archives
of thermodynamics
Vol. **34**(2013), No. 3, 89–104
DOI: 10.2478/aoter-2013-0017

Selection of the rotor heat-up rate for supercritical parameter turbines

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Abstract The paper presents the results of the numerical analyses for the steam turbine rotor, dedicated for the newly-designed 900 MW steam unit with supercritical steam parameters (650 °C, 30.0 MPa). Basing on the design calculations, an optimal design solution was determined. Review of the available literature on materials for turbine rotors with supercritical steam parameters was done. Then the start-ups of the turbine were simulated. Thermal and strength states were analyzed. As a result, an optimal start-up characteristic was obtained.

Keywords: Steam turbines; Steel for ultra-supercritical steam unit; Unsteady states

Nomenclature

m/m_o	–	turbine feed steam mass flow to the nominal steam mass flow ratio
n	–	number of stage, rotor revolutions
p	–	live steam pressure
$R_{0.2}$	–	yield stress
t	–	time
T	–	live steam temperature

Greek symbols

σ	–	stress
σ_{eqv}	–	equivalent (von Mises) stress

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1 Introduction

Recent coal technologies using ultra-supercritical steam parameters require the application of new design solutions as well as new materials in the construction of turbines that will ensure their safe operation and comply with the operating principles.

In the first stage of the analysis, a preliminary design for a 900 MW turbine intended for an ultra-supercritical power unit was carried out. As a result of thermal calculations, steam parameters at characteristic points of the cycle were obtained. They constitute the basis for preliminary design calculations of the high- and intermediate pressure parts (HP and IP) of the turbine which include the geometrical dimensions of the stages of the HP and IP parts, the thermodynamic parameters of the steam stream in the flow cycle and the steam kinematic parameters. The second step was a preliminary selection of the design structural form of rotors. Presenting research results works concerning the optimization of the form of the rotor design are included, among others, in [1]. The design form of the rotor and its operating conditions have a direct impact on the stress state and, consequently, on its life. Another factor affecting life are the material properties, in particular – the rotor steel creep strength.

The way in which the turbine is operated, and especially the start-up method, is one more essential thing that affects the reliability and life of the turbine components. The unsteady temperature fields that then arise feature high gradients, which in turn generate high values of thermal stress. This has an effect on the durability and safe operating life in future. The results of the thermal and strength state multiobjective calculations given below aimed at developing the turbine start-up characteristic ensuring the shortest possible start-up time without exceeding the permissible stress level. This solution should ensure minimization of start-up losses.

2 Materials in supercritical parameter turbine construction

The research and experience gained by leading research centres and power engineering companies from Europe, Japan and the USA indicate that within the range of temperatures up to 650 °C it is possible to use the ferritic-martensitic 9–12% Cr steel grade, although various modifications are required [2–5].

One of the first steel grades in the 12CrMoV steel group is steel marked with the symbol X21CrMoV121, intended for operation in the temperature of 560 °C. This steel gave rise to three further steel groups manufactured in various countries. It is made in Japan with added tantalum and nitrogen as 11CrMoVTaN steel, with added niobium – by the General Electric Company and with added vanadium – by the Westinghouse Electric Company. Other configurations of additives such as W+Nb+N or W+Ta+N and also with boron raise the temperature at which the steels can be used. The research resulted in new steel grades HR1200, FN5 and FB2, which are capable of operating in temperatures up to 650 °C, ensuring the rotor life of at least 100,000 h with the maximum stress of 125 MPa. The latest publications concerning the testing of this group of steel grades indicate a potential for a further improvement in the properties by changing the mutual proportions of alloy additives. Figure 1 presents a chart of the values of destructive stress depending on time for the FB2 steel at the temperature of 600 °C and 650 °C. The charts of the dependence of creep strength of selected rotor steels [2–5] on the Larson-Miller parameter are given in Fig. 2.

