Rocznik Ochrona Środowiska

Volume 23	Year 2021	ISSN 1506-218X	pp. 408-419

https://doi.org/10.54740/ros.2021.027 open access

Received: 18 June 2021 Accepted: 21 July 2021 Published: 06 December 2021

Impact Estimation of a Transient Temperature Field on the Service Life of the High Pressure Rotor of K-1000-60/3000 Turbine

Olga Chernousenko
National Technical University of Ukraine
"Igor Sikorsky Kyiv Polytechnic Institute", Kyiv, Ukraine
https://orcid.org/0000-0002-1427-8068

Tetyana Nikulenkova[*]
National Technical University of Ukraine
"Igor Sikorsky Kyiv Polytechnic Institute", Kyiv, Ukraine
https://orcid.org/0000-0003-1880-1124

Anatolii Nikulenkov
Separated Subdivision "Scientific and Technical Center" of the State Enterprise "National Nuclear Energy Generating Company "Energoatom", Kyiv, Ukraine
https://orcid.org/0000-0003-4345-8575

[*]*corresponding author's e-mail: tetyana.nikulenkova@gmail.com*

Abstract: The one of purposes of this paper is to estimation some impact on the service life of the high-pressure cylinder rotor of a typical high-speed turbine K-1000-60/3000. The residual life assessment of power equipment would require determining viability and damage of its base metal. Typical degradation mechanisms of steam turbine equipment include long-term strength reduction and low cycle fatigue accumulation. Intensity of their impact is determined by a numerical examination of equipment thermal (TS) and stress strain states (SSS) for standard operation modes. To perform a numerical examination of the stress strain state would require solving a thermal conductivity boundary problem in quasi-stationary (for nomal operation modes) and nonstationary models (for transients). It is convenient to solve such problems of mathematical physics through discretization of the calculation object using the finite element method (Chernousenko et al. 2018). The service life of steam turbine is determined as an individual one and is assigned based on the results of individual an inspection of a separate element or the largest group of single-type equipment elements of the considered plant. The fleet service life being reached is followed by diagnostics of specific units of power installations and analysis of their operation, measurement of actual dimensions of components, examination of structure, properties and damage accumulation in the metal, non-destructive testing and estimate of stress strain state and residual service life of the component. The results of performed studies are used to determine an individual service life of each element of energy equipment (Nikulenkov et al. 2018).

Keywords: service life, steam turbine, temperature, ANSYS, 2-D and 3-D geometrical models, K-1000-60/3000, nuclear power plants, CFD-codes

1. Introduction

The problem of defining service life of nuclear power plants considering life cycles of their major equipment is becoming increasingly important each year. This raises questions relating to reasonable decision-making scheme on the due time for decommissioning of NPPs and feasibility of replacing of any major equipment considering safety and economic factors.

With extended operation of power plant equipment, the definition of its service life has changed. After the fleet life is reached, an in-depth diagnostic is carried out for specific nodes of electric power installation, including analysis of its operating conditions, measurement of the actual component geometry, examination of steel structure, its properties and accumulated damage, non-destructive testing and calculated estimate of stress state and residual service life of components.

Based on the results of performed studies an individual residual service life is established for a specific component of the power equipment.

The decision-making algorithm regarding capability and conditions for equipment operation throughout the individual service life can be described as follows (Nikulenkova et al. 2020):

1) assessment of actual operating conditions for the entire period of component use;
2) conducting repeated strength analysis based on the refined operation data;
3) defectoscopy (visual inspection, ultrasonic testing, X-ray examination, magnetic particle testing, lab examinations of steel samples);
4) assessment of the expired service life and forecasting further operation after defining equipment conditions.

This approach allows combining calculation methods, results of steel examination and samples tests, which complement each other. The set purpose is to be achieved by reaching the objectives as follows:

1) analysis of the known ways for service life extension of energy equipment that has reached the end of its fleet service life;
2) the results of metal inspection throughout the entire operating lifetime and analysis of technical audit data relating to damages and geometry changes during refurbishment of steam turbine elements;
3) analysis of the results of experimental researches and estimate of residual service life of steam turbines considering actual operating conditions and local damages of separate turbine components;
4) elaborating proposals regarding approaches to extension of service life of steam turbines.

