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Profits from the modernization of the start-up procedures for steam turbines aimed to achieve the planned lifetime

K e y w o r d s

Modernization, steam turbine, start-up, start-up losses, life time.

S ł o w a k l u c z o w e

Modernizacja, turbina parowa, rozruch, straty rozruchowe, czas pracy, trwałość.

S u m m a r y

This paper analyses the task of the modernisation of the start-up processes for steam turbines. The modernisation is aimed to extend the total lifetime. The methodology is presented, which chooses the new start-up conditions with the regard to the actual material wear of the components. The paper describes the range of the conducted research and its results. The choice of the specific optimisation approach should be based on the economic calculations. Therefore the solution of the formulated problem regards the criterion of the minimum costs in the longer periods.

1. Introduction

An existing power cycle is under investigation here. Its machines are exploited in a considerable degree. The assessment of the state of health

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conducted for the steam boiler and the turbine revealed a high level of material wear. This fact has a decisive influence on the further operation of the power cycle. Such a situation requires an analysis of various approaches towards modernisation, which guarantee further savings and effective operation [1 - 3].

The modernisation should aim to obtain the desired (expected, assumed, planned) time of the further operation ($t_{planned}$).

The development of the detailed assumptions for the modernisation begins with the analysis of the initial state of health of the investigated cycle. In the case of the power cycle the state of health is described by the following: the efficiency of the whole cycle and its components, the degree in which the cycle satisfies the environment protection criteria and the level of material wear of the main components. The final result of the analysis of the actual state of health for the steam turbine determines [4] the following:

- The residual time of operation for the main components: valves, casings and rotors ($t_{res,i}$), and
- The residual time of operation for the whole machine (t_{res}).

The basic condition of the further savings in operation may be presented as follows:

$$t_{res} \geq t_{planned} \tag{1}$$

which means that the residual time of operation must be greater than the desired one.

If the condition (1) is not satisfied, then the residual time of operation should be extended. This may be achieved through the following:

- The replacement of the most exploited components (the case when the whole machine is replaced must also be taken into consideration), and
- The actions which decrease the rate of material wear during the operation.

The rate of the material wear may be decreased by changing the operation procedures for various periods of the operation. In practice, the modernisation most often affects the following:

- The steady states, and
- The start-ups from various initial thermal states.

Each of the above mentioned actions for the modernisation includes two stages, two partial tasks aimed to determine the following:

- Such conditions for the operation, which allow to achieve the planned time of operation ($t_{planned}$) and satisfy the Equation (1); and,
- The profit, if any, from the modernisation.

The replacement or repair of the components is connected with some investment costs. The modernisation of the operation procedures influences the working costs (for example the costs connected to the start-up losses), which must be considered during the economic assessment of the modernisation [5, 6].

The modernisation understood in such a manner, meaning a solution of the two partial tasks described above, is discussed in this paper. Especially the choice of the new start-up conditions is analysed here in detail.

2. The formulation of the modernisation task for the start-up procedures

The modernisation of the start-up conditions for the steam turbine aimed to achieve the desired time of operation is considered as a task in which the total costs of the operation must be minimised over a longer period of time. There are two detailed problems:

a) The optimisation of the start-up, and

b) The optimisation of the operation conditions in longer periods of time.

The first problem is illustrated in Fig. 1. Let the point 1 determine an arbitrary, real turbine start-up. Let $t_{st,1}$ be the total duration of the start-up. The start-up is conducted in such a manner that the maximal amplitude of the stresses in the analysed component is $\Delta\sigma_1$ during one whole cycle of load changes. Then the points 2-6 in Fig. 1 describe the possible approaches towards the modernisation.

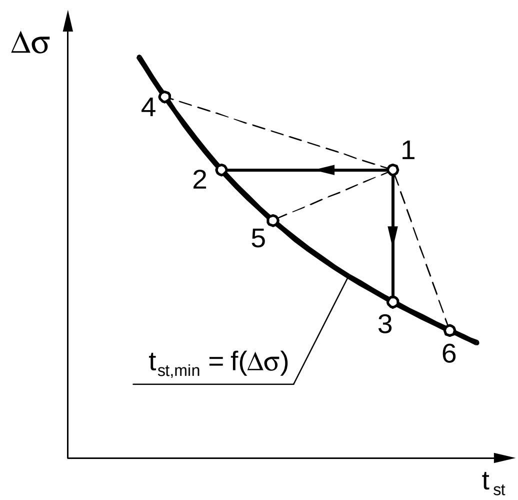

Fig. 1. Options of the modernisation of the turbine start-ups
Rys. 1. Możliwości modernizacji rozruchów turbiny