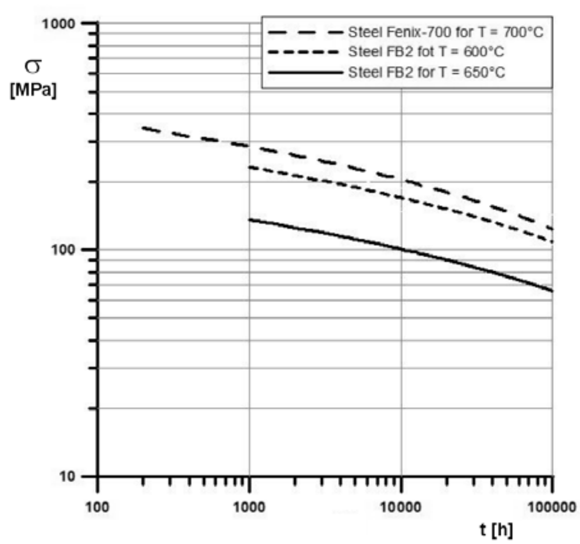

Figure 1. Chart of destructive stress values for FB2 and Fenix-700 steel grades.

Based on literature data [2–5], the stress values in the rotor that would allow its operation for 100,000 or 200,000 h in the temperature 650 °C are

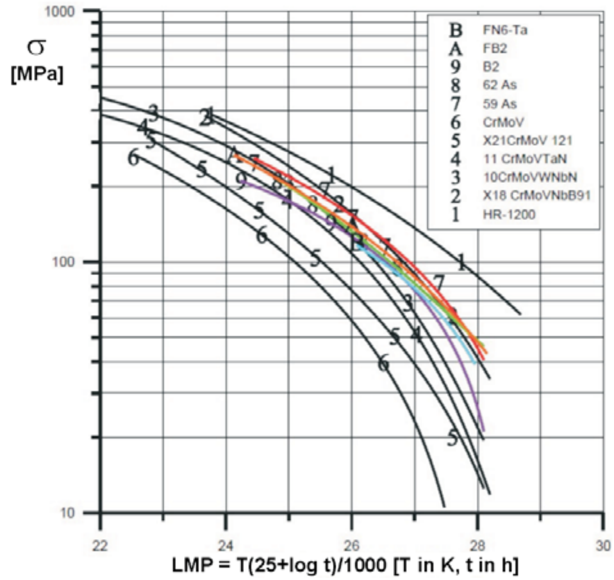

Figure 2. Creep strength of rotor steels.

listed in Tab. 1 for individual steel grades. For higher steam parameters nickle alloys have to be applied. One of them is Fenix-700, which features high-temperature creep resistance. The main additive elements are nickel and chromium. Other alloy additives are: Mo, V, W, Mn, (Al, Ti up to 1%).

Table 1. Permissible stress levels.

Steel	σ [MPa]	σ [MPa]
	$t = 100000$ h; $T = 650$ °C	$t = 200000$ h; $T = 650$ °C
CrMoV	6	–
X21CrMoV121	21	15
11CrMoVTaN	25	17
10CrMoVWNbN	32	23
X18CrMoVNbB91	55	43
HR-1200	101	84
59As	60	47
62As	57	50
B2	42	28
FB2	59	49
FN6-Ta	50	36

Fenix-700 originated from a modification to steel Alloy 706. The improvement consists in that steel Fenix-700 contains a small addition of niobium (approx. 2% on average) [6]; steel Alloy 706 did not contain niobium at all [7]. Owing to that, creep properties improved, which allows operation at temperatures exceeding 700 °C. Moreover, the main downside of steel Alloy 706 – the defects arising during the solidification process – was eliminated. The curve illustrating the strength of steel Fenix-700 depending on time is shown in Fig. 1.

3 Optimization of the turbine high pressure part rotor heat-up process

The calculations of the entire supercritical cycle and the thermal and flow calculations of the turbine make it possible to develop the turbine start-up characteristics. The characteristics were constructed based on the following assumptions [8,9]:

- there is a slide pressure adjustment of live steam in the boiler,
- operation with slide pressure occurs in the 40–100% range of the load,
- the pressure of reheated steam for loads included in the range of 0 to 40% is maintained at a constant level by means of an intermediate-low pressure bypass station and a valve before the IP part (the pressure value should result from the cooling conditions of the steam reheater, and the bypass of the HP part is closed at 40% of the load).

The thermal and flow calculations made it possible to determine the number of stages, the flow parameters for the nominal conditions of operation and the main geometrical dimensions of the flow system of the turbine HP part [10]. Example temperature and pressure distributions in the turbine flow system are presented in Figs. 3 and 4.