2. Materials and methods

Approaching the end of the established life of NPP equipment poses a number of challenges to nuclear industry:

1) to increase the installed capacity while maintaining the required safety level of operating power units using the built-in engineered margins of operating units along with the ever increasing pace of science and technology development, and taking due account of international practice;
2) to carry out a range of works and upgrades to ensure operation of power units beyond their design life while maintaining the required safety level.

The range of works to be carried out when assessing the service life of the critical elements of the turbine is comprised of several phases.

In the fist phase, the 3-D analogues of the rubine machine elements were built based on the results of the technical audit and conclusions of the visual inspection, when different types of damages are localized in the geometrical model of a turbine element in the form of steel samples of differenet shape. Such approach allows to bring the calculation model of the steam turbine element close to real conditions after continiuous operation.

The next phase is to calculate initial and boundary conditions (using CFD-codes or criterial equations as specified in (Nikulenkov et al. 2018, Nikulenkov et al. 2019)) and determine a nonstationary temperature field in the solid critical element for further calculation of thermal load.

It starts with solving the non-stationary thermal conductivity equation and assigning boundary conditions for heat transfer on the surfaces of the rotor based on 2-D and 3-D geometrical models. The non-stationary thermal conductivity equations are given below:

$$\mathrm{div}[\lambda(T)\cdot \mathrm{grad}(T)] = c(T)\cdot\gamma(T)\cdot dT/d\tau \qquad (1)$$

where: λ – coefficient of thermal conductivity, c – specific heat capacity, γ – specific weight, which are functions of temperature and coordinates under initial conditions $T_0 = T(x, y, z, 0) = f_0(x, y, z)$.

The third phase involves using the ANSYS package to determine the stress strain state of the high pressure cylinder rotor considering its complex spatial geometry, damages over ther period of operation, and repair and renewal changes of the design geometry (Peshko et al. 2016, Chernousenko et al. 2020).

The outcome is calculations of equivalent elastic strain, von Mises equivalent strain, principal stresses, taking into account the effect of the centrifigual forces, temperature and steam pressure loads during start-up of the K-1000/60-3000 turbine from cold (CS), warm (WS) and hot states (HS).

1) Equivalent elastic strain shall be calculated by the formula:

$$\varepsilon_e = (1/1 + \nu')(1/2[(\varepsilon_1 - \varepsilon_2)^2 + (\varepsilon_2 - \varepsilon_3)^2 + (\varepsilon_3 - \varepsilon_1)^2])^{1/2} \qquad (2)$$

where ν' – the effective Poisson's ratio defined as: 1) the Poisson's ratio at the relevant temperature of the considered body for elastic and thermal deformations; 2) 0.5 for plastic differmations.

2) Von Mises equivalent strain shall be calculated by the formula:

$$\sigma_e = [((\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2)/2]^{1/2} \qquad (3)$$

3. Principal stresses

It is well-known from the theory of elasticity that an infinitely small volume of material in the arbitrary point of the solid body and inside it can be rotated so that there remain only normal stresses, and all shear stresses are equal to zero. The three remaining normal stresses are called principal stresses.

Principal stresses are always arranged as follows: $\sigma_1 > \sigma_2 > \sigma_3$, where: σ_1 – maximum principal stress, σ_2 – middle principal stress, σ_3 – minimum principal stress.

To calculate transient temperature fields for CS, WS and HS the boundary conditions were determined for temperature distribution in the rotor (t = f(x,y) at the time $\tau = 0$, $\tau = 2760$, $\tau = 6600$, $\tau = 22740$). The boundary conditions and the rotor temperature field are presented in Fig. 1-9.

