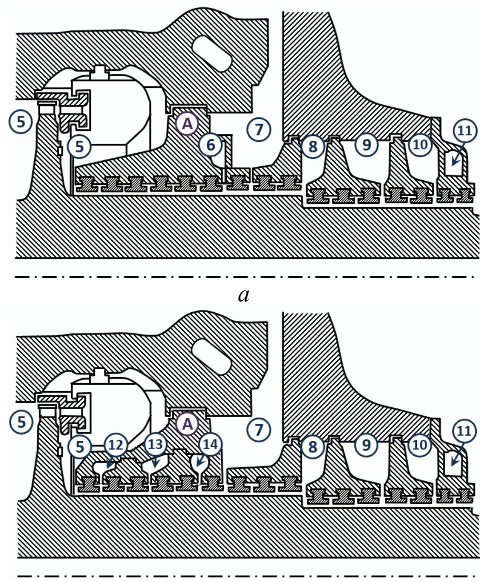


Figure 4 – Rotor Thermal State during CS (Baseline Design)



a

b

Figure 5 – Front End Seals Design: (*a*) Baseline; (*b*) Modified

At the first phase of start-up, steam from steam header additionally comes to the chambers 8, 12 and 14. Steam parameters for this case are equal to parameters in chambers 2 and 10 (temperature T = 180 °C, pressure P = 130 kPa).

At the second phase of start-up, the steam goes from cold reheater through the exhaust hood to 13th chamber with the similar to flow path and inter-casing space parameters. Chambers 3, 9, 12 and 14 are connected to the condenser.

Thermal analysis has been performed for the modified design according to approaches described above. Rotor thermal state during cold start-up for the modified design is presented in fig. 6. Thermal analysis results show that at pre-warming phase rotor portion under carrier 'A' is heated more uniformly and intensively in comparison with the baseline design.

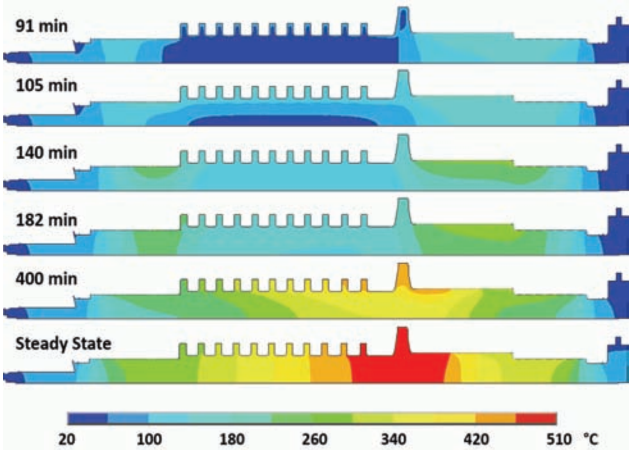


Figure 6 – Rotor Thermal State during CS (Modified Design)

Rotor ***structural analysis***has been done in elasto-plastic formulation. The effect of material plasticity was taken into the account to estimate total deformations in critical rotor regions and LCF life with high accuracy. Experimental stress-strain and strain-life data at room and elevated temperatures for the rotor steel grade 20H3MVFA have been used and can be found in [11]. The rotor material assumed to be cyclically hardened and the multi-linear kinematic hardening plasticity model has been applied for the thermo-structural simulation. The analysis model includes the Bauschinger effect and geometrical nonlinearity.

The thermal gradients contribute a major portion of stresses into the entire stress-strain state for the HP rotor. The transient temperature distribution, calculated earlier, is applied to the structural FE model as the thermal load at appropriate time steps to simulate thermal stresses. Structural BC and centrifugal loads were also considered in the analysis.