The optimization of the heat-up process in terms of a change in the rate of the increment in live steam temperature was carried out for start-ups from the initial cold state. This is one of the most dangerous start-up methods due to the high level of stress arising during the process. The stress values exceed the levels occurring at other start-up types substantially. Therefore start-ups from initial cold states present the most serious risk to the machine, considering the stress level, the brittle cracking hazard and the anticipated life of the machine.

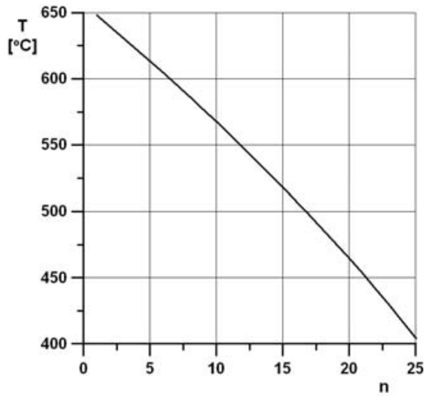

Figure 3. Change in steam temperature along the flow system of the turbine HP part (n – number of stage).

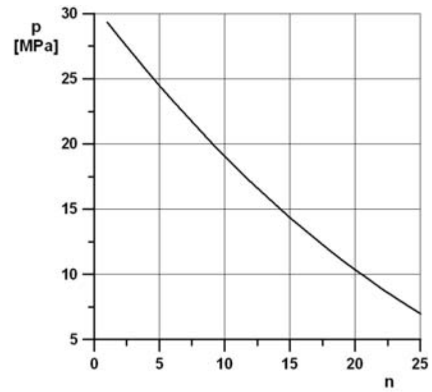

Figure 4. Change in steam pressure along the flow system of the turbine HP part (n – number of stage).

For the numerical analyses of unsteady thermal and stress states, the thermal boundary conditions and the distribution of pressure on individual surfaces of the components were assumed based on the calculation results obtained from the dependences and procedures developed at the Institute of Power Engineering and Turbomachinery of the Silesian University of Technology [10]. The calculation results in the form of curves illustrating changes in temperatures and equivalent (von Mises) stress in the rotor critical areas are presented below in the further part of the paper. The rotor thermal and strength calculations were made using the ANSYS software [11]. Considering the blade groove load state, the body force of rotating blades was taken into account. The transient temperature distribution calculations were made using the third kind boundary condition. Heat transfer coefficients were determined on different surfaces of the rotor, including the sealing area, the blade fixing area, the blade grooves, the shaft surface, etc. [11]. All of the presented calculations performed for areas, in which level of the stresses – during the start-ups – was maximal. Such areas named critical and marked (in Fig. 12.) by points: A – first thermal groove, B – bottom land of the first blade groove, C – bottom land of the seventh blade groove and D – corner of the internal chamber.

3.1 Start-up from the initial cold state with the average rate of the live steam temperature increment of $\Delta T/\Delta t = 4.0$ K/min

Based on own studies and rather scarce operating experience, it is assumed that the increment in the live steam temperature should not be higher than 4.0 K/min. Therefore, in the first computational approximation, this value was assumed to be the upper bound.

The numerical analysis of the start-up from the initial cold state was made according to the dependence shown in Fig. 5 which presents a start-up curve. It is assumed that the $\Delta T/\Delta t$ gradient of the live steam temperature increment is 4.0 K/min. The initial live steam temperature is 320 °C. The turbine reaches its nominal parameters about 100 min after the process begins. The nature of changes in temperature and in the equivalent (von Mises) stress during start-up in the monitored critical areas of the rotor (points A, B, C and D in Fig. 12) is shown in Fig. 6.

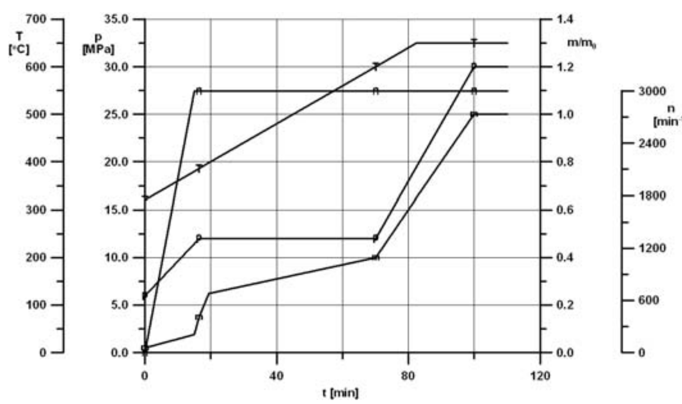

Figure 5. Power unit start-up curve from initial cold state for the live steam temperature increment $\Delta T/\Delta t = 4.0$ K/min (T – live steam temperature, p – live steam pressure, n – rotor revolutions, m/m_o – turbine feed steam mass flow to the nominal steam mass flow ratio).