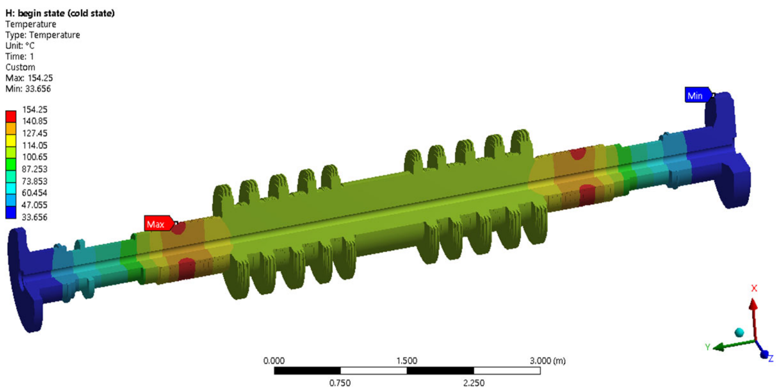

Fig. 1. Initial temperature distribution in the rotor during cold start-up

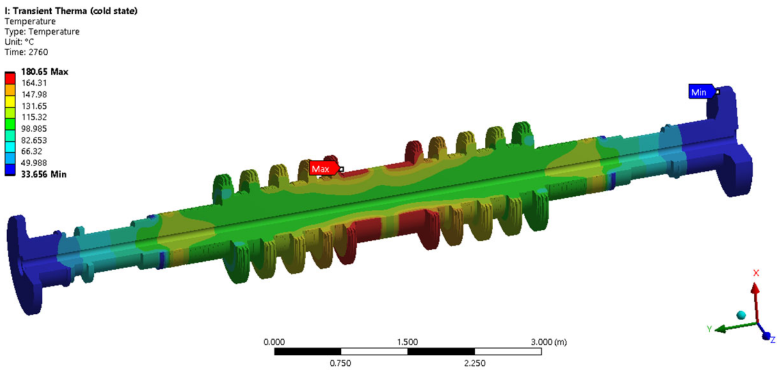

Fig. 2. Temperature field of the 1000/60-3000 steam turbine rotor 2760 seconds after cold start-up of the turbine

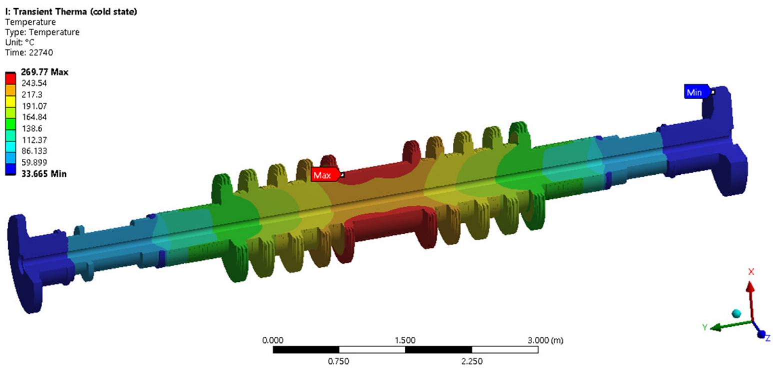

Fig. 3. Temperature field of the 1000/60-3000 steam turbine rotor 22740 seconds after cold start-up of the turbine

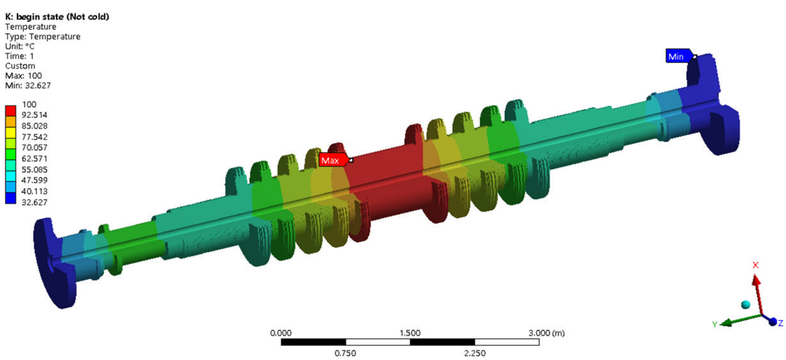

Fig. 4. Initial temperature distribution in the rotor during warm start-up

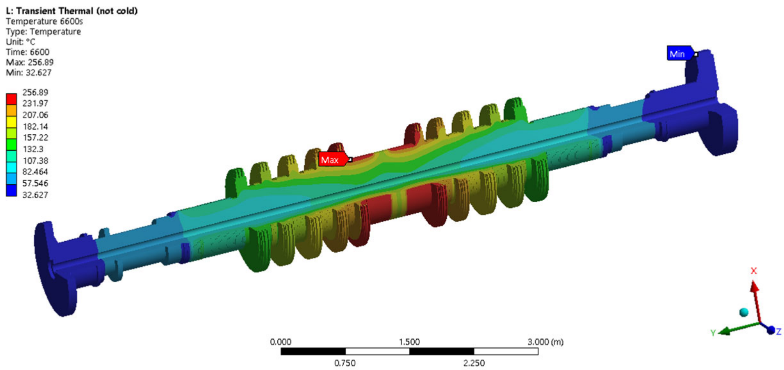

Fig. 5. Temperature field of the 1000/60-3000 steam turbine rotor 6600 seconds after warm start-up of the turbine

