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Approach to Impact Assessment of the Rated Power Uprate of NPP Unit on the Service Life of the Turbine Critical Elements

Olga Chernousenko[1], Tetyana Nikulenkova[1],*
Vitaliy Peshko[1], Anatolii Nikulenkov[2]
[1]National Technical University of Ukraine
Igor Sikorsky Kyiv Polytechnic Institute, Ukraine
[2]The State Enterprise National Nuclear Energy Generating Company
"Energoatom", Ukraine
**corresponding author's e-mail: tetyana.nikulenkova@gmail.com*

1. Introduction

The practical exhaustion of the energy equipment life and fossil fuel shortage at thermal power plants determine significant contribution of NPPs to the energy sector of Ukraine. Therefore, utilization of power uprate margins of existing NPP (nuclear power plant) units is an urgent task which, if solved, would increase power generation at no significant cost (Rokicki et al. 2019).

There are objective preconditions for looking into and utilization of design basis margins of VVER units owing to accumulated VVER operating experience, as well as accuracy of thermal and neutron-physical calculations (Nikulenkov et al. 2018). When increasing NPP capacity to 104% there is a need to estimate the residual life of plant's typical elements and continue their operation.

The extension of NPPs lifetime subject to adherence to nuclear and radiation safety standards is one of the most effective ways for replacement of generating capacities. At the same time, specific financing costs for fulfilling requirements of normative documents allowing to obtain a license for NPP operation for an additional life period are much lower than costs of new nuclear builds. Revision of previously set operating life of NPP power equipment provides for an assessment of residual life of power equipment based on defining thermal and stress-strain states. However, reliability criteria for low-cycle fatigue and static damage require special consideration for steam turbines at NPPs (Nikulenkov et al. 2018).

2. Problem statement

Approaching the end of the established service life of NPP power equipment and the need to increase electricity generation due to ever-increasing consumer demands pose two major challenges for the nuclear industry (Chernousenko et al. 2018):

1) using the inherent design margins of operating power units in combination with increasing pace of science and technology development, as well as taking into account international experience backed by sufficient analytical justification to increase the installed capacity while ensuring the required safety for operating NPPs.
2) to carry out a set of works and modernizations to operate power units beyond the design period while ensuring the required safety.

To solve these challenges in the work is considered:

- impact assessment of the modification on the service life of high pressure cylinder (HPC) critical elements of the K-1000-60/3000 steam turbine using system one-dimensional and CFD-modeling codes;
- assessment of the possibility to continue high pressure rotor (HPR) operation of the K-1000-60/3000 steam turbine which includes calculated study of the residual life and acceptable number of start-ups from different thermal states under cyclic rotor loading.

3. Impact assessment of the modification on the service life of HPC critical elements of the K-1000-60/3000 steam turbine of 1000 MW NPP

When assessing impact of the modification on the service life of critical elements of the examined turbine it is suggested to use the pattern as follows (Nikulenkova et al. 2019):

1) building a 3-D model (3-D model of the high-pressure cylinder was developed, as well as CFD modelling to identify boundary conditions for subsequent determining of low-cycle loads for with and without modification cases),
2) calculation of initial and recalculation of boundary conditions (using CFD-codes or criteria equations),
3) determining a nonstationary temperature field in the solid critical element for further calculation of thermal load,
4) strength calculations (low-cycle fatigue, static loading, etc.) to determine a stress-strain state,

5) assessment of remaining service life (the remaining service life of a rotor is determined by assessing its accumulated damage and design service life, and the design remaining service life is a remainder between the design service life and its operating life at the time of forecasting,
6) assessing impact of the modification on remaining service life.

As previously specified, building a 3-D model is the first step in examining impact of the modification on the service life of the turbine's critical element. Figure 1 provides a 3-D model of the high-pressure rotor (Nikulenkova et al. 2019). The presented 3-D model was developed based on design and engineering documentation.