Introducing the obtained maximum values of von Mises stress depending on the metal temperature into the coordinate system and marking the yield point, a chart was obtained that determines the range of a safe rate of the machine start-up (Fig. 18.). Running the start-up process at the increment rate of $\Delta T/\Delta t = 4.0$ K/min results in the yield point being exceeded considerably, which poses a great risk of damage to the machine.

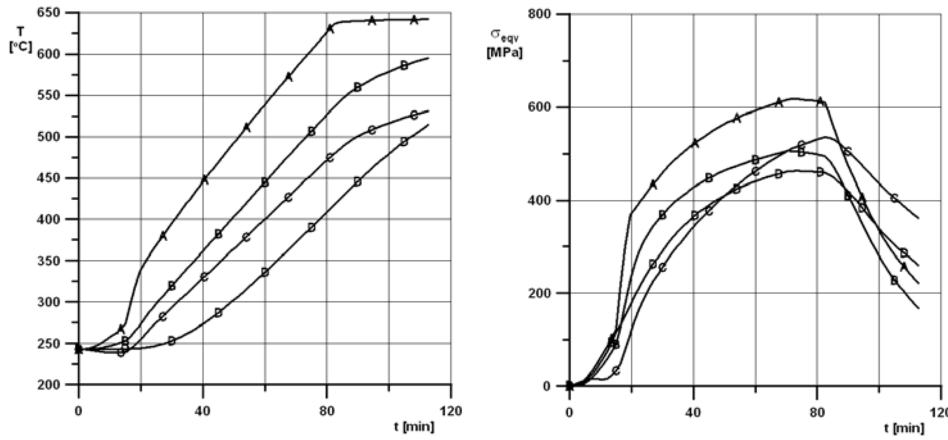

Figure 6. Curves illustrating changes in the metal temperatures and in the equivalent (von Mises) stress in the critical areas of the rotor of the turbine HP part for $\Delta T/\Delta t$ = 4.0 K/min (A – first thermal groove, B – bottom land of the first blade groove, C – bottom land of the seventh blade groove, D – corner of the internal chamber).

3.2 Start-up from the initial cold state with the average rate of the live steam temperature increment of $\Delta T/\Delta t = 1.5$ K/min

The slowest and also the safest start-up which is economically justified is the process run at the increment rate of $\Delta \mathrm{T}/\Delta t$ = 1.5 K/min. This value of the gradient of the change in the live steam temperature is assumed as the lower bound. The steam initial temperature was 320 °C, and the turbine reached its nominal parameters after 270 min from start-up.

The curves illustrating changes in the metal temperature and in the equivalent (von Mises) stress during start-up in the monitored critical areas of the rotor are presented in Fig. 7. Putting the maximum values of von Mises stress observed at the critical points (depending on the metal temperature) onto Fig. 18, it can be seen that there is a considerable reserve of stress compared to the boundary value of the conventional yield point. Therefore it may be assumed that start-ups of the machine under analysis can be carried out at a rate faster than the minimum, not exceeding however the increment rate of $\Delta \mathrm{T}/\Delta t$ = 4.0 K/min.