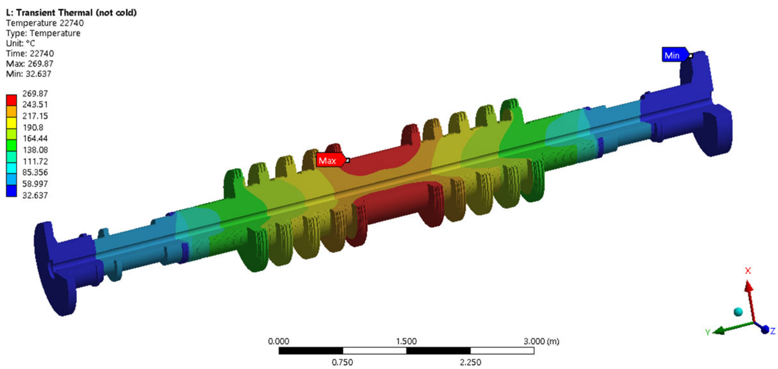

Fig. 6. Temperature field of the 1000/60-3000 steam turbine rotor 22740 seconds after warm start-up of the turbine

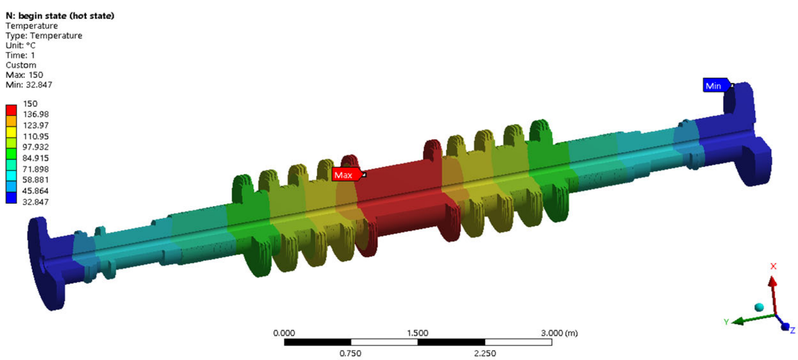

Fig. 7. Initial temperature distribution in the rotor during hot start-up

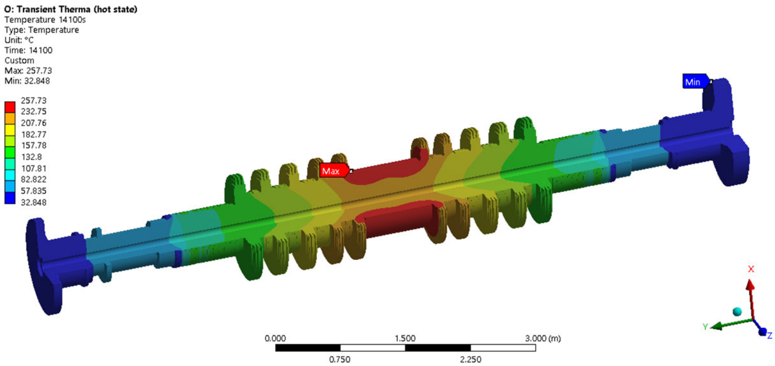

Fig. 8. Temperature field of the 1000/60-3000 steam turbine rotor 14100 seconds after hot start-up of the turbine