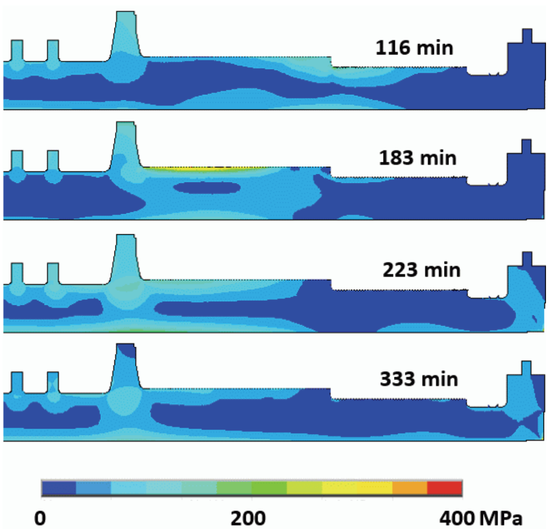


Figure 7 – Rotor Von Mises Stresses during CS for Baseline Design

The results of the thermo-structural analysis are presented in fig. 7-9. Von Mises stresses distributions for the rotor at front-end seals region during cold start-up are presented in fig. 7 for baseline design (corresponding scheme in fig. 5, *a*) and in fig. 8 for modified design (corresponding scheme in fig. 5, *b*).

Equivalent von Mises stresses versus time during turbine pre-warming phase and cold start-up for the monitoring point #4 (fig. 3) and corresponding metal temperatures at this point are presented for baseline and modified designs in the fig. 9.

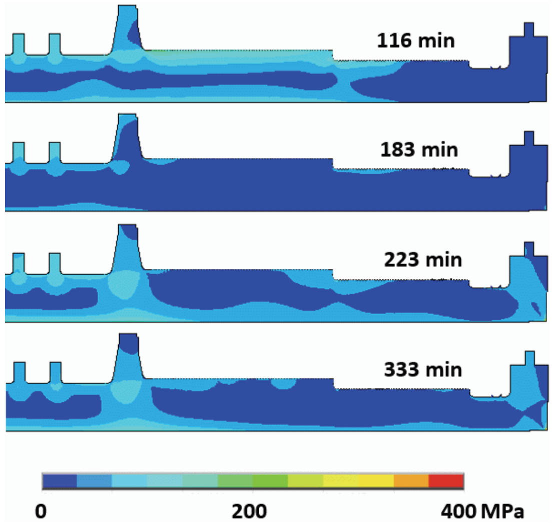


Figure 8 – Rotor Von Mises Stresses during CS for Modified Design

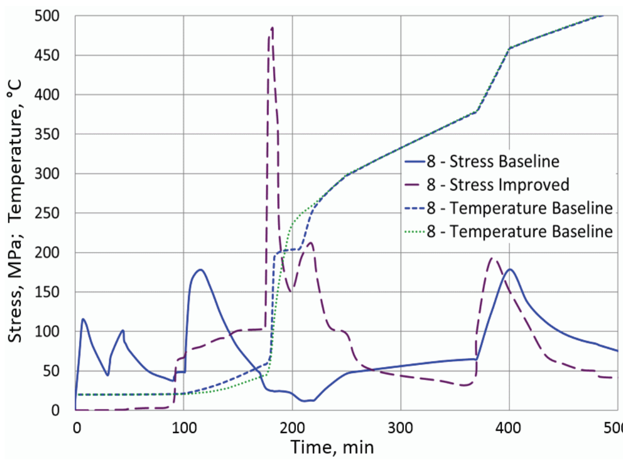


Figure 9 – Stresses in Monitoring point #4 during CS for Baseline and Modified Designs

The highest level of thermal gradients and stresses for the baseline design can be observed at front-end seals zone under the carrier ‘A’ (fig. 5, *a*) at 183 min from the beginning of cold start-up. At this time, hot steam comes in the turbine flow path and get into the seals under the carrier, where steam condensation process takes place. The analysis shows that the thermal shock at this time period is more critical than at all following start-up steps.

For the modified design (fig. 5, *b*) maximal stresses appear at 116 min in the front-end seals region. It should be noted that as the result of more uniform heating under the front-end seals carrier, overall stress level during turbine cold start-up for the proposed variant is much lower (see the chart in fig. 9).

Lifetime Analysis. There are two major factors that limit high-temperature components service life: thermo-mechanical fatigue (LCF) and creep. For HP turbine rotor, thermo-mechanical fatigue evolves due to varying stresses during start-up – shut down cycles. While creep associated with the time of turbine continuous operation at steady state. The goal of the study is to estimate the number of steam turbine start-ups. Thus, the focus was paid to the LCF analysis only and creep effect was not considered in the present study.

LCF analysis is performed based on calculated thermo-mechanical stress-strain state in a non-linear plastic statement and experimental strain-life diagrams for the rotor material [11].Two full cycles of start-up – nominal operation - shut down were considered in the thermo-structural analysis to reach stabilized stress-strain hysteresis loops for the rotor critical regions with regards to LCF crack initiation(stress monitoring points in fig. 3).