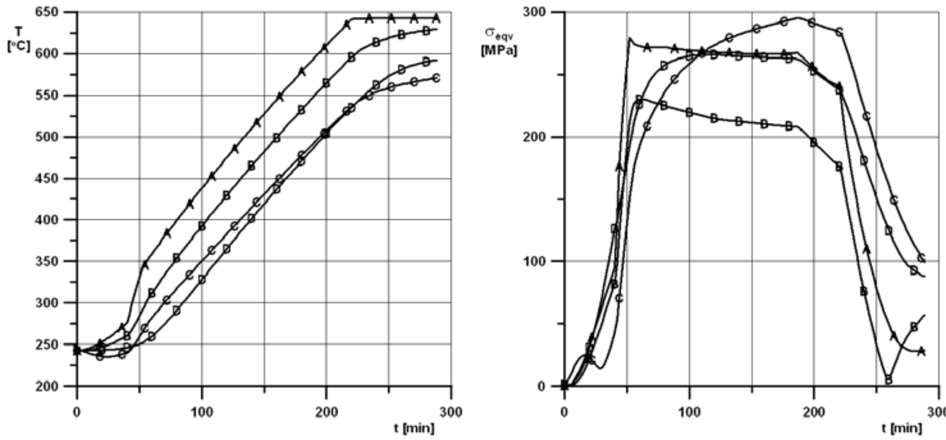

Figure 7. Curves illustrating changes in the metal temperatures and in the equivalent (von Mises) stress in the critical areas of the rotor of the turbine HP part for $\Delta T/\Delta t = 1.5$ K/min.

3.3 Start-up from the initial cold state with the average rate of the live steam temperature increment of $\Delta\mathrm{T}/\Delta\mathrm{t} = 3.0$ K/min and $\Delta\mathrm{T}/\Delta\mathrm{t} = 2.0$ K/min

Considering the results of the analyses presented above, the range of the live steam temperature gradient was narrowed. A decision was made to reduce the maximum rate of the live temperature increment to the value of 3.0 K/min to ensure safe operation of the machine. To improve the economy of the operating processes, the lower bound of the $\Delta T/\Delta t$ value was raised to the level of 2.0 K/min. For thus assumed live steam temperature increments, numerical analyses were performed with a view to identifying the real stress states in the rotor critical areas. Simulations were carried out for the live steam initial temperature of 320 °C for both bound values of the temperature increment.

The nature of changes in the metal temperature of the critical areas of the rotor and of the equivalent (von Mises) stress arising during start-up is shown in Figs. 8. and 9.

Analyzing the obtained results of the maximum values of von Mises stress (Fig. 18), it can be seen that the values from start-up at the rate of 2.0 K/min do not exceed the permissible limit and they still feature a stress reserve. However, the start-up process run at the rate of $\Delta\mathrm{T}/\Delta t = 3.0$ K/min resulted in the stress level reaching dangerous values. Therefore it seems

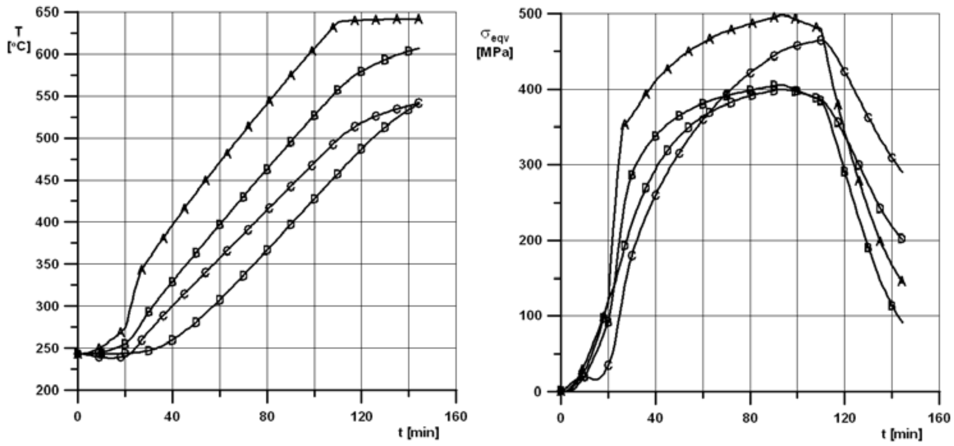

Figure 8. Curves illustrating changes in the metal temperatures and in the equivalent (von Mises) stress in the critical areas of the rotor of the turbine HP part for $\Delta T/\Delta t = 3.0$ K/min.