In each case the start-up is duration-optimal (for the assumed limit stress amplitude the live steam temperature and electric power are increased in such a manner that the maximal stress amplitude in an analysed component equals the limit value and the duration is the shortest). However, the total effects of modernisation differ in each case (points 2 - 6 in Fig. 1):

- ♦ Start-up optimisation with an unaffected stress value (passing from point 1 to 2).
  This optimisation decreases the duration of the start-up. Shorten duration results in decreased start-up losses. The rate of the fatigue wear and the residual time of operation remain the same.
- ♦ Start-up optimisation with the unaffected start-up duration (passing from point 1 to 3).
  This optimisation allows a decrease in the stress amplitude. The rate of fatigue wear also decreases and the residual time of operation becomes longer. In such a situation, the production of the electricity is larger. The start-up losses remain unaffected.
- ♦ Intermediate variant of the optimisation (passing from point 1 to 5)
  Optimisation decreases both the stress amplitude as well as the start-up duration. The residual time of the operation is longer and more electricity is generated. The start-up losses are lower.

2.1. Modernisation of the turbine start-ups over longer periods of time

Summarising the conducted research, it should be stated that each point 2 - 6 in Fig. 1 depicts another decrease of the start-up duration and therefore other start-up losses. Also the fatigue wear varies, as does the residual time of the operation.

This research proposes to make the final choice of the modernisation variant during the second stage of the modernisation. The choice of the start-up conditions for the steam turbine is based on the economic calculation performed for a longer period of the operation.

The task is formulated as follows:

- The start-up duration t_{st} is under optimisation.
- The following task is already solved: the start-up may be optimised for any single main component of the steam turbine. This means that the relationship $t_{st,min} = f(\Delta\sigma)$ - Fig. 2 - is known.
- The conditions of operation in steady states remain unchanged.
- The task is to determine such a duration of the start-up t_{st}, which would allows the extension of the residual time of the operation to the desired value (1)

$$t_{res} = t_{planned} \tag{2}$$

- The task requires also the economic analysis of the optimisation. This assessment is only to verify whether the optimisation is profitable.

The solution to the task determines such a position of the point “1” with the coordinates $t_{st,1}$ and $\Delta\sigma_1$ on the curve $t_{st,min} = f(\Delta\sigma)$, which satisfies the above assumptions. Point “1” describes new conditions of the start-up that also consider the residual time of the operation of the turbine. The conditions of the operation prior to the analysis are described by the point “0” with the coordinates $t_{st,0}$ and $\Delta\sigma_0$. If all the start-ups prior to the analysis were duration-optimal (point “0” lies on the curve $t_{st,min} = f(\Delta\sigma)$ in Fig. 2), then the modernisation of the start-ups aimed to extend the residual time of the operation extends all the start-ups, regardless of the initial thermal state.

$$t_{st,1,i} > t_{st,0,i} \quad i = c,w,h \tag{3}$$

where: $t_{st,0}$ - duration of the start-up before the modernisation
$t_{st,1}$ - duration of the start-up after the modernisation

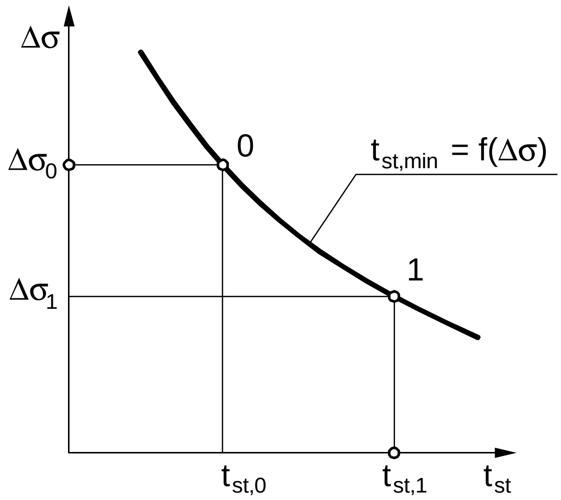

Fig. 2 Duration-optimal start-ups
Rys. 2. Rozruchy czasowo-optymalne

2.2. Assumptions, basic relationships and input data

The following analyses are correct for the assumptions and basic relationships presented below. It is also assumed that all the values defined as input data for the analysis are already known.