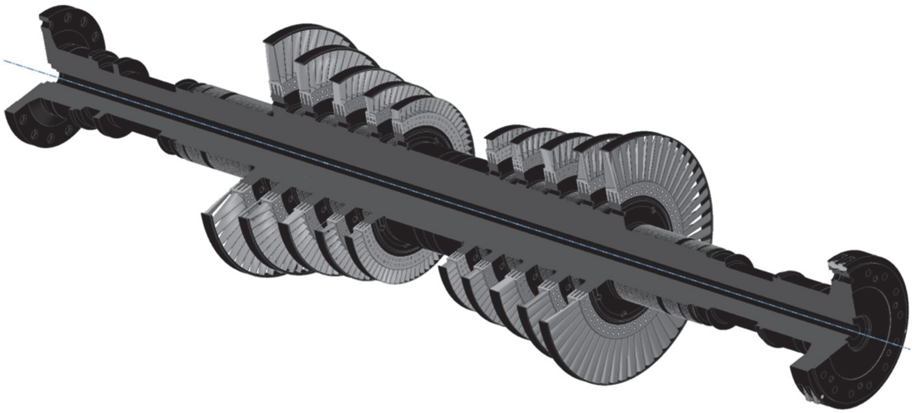


Fig. 1. 3-D model of the high-pressure rotor of the K-1000-60/3000 turbine

Since the high-pressure rotor of the K-1000-60/3000 turbine is geometrically symmetrical at the flow section and end seals and nature of the processes in the left and right parts are similar it was decided that for the purpose of estimate and in order to reduce the computational resources (scope and calculation time) the research area will be reduced from the first stage to the end seal last chamber of the right part of the rotor without operating blades (Figure 4).

The second step is to identify boundary conditions and determine temperature field in high-pressure rotor. It should be noted that calculation of boundary conditions of the third kind to solve a differential thermal conductivity equation in the works related with extension of service life of rotors (Bakhmutskaya et al. 2017), was performed primarily using criterion equations obtained by summarizing experimental data.

An alternative method would be using CFD modeling. To test this method considered nominal operation mode of the turbine set in a stationary position for the 1st stage of the HPC flow section. The computational model (Figure 2) consists from one solid and three fluid domains. The first stationary fluid domain models the flow of wet steam through nozzle blades, the second rotating fluid domain models the flow of wet steam through working blades of the turbine, the third rotating fluid domain models air flow in the central opening of the rotor designed for handling operations related with package inspection. Wet steam is modeled as a homogeneous binary mixture based on IAPWS IF97 condition data for water and water steam.

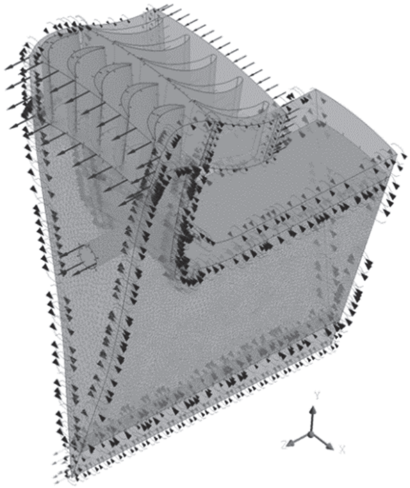


Fig. 2. Schematic diagram of the assigned boundary conditions in the ANSYS CFX computer environment

The boundary conditions at the inlet and outlet of the fluid domains were assigned as specified below.

Initial calculation parameters for Nominal value/Nominal value with modification:

- Mass steam flow rate per turbine, kg/s – 1622/1706 (Nikulenkova et al. 2018)
- Inlet static pressure, MPa – 5.839/5.839
- Inlet static temperature, K – 546.96/546.96
- Modelled medium (fluid 1 and fluid 2) – wet steam
- Modelled medium (fluid 3) – air
- Material of solid domain – steel
- Steam moisture content at the inlet – 0.002/0.002
- Rotor speed, rpm – 3000/3000

A boundary condition permitting flow reverse circulation is applied at the outlet of the domain modeling air flow. The side edges with Z as rotation axis received periodical boundary conditions. The obtained results specified correspond with controlled parameters during nominal operation mode.

The results are provided based on the calculations of boundary conditions of the third kind (Nikulenkov et al. 2018) and 3-D temperature field in the rotor (Figure 3).