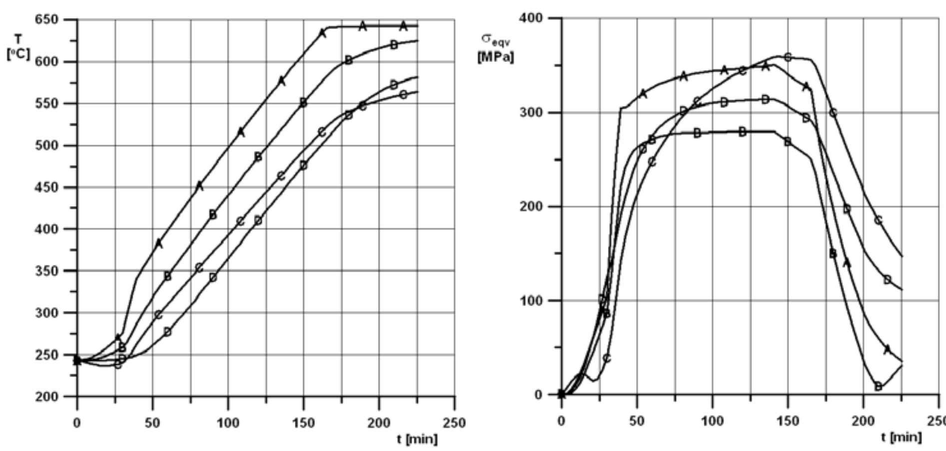

Figure 9. Curves illustrating changes in the metal temperatures and in the equivalent (von Mises) stress in the critical areas of the rotor of the turbine HP part for $\Delta T/\Delta t = 2.0$ K/min.

correct to assume that the turbine start-up processes could be run at a rate higher than $\Delta T/\Delta t = 2.0$ K/min, not exceeding however the value of 3.0 K/min.

3.4 Start-up from the initial cold state with the average rate of the live steam temperature increment of $\Delta T/\Delta t = 2.5$ K/min

Considering the calculation results presented above, it is assumed that the optimum rate of the start-up process – in terms of the permissible stress level – is the one with the gradient of $\Delta T/\Delta t = 2.5$ K/min. The correctness of this assumption was checked by means of numerical computations identifying the real thermal and stress states in the machine during start-up. The analyses were carried out for the live steam initial temperature of 320 °C. The steam parameters stabilised after 162 min after the start-up process began. The range of changes in the metal temperature and in the equivalent (von Mises) stress during start-up in the critical areas of the rotor is presented in Fig. 10.

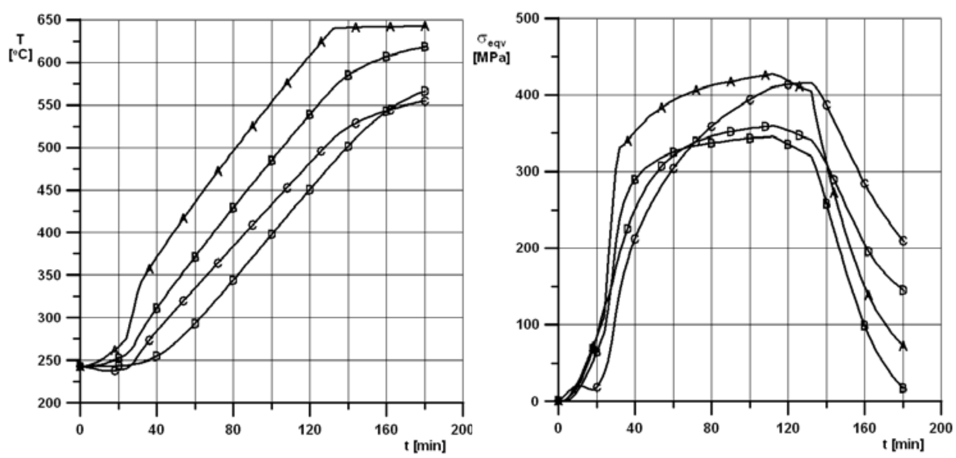

Figure 10. Curves illustrating changes in the metal temperatures and in the equivalent (von Mises) stress in the critical areas of the rotor of the turbine HP part for $\Delta T/\Delta t = 2.5$ K/min.

All the obtained values of the maximum von Mises stress in the monitored critical points of the rotor are included below the short-term yield point (Fig. 18.). Therefore it may be assumed that running the start-up process from the initial cold state with the live steam temperature gradient of 2.5 K/min will not present any risk of permanent damage to the turbine.

3.5 Start-up from the initial cold state with the average rate of the live steam temperature increment of $\Delta T/\Delta t = 2.6$ K/min

The start-up rate assumed in previous analyses ($\Delta T/\Delta t = 2.5$ K/min) ensures a safe mode of the turbine start-up in terms of minimum stress. However, there is another operating criterion that has to be taken into account, namely to bring down the costs related to the completion of each start-up phase of turbomachinery to the minimum. A reduction in operating costs is possible by, among others, shortening the times of start-up or shutdown of the machine. As there was a considerable stress reserve between stress values at start-up at the rate of 2.5 K/min and the conventional yield point of the rotor material (Fig. 18), the start-up increment rate was raised by 0.1 K/min. The further calculations aim to check whether a faster start-up could result in exceeding the permissible stress level for the machine material. The simulations were carried out for the live steam initial temperature assumed at 320 °C. The changes in the metal temperature and in the equivalent (von Mises) stress during start-up in the rotor critical areas are presented in Fig. 11.