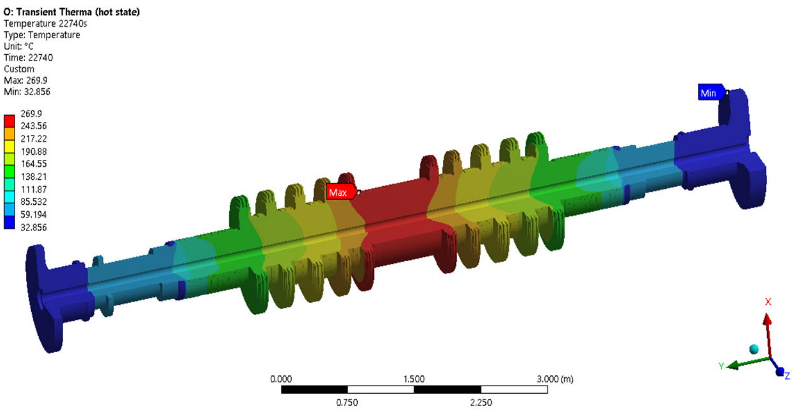

Fig. 9. Temperature field of the 1000/60-3000 steam turbine rotor 22740 seconds after hot start-up of the turbine

4. Results and discussion

Initial data

The condensate steam turbines of thermal and nuclear power plants with high temperature elements in 3-D setting are considered. The boundary conditions are established for heat exchange on the rotor surfaces using ANSYS digital model based on built geometrical 3-D models corresponding to operating modes by start-up types from cold, hot and warm conditions and stationary mode (Nikulenkova et al. 2019).

Model testing and setup

The calculations determine principal stresses and intensity of stresses over entire life corresponding to start-up and stationary operating conditions in all division points of hight temperature elements of the stream turbine.

The results of stress and deformation calculations under cold start-up of the K-1000/60-3000 turbine are provided below.

Fig. 10-15 show the change of maximum stress (equivalent (von-Mises) stress, principal sress) during the cold, warm and hot start-up.

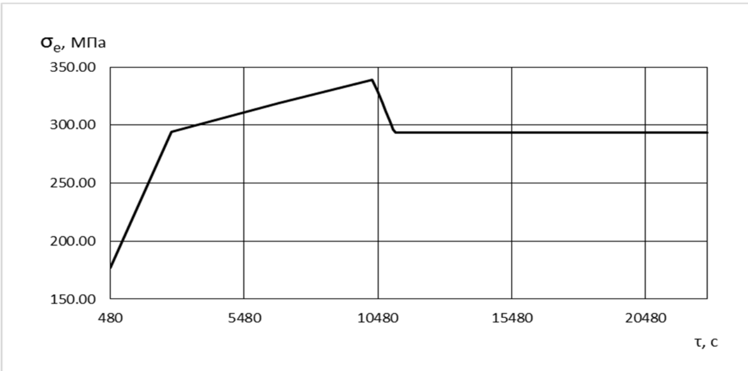

Fig. 10. Time change of maximum equivalent stress (von Mises) during cold start-up

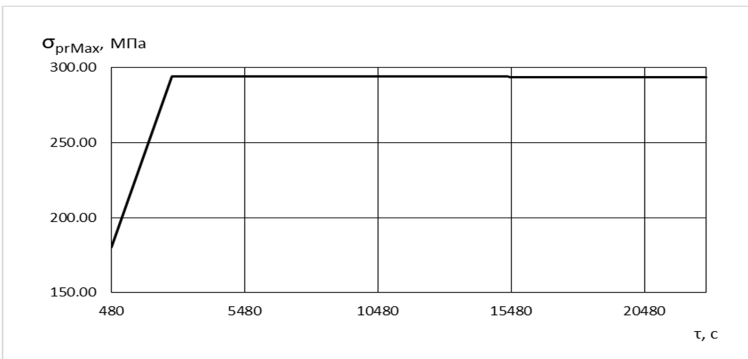

Fig. 11. Time change of the maximum value of maximum principal stress during cold start-up

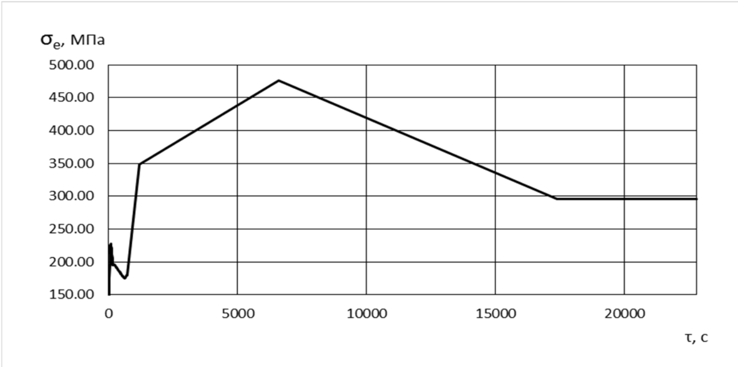

Fig. 12. Time change of maximum equivalent stress (von Mises) during warm start-up