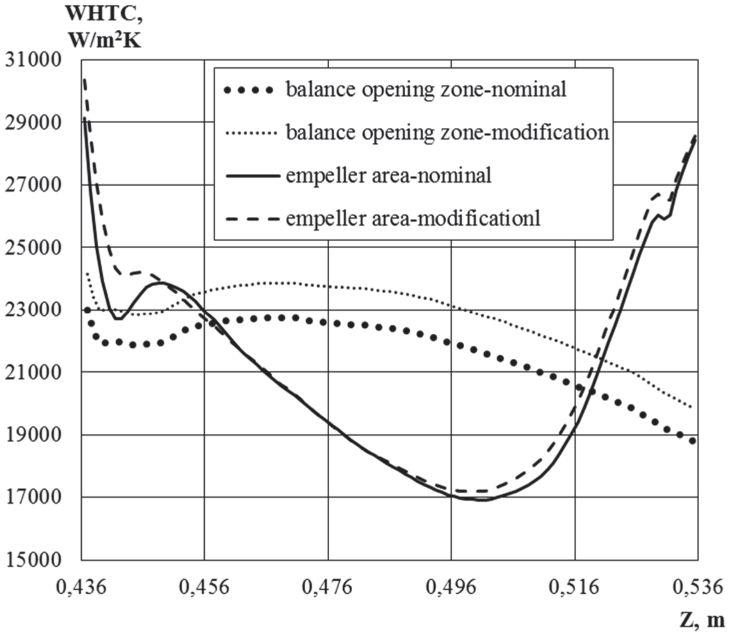


Fig. 3. Change in wall heat transfer coefficient along the flow section for either modification and rated power variants

The provided results show that increase in steam flow rate leads to increase of wall heat flux and wall heat transfer coefficient, and, consequently, to decrease of rotor wall temperature.

Further it is necessary to perform CFD modeling for all stages of the turbine in transient loads from cold, warm and cold shutdown to ensure possibility of strength calculations with subsequent impact assessment of the modification on the service life.

4. Calculation of the residual service lifetime of the high-pressure rotor of K-1000-60/3000 steam turbine

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 using integrated scheme provided in the study (Peshko et al. 2016, Chernousenko et al. 2018).

To perform a numerical examination of the stress-strain state would require solving a thermal conductivity boundary problem in quasi-stationary (for normal 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.

For complex designs of a high-pressure rotor (HPR) the geometric model is built in the 3-D mode with account of the main elements (Figure 4). The model is build using specification drawing of the K-1000-60/3000 turbine. Typical HPR examination areas include areas which, usually, have maximum temperature gradients and stress intensities.

In solving the problem of thermal conductivity, the boundary conditions of heat exchange of the I-IV kind were set in all typical regions calculated by the authors earlier (Chernousenko et al. 2018). Based on the calculation of the basic thermo- and hydrodynamic parameters of the flow part for normal and transient operating modes, the values of temperatures, heat transfer coefficients and heat flux density were determined for all surfaces of the geometric model.

The results of examination of the HPR thermal state at nominal operation are presented in Figure 4a. The temperature of the first-stage pressure is 261-270°C, for areas from the second to the fifth stage – 166-255°C and for end seals area – 83-142°C.

The stress-strain state (Figure 4b) was obtained taking into account basic loads, namely: stresses from temperature expansions, irregularities of temperature fields, centrifugal forces and stresses from the steam pressure. The maximum stress intensity occurs in the axial orifice and in the unloading openings of the discs of all five stages σ_i = 158 MPa. In other HPR typical regions the stress intensity is 66-105 MPa.

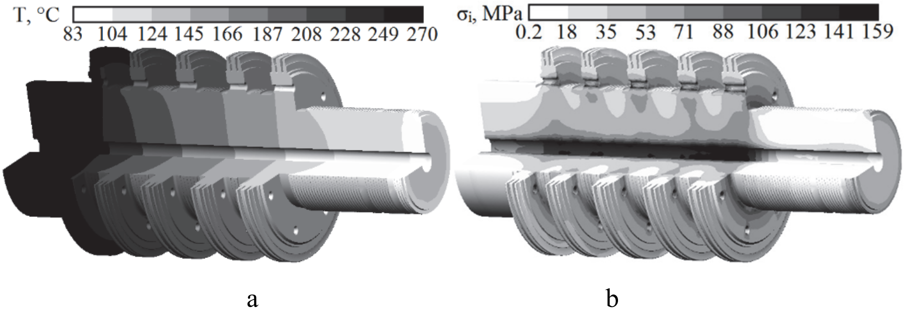


Fig. 4. Calculation results for nominal operation: a – thermal state; b – stress-strain state

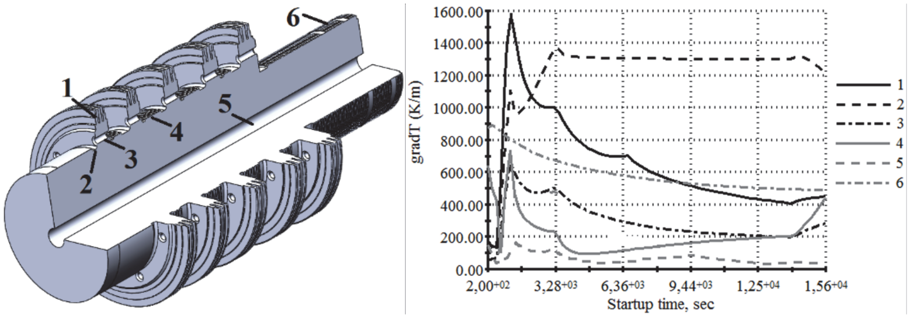
The considerable level of stress intensity at axial orifice is explained by large values of centrifugal forces acting on the discs of the pressure stages and rotating blades. The highest level of stress under this condition is observed closer to the fifth stage, which is the most massive and is bladed by the longest blades.