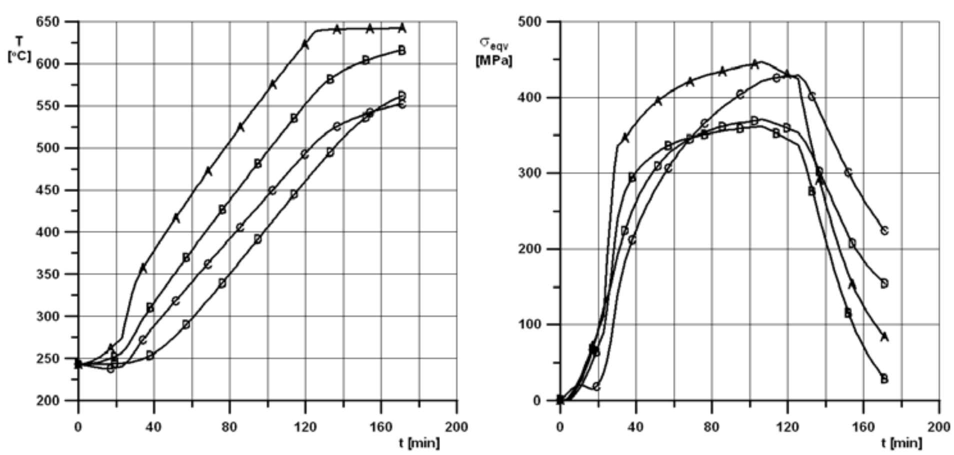

Figure 11. Curves illustrating changes in the metal temperatures and in the equivalent (von Mises) stress in the critical areas of the rotor of the turbine HP part for $\Delta T/\Delta t = 2.6$ K/min.

Putting the obtained maximum values of von Mises stress onto Fig. 18, it can be stated that the economy of the start-up process was improved, with the criterion of the turbine safe operation satisfied at the same time.

Therefore it may be assumed that running start-up processes of the analyzed machine from the initial cold state at the live steam temperature increment rate of 2.6 K/min is the optimum solution.

The Figs. 12–17 present distributions of the temperature fields (in [°C]) and of the values of equivalent (von Mises) stress (in [MPa]) for the optimum start-up ($\Delta T/\Delta t = 2.6$ K/min) at the moment when maximum values of stress appear, i.e., in the 106th minute of the process.

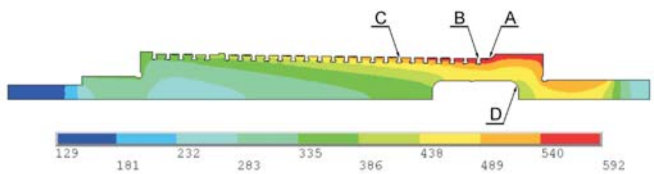

Figure 12. Temperature distribution in the rotor of the turbine HP part in the 106th minute of the start-up process.

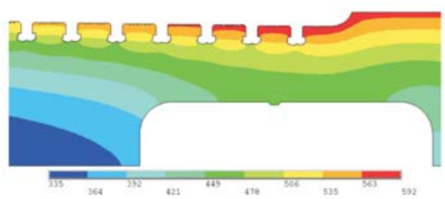

Figure 13. Temperature distribution in the first seven stages of the rotor of the turbine HP part in the 106th minute of the start-up process.

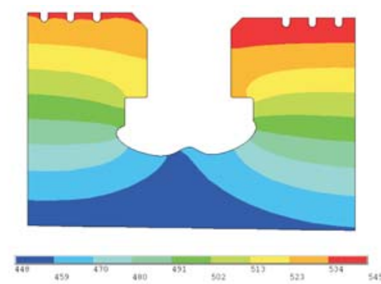

Figure 14. Temperature distribution in the groove area of the seventh stage of the rotor of the turbine HP part in the 106th minute of the start-up process.