a. The conditions of the operation in steady states are defined uniquely by the values:

$$\{T_0, p_0, t, \sigma^c_j\} \tag{4}$$

T_0, p_0 – live steam temperature and pressure,
t – the duration of the steady state,
σ^c_j – maximal stress in the j-th component of the turbine, calculated with the respect to the material creep.

b. The conditions of the start-up are defined uniquely by the values:

$$\{t_{st}, \Delta\sigma_j\} \tag{5}$$

$\Delta\sigma_j$ – amplitude of the stresses in the j-th component of the turbine calculated for the whole cycle load.

c. The basic data required when determining the present state of health of the main components of the steam turbine includes the following:

- The total time of operation prior to the analysis - t_0 ;
- The total number of start-ups prior to the analysis - N_0; and,
- The records of the turbine start-ups, extraordinary states of operation and failures.

In the list above, the start-ups are divided into the number of start-ups from the cold ($N_{0,c}$), warm ($N_{0,w}$) and hot ($N_{0,h}$) initial thermal state.

d. All the events, which significantly affect the rate of material wear, are treated with special attention. This involves extraordinary states of operation and failures.

e. The amplitude of the stresses is calculated for each group of the start-ups for the whole load cycle, which includes a start-up, an operation in steady states under various loads, and a shut down during which the turbine cools off. In this paper, it is assumed that the results of such analysis are already known.

f. Based on the linear cumulative damage theory, the component wear prior to the analysis (the present wear, initial for the further operation) is a sum of the creep and fatigue wear.

$$Z_0 = \frac{t_0}{t_f} + \sum_i \frac{N_{0,i}}{N_{f,i}} \qquad i = c,w,h \tag{6}$$

where:

t_f – maximal time of the operation under the given stress σ^c and temperature T taken from the creep characteristics $t_f = f(T,\sigma^c)$,

N_f – the limit number cycles with load changes before the damage; this number is taken from the material fatigue characteristics $N_f = f(\Delta\sigma)$.

g. The frequency of the turbine start-ups remains unchanged, which means that the following proportion is satisfied:

$$\frac{N_{res,i}}{t_{res}} = \frac{N_{0,i}}{t_0} \qquad i = c,w,h \tag{7}$$

The conditions of the operation in steady states remain unaffected. Therefore, the stress σ^c and metal temperature T both remain unchanged, namely:

$$\sigma^c_{j,1} = \sigma^c_{j,0} = \sigma^c_j$$

$$T_{j,1} = T_{j,0} = T \tag{8}$$

where “j” is the number of the component.

The duration of the start-up changes as well as the amplitude of stresses in the j-th component for the whole load cycle after the start-up from the initial cold, warm or hot thermal state as follows:

$$t_{st,1,i} \neq t_{st,0,i}\ ,$$
$$\Delta\sigma_{j,1,i} \neq \Delta\sigma_{j,0,i} \qquad i = c,w,h \tag{9}$$

3. The dependency between the amplitude of stresses in the components and the duration of the start-up

The stresses in the components of the steam turbine change according to the present condition of the operation. Some phases of the load cycles may be highlighted as they significantly affect the stresses in the components. There is a start-up or a rapid change of the load and, on the other end, there is a shutdown load decrease or a cooling-off. Among these phases, the maximal stresses appear during a start-up.

According to the above issues, the determination of the stress amplitude $\Delta\sigma$ in the components for whole load cycle is reduced (simplified) to a determination of the maximal effective stresses during start-up. The assumption is that the cooling-off after a shutdown proceeds in a natural manner, and this process does not affect the amplitude of stresses. Hence,

$$\Delta\sigma(t_{st}) = \sigma_{red,max}\,(t_{st}) \tag{10}$$

The sought dependency between the amplitude of the effective stresses and the duration of the start-up is the solution to the task of the start-up optimisation (first detailed optimisation task formulated in Section 2). In this paper, it is assumed that the results of such an analysis are already known. Only duration-optimal start-ups are under further analysis.

An example of the dependency for the amplitude of the stresses for two components of the turbine (denoted as A and B) is shown in Fig. 3.