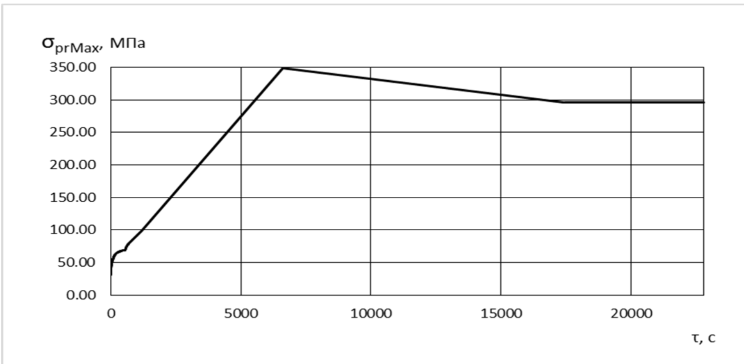

Fig. 13. Time change of the maximum value of maximum principal stress during warm start-up

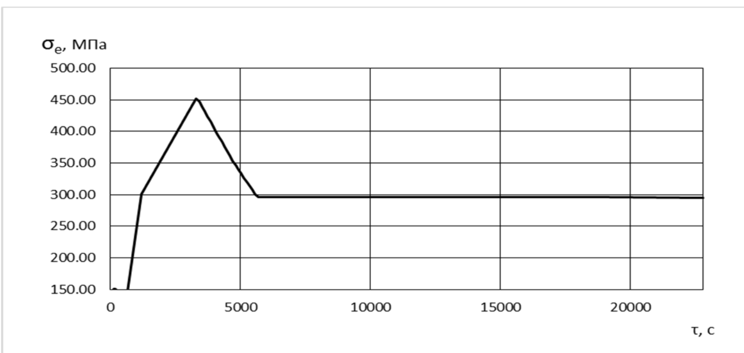

Fig. 14. Time change of maximum equivalent stress (von Mises) during hot start-up

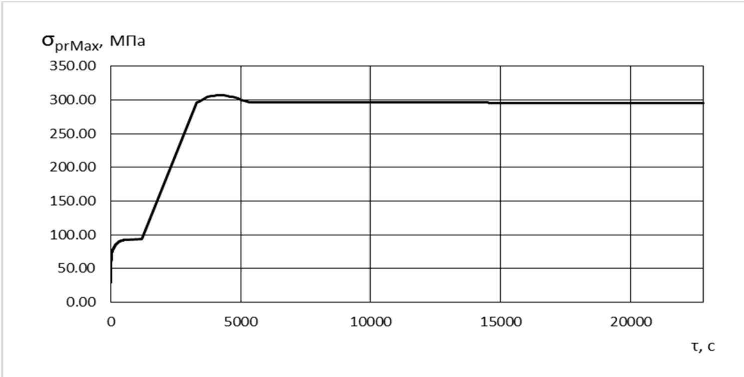

Fig. 15. Time change of the maximum value of maximum principal stress during hot start-up

The maximum equivalent stress is 338.9 MPa reached at 10260 s during cold start-up. The stress peak shifts from end seals (during warming-up of the turbine due to steam directed onto seals) to the first stage disk and further to the coupling when reaching nominal conditions. The maximum value of maximum principal stress is 294.16 MPa reached at 2760 s.

The maximum equivalent stress is 452.14 MPa reached at 3300 s during hot start-up. The stress peak shifts from end seals (during warming-up of the turbine due to steam directed onto seals) to the first stage disk and further to the coupling when reaching nominal conditions (Nikulenkova et al. 2020).

The calculation results of the stress strain state of the high-temperature elements of the steam turbine obtained using ANSYS in different spatial settings (2-D and 3-D) were compare between each other and with the results obtained by other authors (Bakhmutskaya et al. 2017, Shulzhenko et al. 2011).

According to the calculations the maximum stress is 338.9 MPa reached at 10260 s. The stress peak shifts from end seals to the first stage disk and further to the coupling when reaching nominal conditions.