Similar data were obtained for transient operating modes. It should be noted that variation of temperature gradients and stress intensity are of particular interest when examining non-stationary operation. For example, when start-up is performed from a hot state (temperature of the first stage metal t_m = 150°C) maximum values of the temperature gradient are observed at the rotor push (estimated time τ = 600 s) and for the front fillet of the first-stage pressure gradT = 1570 K/m (Figure 5). The following local maximums of the temperature gradient are observed at 400 MW of electrical power (time point τ = 3200 s) and at the end of start-up mode at power output of 1000 MW (time point τ = 14100 s). A significant temperature gradient is observed throughout the hot start-up gradT = 1310 K/m at the tail joint of the rotor disk and the first-stage operating blades.

The change in intensity of stresses during hot start-up is shown in Fig 6.

The highest values of stresses σ_i = 207 MPa are observed at the axial opening of the turbine (curve 5) at the time τ = 6600 s (holding the turbine at 750 MW capacity).

The highest compression stresses σ_i = -182 MPa are observed at the front fillet of the first stage at the time τ = 3200 s (ramping up 400 MW). At the end of the start-up period the intensity of stresses in all examined regions gradually decreases to the values corresponding to the nominal operation mode (Figure 4b).



a b

Fig. 5. Dynamics of variation of irregularity of the rotor temperature field at hot start-up: a – typical examination areas, b – temperature gradient during start-up

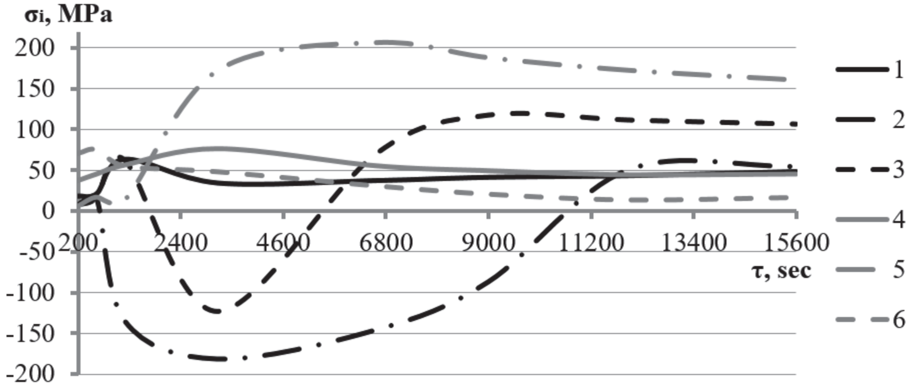


Fig. 6. Dynamics of variation of intensity of stresses in characteristic areas of research during start-up from hot state of metal

Similar data were obtained for other typical operating modes, which are presented in (Chernousenko et al. 2018, Chernousenko et al. 2019).

Calculation of damage from low-cycle fatigue involves setting the acceptable number of start-ups from different thermal states. Experimental curves of low-cycle fatigue are used for this purpose. However, for the 30CrNi3Mb1V steel from which the HPR is made, such curves are absent in the literature. Therefore, it is proposed to calculate the acceptable number of cycles using correlation dependencies of low-cycle fatigue:

$$N_{per} = \left[1 - \left| \frac{1{,}25\sigma^{s}}{\sigma_{l.s.}} \right|^{q} \right] min \left\{ \frac{N_1}{n_N} ; N_2 \right\} \tag{1}$$

$$N_{1,2} = \left[\frac{\frac{1}{4}\ln\frac{100}{100-\psi_{l.d.}}}{C\left(n_{1,2}\varepsilon_a + \frac{1-2\nu}{3E}\sigma_i\right) - \frac{\sigma_N}{E}} \right]^{\frac{1}{0,6}} \qquad (2)$$

where:

σ^s – intensity of stresses in the steady creep state,

$\sigma_{l.s.}$ – long-term strength limit,

q – exponent in the long-term strength equation,

n_N – strength margin by number of cycles,

$\psi_{l.d.}$ – long-term ductility determined by the median values for each temperature level θ_1-θ_2,

θ_1 i θ_2 – temperatures corresponding to maximum and minimum strain rates in the load cycle,

C – coefficient of the current number of cycles,

$n_{1,2}$ – strength margin by strain rate,

ε_a – amplitude of the strain intensity in the cycle.