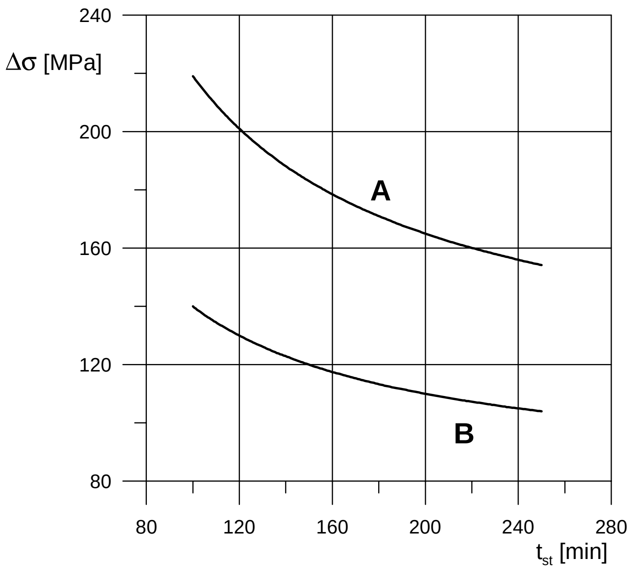

Fig. 3. Dependency between the amplitude of stresses and duration of the start-up
(A, B - the components of the turbine)
Rys. 3. Zależność amplitudy naprężeń w elementach turbiny od czasu rozruchu
(A, B - elementy turbiny)

4. The effect of the start-up on the residual time of operation of the turbine components

The problem of determining the residual time of operation for the turbine components was analysed in details in [4, 7]. The total material wear of the component Z_{tot} may be presented as the sum of the material wear prior to the analysis Z_0 and the residual (future) material wear Z_{res}:

$$Z_{tot} = Z_0 + Z_{res} = Z_0 + Z_{N,res} + Z_{t,res} \tag{11}$$

where: $Z_{t,res}$ – residual (future) creep wear

$$Z_{t,res} = \frac{t_{res}}{t_f} \tag{12}$$

$Z_{N,res}$ – residual (future) fatigue wear

$$Z_{N,res} = \sum_i \frac{N_{res,i}}{N_{f,i}} \qquad (i = c,w,h) \tag{13}$$

$N_{res,i}$ $(i = c,w,h)$ – residual number of start-ups from the cold, warm and hot initial thermal state.

Inserting (12) and (13) into (11) yields:

$$t_{res} = t_f \left(1 - Z_0 - \sum_i \frac{N_{res,i}}{N_{f,i}} \right) \quad (i = c,w,h) \tag{14}$$

The last equation states that the residual time of operation of the turbine components depends on the present degree of the material wear Z_0, future conditions of the operation in steady states (the time t_f depends on the stress σ^c and temperature T), future conditions of the operation in unsteady states (the amplitudes $\Delta\sigma_i$, which affect the $N_{f,i}$), and residual number of start-ups from various initial thermal states ($N_{res,i}$).

If the conditions of the turbine operation remain unchanged, then the formula (14) becomes more simplified.

$$t_{res,0} = t_0 \frac{1 - Z_0}{Z_0} \tag{15}$$

In the analysed problem of the modernisation of the turbine start-up procedures, only the amplitudes of the stresses $\Delta\sigma_i$ change. The assumptions (7) and (8) remain correct. In this situation, Equation (14) becomes the following:

$$t_{res} = \frac{1 - Z_0}{\frac{1}{t_f} + \sum_i \frac{N_{0,i}}{t_0 \, N_{f,i}}} \quad (i = c,w,h) \tag{16}$$

The applied load affects the maximal value of the stress σ^c in the steady state and the amplitude of stresses $\Delta\sigma$ during the change of the load. To simplify the analysis, it is assumed that the temperature T and the stress σ^c remains unchanged at the steady state and that the consecutive load cycle causes the same amplitude of stresses.

For a known maximal stress in a steady state σ^c and component temperature T, the maximal time of possible operation is determined from a creep characteristic.

The fatigue characteristics allow determining the acceptable (maximal) number of start-ups $N_f = f(\Delta\sigma)$. In practice, this dependency is approximated as follows:

$$N_f = C \left(\frac{\Delta\sigma}{E} \right)^{-D} \tag{17}$$

where: C, D – constants,
E – Young modulus,
$\Delta\sigma$ – amplitude of stresses.