The final phase implies development of a methodological approach to calculaton of the low cycle fatigue with account of changes in the stress strain state of the K-1000/60-3000 turbine elements for optimization of strength margins by number of cycles and deformations (Nikulenkov et al. 2018).

The described methodology was used to develop a software for numerical analysis of the residual service life of steam turbines used at thermal and nuclear power plants.

5. Conclusions

1. The set of works to estimate the service life of the critical elements of the K-1000/60-3000 turbine has been described in phases.
2. The calculations have been made for equivalent elastic strain, von Mises equivalent strain, principal stresses, taking into account the effect of the centrifugal forces, temperature and steam pressure loads during start-up of the K-1000/60-3000 turbine from cold, warm and hot states.
3. The maximum stress has been calculated as 338.9 MPa reached at 10260 s during cold start-up, 476.55 MPa reached at 6600 s during warm start-up, 452.14 MPa reached at 3300 s during hot start-up of the K-1000/60-3000 steam turbine.
4. The maximum equivalent elastic strain has been calculated as 1.76E-03 m/m reached at 10260 s during cold start-up, 2.47E-03 m/m reached at 6600 s during warm start-up, 2.35E-03 m/m reached at 3300 s during hot start-up of the K-1000/60-3000 steam turbine.

References

Bakhmutskaya, Y., Goloshchapov, V. (2017). K-325-23,5 Steam Turbine High-Pressure Rotor Thermal and Thermo-structural State During Cold Start-up. *Journal of Mechanical Engineering*, *2*(20), 3-11.

Chernousenko, O., Nikulenkov, A., Nikulenkova, T., Butovskiy, L. & Bednarska, I. (2018). Calculating boundary conditions to determine the heat state of high pressure rotor of the turbine NPP K-1000-60/3000. *Bulletin of the National Technical University "KhPI"*, *12*(1288), 51-56. DOI: 10.20998/2078-774X.2019.03.01

Chernousenko, O., Rindyuk, D., & Peshko, V. (2019). The strain-stress state of K-1000-60/3000 turbine rotor for typical operating modes. *Bulletin of the National Technical University "KhPI"*, *3*(1328), 4-10. DOI: 10.20998/2078-774X.2019.03.01

Chernousenko, O., Nikulenkova, T., Peshko, V., & Nikulenkov, A. (2020). Approach to impact assessment of the rated power up-rate of NPP unit on the service life of the turbine critical elements. *Rocznik Ochrona Srodowiska*, *22*(1), 105-116.

Nikulenkov, A., Chernousenko, O., & Nikulenkova, T. (2018). Analysis of influence of heat power rate increase on beyond design basis accident for NPP unit. *Bulletin of the National Technical University "KhPI"*, *13*(1289), 37-45. DOI: 10.20998/2078-774X.2018.13.07

Nikulenkov, A., Samoilenko, D., & Nikulenkova, T. (2018). Study of the impact of NPP rated thermal power uprate on process behaviour at different transient conditions. *Nuclear & Radiation safety*, *4*(80), 9-13.

Nikulenkova, T., Nikulenkov, A. (2019). Calculation of boundary conditions using CFD modeling as part of a comprehensive approach to impact assessment of modifications on the service life of critical elements of a nuclear power plant turbine. *The 16th International Conference of Young Scientists on Energy Issues*, VII, 267-278.

Nikulenkova, T., Nikulenkov, A. (2020) Impact analysis of a transient temperature field on the service life of the high pressure rotor of K-1000-60/3000 turbine. *Bulgarian Chemical Communications*, *52*, 36-41

Peshko, V., Chernousenko, O., Nikulenkova, T., & Nikulenkov, A. (2016). Comprehensive rotor service life study for high & intermediate pressure cylinders of high power steam turbines. *Propulsion and Power Research*, *5*(4), 302-309. DOI: 10.1016/j.jppr.2016.11.008

Shulzhenko, M., Hontarovskyi, P., Matiukhin, Yu., Melezhyk, I., & Pozhydaiev, O. (2011). Determination of estimated resource and evaluation of rotor life and body parts of turbines: Methodological guidelines, *Regulatory document SOU-N MEV* 0.1–21677681–52: approved by the Ministry of Energy and Coal Mining of Ukraine: effective as of 07.07.11. Kyiv: MECM of Ukraine, 24.