The calculated indicators of low-cycle fatigue and long-term strength are specified in Table 1.

To assess life performance of the K-1000-60/3000 turbine the Rivne NPP Unit 3 of the National Nuclear Energy Generating Company (NNEGC) Energoatom was selected. As of November 2019, the unit's operating time is 209 690 h, and the number of start-up from different thermal states is 271. At the same time, according to the normative documents of NNEGC Energoatom, the fleet life of the power unit with the K-1000-60/3000 turbine is 220,000 h with 600 start-ups.

The life performance calculation results of the K-1000-60/3000 high-pressure rotor at Rivne NPP Unit 3 are given in Table. 1. The strength factor in the calculations is accepted as 10 by the number of cycles and 1.5 by deformation in accordance with the normative documents.

Low-cycle fatigue is 11.2% estimated by the acceptable number of start-ups from different thermal states calculated using the correlation dependence of the fatigue of 30CrNi3Mb1V steel. The static damage component is 55.2%. In other words, for NPP turbines the low-cycle fatigue as a degradation mechanism has less significant impact than reduction of long-term strength of metals. The total damage of the high-pressure rotor is 66,4%. This determines its residual life at 106200 h while maintaining operating conditions which were typical until November 2019.

Table 1. Life performance indicators of the K-1000-60/3000 high-pressure rotor at Rivne NPP Unit 3

Life performance indicators		Values
Operating time		209,690 h
Total number of start-ups		271
Commercial operation year		1986
Current number of start-ups from different thermal states	Cold	58
	Hot	213
Stress intensity at nominal operation		158.5 MPa
Acceptable number of start-up cycles from different thermal states	Cold	1945
	Hot	2591
Cyclic damage		11.2%
Acceptable operation time		380,000 h
Static damage		55.2%
Total damage		66.4%
Residual life		106200 h

The above circumstances allow continuing operation of the HPR of the K-1000-60/3000 steam turbine for additional 50 thousand hours until the next preventive maintenance.

5. Conclusions

This paper describes an approach to impact assessment of the rated power uprate of NPP unit on the service life of the turbine critical elements.

1. Based on design and engineering documentation a 3-D model of the high pressure rotor of the K-1000-60/3000 high-speed turbine was developed which can be subsequently used for CFD modeling and strength calculations.
2. Calculations performed using CFD code show that the impact of the modification on the wall heat transfer coefficient is negligible.
3. The numerical studies of the stress-strain state of the K-1000-60/3000 turbine high pressure rotor allowed to establish that the most loaded areas are axial opening of the turbine, fillet rounding's and unloading openings of all pressure stages.
4. According to life performance indicators calculation results it was established that reduction of the long-term strength has a dominant effect as degradation mechanism compared to accumulation of low-cycle fatigue. For the high pressure rotor of Rivne NPP Unit 3 the total damage to the base metal is 66,4% which determines its residual life at 106,200 h.

5. Since the residual life exceeds twofold the value of the planned overhaul period, the possibility of increasing the installed capacity of the unit by 4% is justified in terms of maintaining the operation life of equipment.

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Abstract

Nuclear power plants play an important role in power systems of many countries. Ability to reasonable increase installed capacity of nuclear power units allow to reduce the cost for building of new power plants. When increasing NPP capacity to 104% there is a need to estimate the residual life of plant's typical elements and continue their operation. The mathematical model of estimation of service life indicators of steam turbine K-1000-60/3000 is developed. The effect of increasing the capacity of a nuclear reactor on the heat transfer coefficients of a steam in the nozzle segments of high-pressure cylinder was established by using CFD modeling. The thermal and stress-strain state of the high-pressure rotor for the most typical operating modes are calculated. Using the correlation dependences of low-cycle fatigue, the rate of accumulation of cyclic damage of the base metal is established. The resistance of the metal to the exhaustion of long-term strength is also determined. On the example of the high pressure rotor of the 3rd power unit of Rivne NPP the service life indicators are calculated. The validity of increasing the installed capacity of the power unit was also confirmed.

Keywords:
nuclear power plant, reliability, turbine, steam flow, computational fluid dynamics, high pressure rotor, service life, long-term strength, low cycle fatigue