Figure 4 shows the dependency between the residual time of operation and the duration of the turbine start-up for two chosen components. The residual time of operation increases with the elongated duration of the start-up. However, it should be noted that the increase is lower as the duration of the start-up becomes longer. The effectiveness of the modernisation aimed to achieve the desired time of operation for a turbine is then restricted.

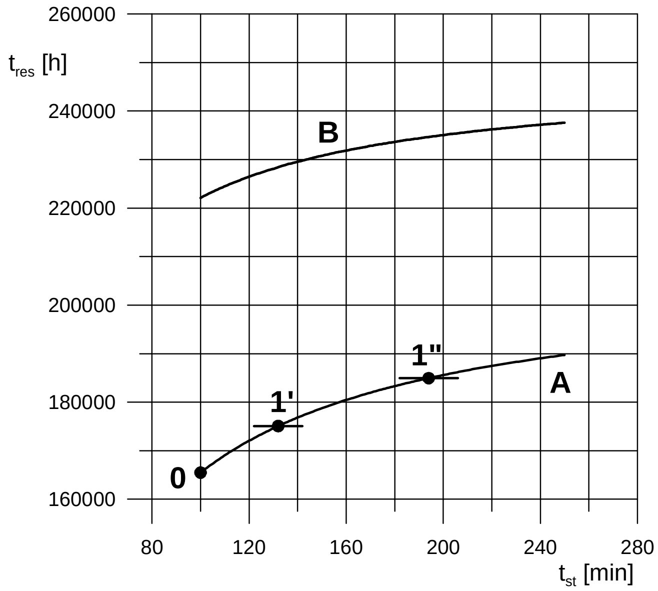

Fig. 4. The dependency between the residual time of operation and the duration of the turbine start-up (A, B - turbine components)
Rys. 4. Zależność pozostałego czasu pracy elementów turbiny od czasu rozruchu (A, B - elementy turbiny)

5. The effect of the start-up duration on the start-up losses

The start-up losses are the sum of the energy losses connected to the cycle of the shutdown, standstill and start-up. In general this is as follows:

$$E_s = E_{in} - E_{out} \quad (18)$$

where: E_{in} – energy supplied in fuel (oil, gas, coal), electricity or in the steam from the external sources,
E_{out} – energy in the generated electric power.

After all the terms in Equation (18) are determined the formula becomes

$$E_S = \left(E_c + E_O + E_g\right) + E_{steam} \frac{1}{\eta_{steam}} + \left(E_{pw} - E_b\right)\frac{1}{\eta_e} \tag{19}$$

where: E_c, E_o, E_g – energy delivered accordingly in coal, oil and gas,
E_{steam} – energy delivered in steam and water from the external sources,
E_{pw} – energy for the internal load of the power cycle,
E_b – gross energy generated in the power cycle,
η_{steam} – efficiency of the steam and water production in the external sources,
η_e – the efficiency of the power generation in the analysed power plant.

The example of the steam from an external source may be the steam delivered during the start-up to the deaerator from the other power unit or from the auxiliary boiler.

Usually, to simplify the calculations, each of the losses are calculated separately: those connected with the turbine shut-off - E_{SO}, turbine cool-off - E_{SS}, the preparation of the live-steam parameters - E_{SP} and turbine start-up - E_{SR}, which means

$$E_S = E_{SO}(t_o) + E_{SS}(t_s) + E_{SP}(t_p) + E_{SR}(t_{st}) \tag{20}$$

The start-up includes the following:

– The increase of the rotation speed - the period since the rotor starts rotating until the synchronisation of the generator; and.
– The load application - the period since the synchronisation until the required power is obtained.

The results of the analysis on the start-up losses described in the literature prove that the value of the losses depends on the duration of each phase. In the Equation (20), each term depends accordingly on the duration of the shutdown t_o, cool-off t_S and start-up t_{st} [8, 9].

Applying the approach described above to the calculation of losses in each phase, the following dependency is proposed to determine the start-up losses [8]:

$$E_S = \sum_{i=1}^{m} \left[E_s(t)\right]_i = \sum_{i=1}^{m} e_{j,i}\, t_{st,i} \tag{21}$$

where: $e_{j,i}$ – the coefficient, which describes the losses per unit of the duration for the i-th phase of the start-up from the j-th thermal state,
$t_{st,i}$ – the duration of the i-th phase of the start-up.

Therefore, the shutdowns and start-ups are divided into the "i" number of phases, each with a specified coefficient $e_{j,i}$. The losses depend linearly on the duration of the phase.