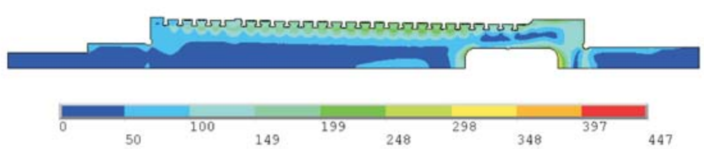

Figure 15. Distribution of equivalent (von Mises) stress in the rotor of the turbine HP part in the 106th minute of the start-up process.

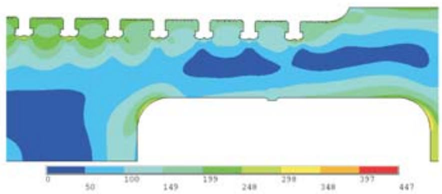

Figure 16. Distribution of equivalent (von Mises) stress in the area of the first seven stages of the rotor of the turbine HP part in the 106th minute of the start-up process.

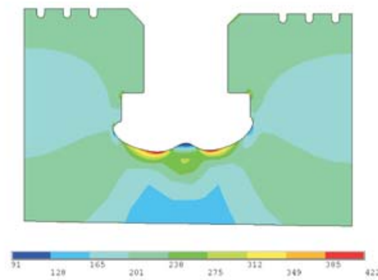

Figure 17. Distribution of equivalent (von Mises) stress in the groove area of the seventh stage of the rotor of the turbine HP part in the 106th minute of the start-up process.

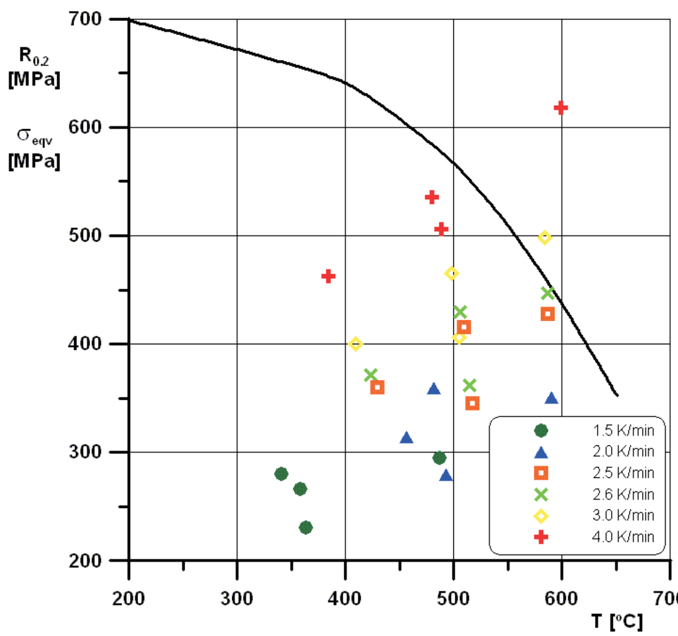

Figure 18. Values of maximum von Mises stress for different increment rates $\Delta T/\Delta t$ during start-up compared to the yield stress (points – maximum values of equivalent (von Mises) stress in start-ups, curve – yield stress $R_{0.2}$).

Figure 18 includes a list of stress values obtained from all performed analyses. It presents the points corresponding to the maximum values of von Mises stress depending on temperature and arising during the simulated start-ups from the initial cold state. The figure also presents the yield point curve, which constitutes the reference limit for the conducted optimization analyses.

4 Conclusions

At present there is still a lack of reliable experience related to the operation of ultra-supercritical parameter power units. It is known, however, that all the factors mentioned in this article, i.e., the design structural form of the components as well as the method of operation will have an essential impact both on the power unit current availability and its service life. Proper selection of geometric and material features, optimal start-up characteristics will help reduce stresses and extend the operating time of more than ten thousand hours. The example selection of the turbine optimum start-up characteristics presented herein indicates that it is possible to run the start-up process in such a way that a safe level of stress for the main components is ensured on the one hand, and – on the other – the power unit start-up losses are kept at the minimum.

Acknowledgement The results presented in this paper were obtained from research work cofinanced by the National Centre of Research and Development in the framework of Contract SP/E/1/67484/10 – Strategic Research Programme – Advanced technologies for energy generation: "Development of a technology for highly efficient zero-emission coal-fired power units integrated with CO_2 capture".

Received 8 July 2013

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