To estimate rotor LCF life, an equivalent effective strain range was calculated based on FE thermo-structural results for the rotor critical zones. The number of cold start-up cycles N to LCF crack initiation was calculated using formulas (1) and presented in table 1 for each critical point from fig. 3 for baseline and modified designs.

$$N = \min\{N_{aN}, N_{a\varepsilon}\};\quad N_{aN} = \frac{N(\varepsilon_a)}{K_N};\quad N_{a\varepsilon} = N(\varepsilon_a K_\varepsilon), \quad (1)$$

where ε_a – strain amplitude, $K_N = 5$, $K_\varepsilon = 1.5$ – safety factors recommended by [11].

Table 1 – LCF Analysis Results

Point #	Baseline Design		Modified Design	
	ε_a, %	N	ε_a, %	N
1	0.2558	320	0.0719	>20000
2	0.1967	1200	0.0606	>20000
3	0.1285	8000	0.0491	>20000
4	0.0508	>20000	0.0498	>20000
5	0.0395	>20000	0.0425	>20000

The LCF analysis results show that maximal deformations for both variants of design appear in the point #1 (fig. 3). For the baseline design there a risk of the crack initiation after 320 cycles of cold start-up (not to take into the consideration other transients). Modified design shows significantly lower strain amplitudes and consequently the much higher allowable number of start-ups.

Conclusions. The improved approach for a steam turbine rotor thermal and thermostructural analysis, which allows to take into the account steam condensation process and calculate thermal BC with high accuracy has been developed. Based on the simulation results for 325 MW steam turbine HP rotor, the design changes of the front-end seals carrier and heating conditions modification during the pre-warming phase are proposed. The influence of heating conditions on thermostresses and LCF lifetime for the baseline and modified designs was estimated and the results show that proposed changes make it possible to

– Provide more uniform heating and lower thermostress level for the HP rotor at front-end seal region during pre-warming phase;

– Increased allowable number of turbine start-ups.

Bibliography:

1. *Peshko V.A.* Establishing control over the residual resource of temperature elements of steam turbines: candidate-degree thesis: 05.14.14 thermal and nuclear power installations / *V.A. Peshko*. – Kyiv, 2017. – in rus.

2. *Sudakov A.V.* Servise Life Extension Substantiation for Steam Turbines with Components which have Deviation from Normative Documentation / *A.V. Sudakov, S.N. Gavrilov, E.V. Georgievskaja, A.I. Levchenko* // Neftegaz.RU. – 2015 – 2, № 1 – PP. 42–47. – in rus.

3. *Brilliant H.M.* Analytical Approach to Steam Turbine Heat Transfer in a Combined Cycle Power Plant / *H.M. Brilliant, A.K. Tolpadi*. – Proceedings of ASME Turbo Expo, Vienna, 2004.

4. *Born D.* Thermal modeling of an intermediate pressure steam turbine by means of conjugate heat transfer – simulation and validation / *D. Born, P. Stein, G. Marinescu, S. Koch, D. Schumacher*. – ASME Turbo Expo. Seoul, South Korea, 2016, GT2016-57247.

5. *Chernousenko O.Ju.* High power steam turbines service life estimation and lifetime extension: monograph / *O.Ju. Chernousenko*. – Kharkiv: FOP Brovin A. V., 2014. – 308 p. – in rus.

6. RTM 108.020.16-83. Steam Turbines Rotors and Casings Thermal Analysis. – M.: Minjenergomash, 1983. – 116 p. – in rus.

7. *Matsevity Yu.M.* Heat exchange in construction of steam turbines elements / *Yu.M. Matsevity, S.V. Alyokhina, V.N. Goloschapov, O.V. Kotulskaja*. – NAS of Ukraine, A.N. Podgorny Institute for Mechanical Engineering Problems, Kharkiv, Ukraine,2012. – in rus.

8. *Maliarenko V.A.* Heat exchange and gas dynamics in extraction chambers of steam turbines / *V.A. Maliarenko, V.N. Goloschapov, V.A. Barsukov, O.V. Kotulskaja, O.Yu. Chernousenko*. – NAS of Ukraine, A.N. Podgorny Institute for Mechanical Engineering Problems, Kharkiv, Ukraine, 1991. – in rus.

9. *Bakhmutska Ju.* 325 MW Steam Turbine High Pressure Cylinder Rotor Thermal and Thermostructural State at Cold Start-up / J*u. Bakhmutska*, *V. Goloshchapov* // Problemi mashinobuduvannja. – 2017. – 20, № 2. – PP. 3-11. – in rus.

10. *Bakhmutska Ju.* Heat Exchange Boundary Conditions at stepped type seals' groves / *Ju. Bakhmutska, V. Goloshchapov* // Compressor and Power Energy Machinery Construction. – Sumy, 2016. – № 3 (45). – P. 21-24. – in rus.

11. RTM 108.021.103-85. Stationary Steam Turbine Components. Low Cycle Fatigue Analysis. – M.: 1985, № AZ-002/7382, 49p. – in rus.

References (transliterated):

1. Peshko V.A. Establishing control over the residual resource of temperature elements of steam turbines: candidate-degree thesis: 05.14.14 thermal and nuclear power installations. Kyiv, 2017.

2. Sudakov A.V., Gavrilov S.N., Georgievskaja E.V., Levchenko A.I. Servise Life Extension Substantiation for Steam Turbines with Components which have Deviation from Normative Documentation. Neftegaz.RU. 2015. Vol. 2, No 1. PP. 42–47.

3. Brilliant H.M., Tolpadi A.K. Analytical Approach to Steam Turbine Heat Transfer in a Combined Cycle Power Plant. Proceedings of ASME Turbo Expo, Vienna, 2004.

4. Born D., Stein P., Marinescu G., Koch S., Schumacher D. Thermal modeling of an intermediate pressure steam turbine by means of conjugate heat transfer – simulation and validation. ASME Turbo Expo. Seoul, South Korea, 2016, GT2016-57247.

5. Chernousenko O.Ju. High power steam turbines service life estimation and lifetime extension: monograph. Kharkiv: FOP

Brovin A. V., 2014. 308 p.

6. RTM 108.020.16-83. Steam Turbines Rotors and Casings Thermal Analysis. Moscow: Minjenergomash, 1983. 116 p.

7. Matsevity Yu.M., Alyokhina S.V., Goloschapov V.N., Kotulskaja O.V. Heat exchange in construction of steam turbines elements. NAS of Ukraine, A.N. Podgorny Institute for Mechanical Engineering Problems, Kharkiv, Ukraine,2012.

8. Maliarenko V.A., Goloschapov V.N., Barsukov V.A., Kotulskaja O.V., Chernousenko O.Yu. Heat exchange and gas dynamics in extraction chambers of steam turbines. NAS of Ukraine, A.N. Podgorny Institute for Mechanical Engineering Problems, Kharkiv, Ukraine, 1991.

9. Bakhmutska Ju., Goloschapov V. 325 MW Steam Turbine High Pressure Cylinder Rotor Thermal and Thermostructural State at Cold Start-up. Problemi mashinobuduvannja. 2017. Vol. 20, No 2. PP. 3-11.

10. Bakhmutska Ju., Goloschapov V. Heat Exchange Boundary Conditions at stepped type seals' groves. Compressor and Power Energy Machinery Construction. Sumy, 2016. No 3 (45). P. 21-24.

11. RTM 108.021.103-85. Stationary Steam Turbine Components. Low Cycle Fatigue Analysis. Moscow: 1985, № AZ-002/7382, 49 p.

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Вплив умов прогріву ротора парової турбіни К-325-23,5 на термонапружений стан і ресурс при пусках / Ю. О. Бахмутська, В. М. Голощапов, Р. Є. Кочуров // Вісник НТУ «ХПІ». Серія: Динаміка і міцність машин. – Х.: НТУ «ХПІ», 2017. – № 39 (1261). – С. 89-94. – Бібліогр.: 11 назв. – ISSN 2078-9130.

Влияние условий прогрева ротора паровой турбины К-325-23,5 на термонапряженное состояние и ресурс при пусках / Ю. О. Бахмутская, В. Н. Голощапов, Р. Е. Кочуров // Вісник НТУ «ХПІ». Серія: Динаміка і міцність машин. – Х.: НТУ «ХПІ», 2017. – № 39 (1261). – С. 89-94. – Бібліогр.: 11 назв. – ISSN 2078-9130.

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