The coefficients $e_{j,i}$ depend on the thermal state of the power cycle, its type, and the conditions under which the start-up is conducted. The coefficients are determined experimentally. For example, for the 220 MW power cycle with a drum boiler, the coefficients for the phase when the live steam parameters are raised have the following values: $e_{c,p}$ = 70 MW; $e_{w,p}$ = 80 MW; $e_{h,p}$ = 108.3 MW (where c, w, h denote the start-up, respectively, from the cold, warm or hot initial thermal state) [8].

The example described below shows how the coefficient $e_{c,st}$ is determined for a start-up from the cold thermal state for a steam turbine of great power. The results of the measurements required to determine the coefficient are shown in Figs. 6 and 7.

Figure 5 shows the changes of the rotation speed and electric power during the start-up until the demanded power of 140 MW was obtained. The start-up lasted for about 260 minutes.

Figure 6 presents the measurements of the amount of coal and fuel oil burned during the start-up. In the first stage of the start-up, only the fuel oil is burned. After the synchronisation, when the load increases, the amount of fuel oil decreases while the amount of coal increases.

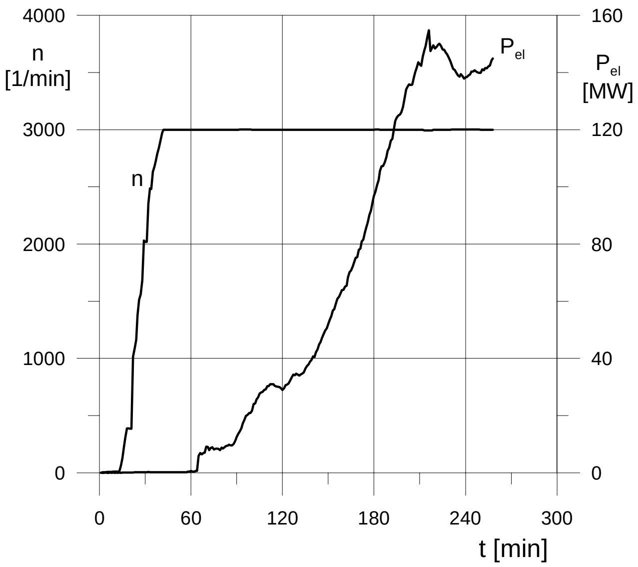

Fig. 5. Rotation speed and electric power during the start-up from the cold thermal state
Rys. 5. Przebiegi czasowe obrotów i mocy w czasie rozruchu ze stanu zimnego

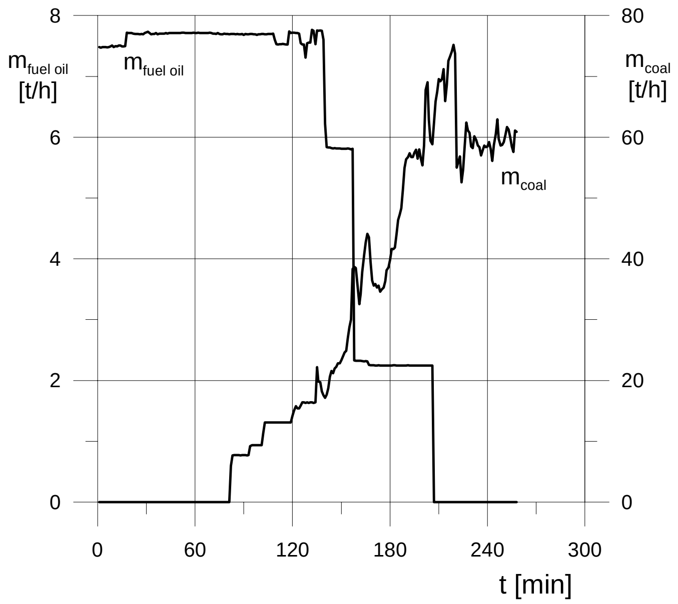

Fig. 6. The amount of coal and fuel oil burned during the start-up
Rys. 6. Wyniki pomiarów zużycia węgla i mazutu w czasie rozruchu

The start-up losses and coefficient $e_{c,st}$ were determined in the direct method. This method balances the energy delivered to the power unit and extracted in the form of energy power.

Only those energy losses are considered that arise during the start-up. In this case, based on the Equations (19) - (21) one obtains the following:

$$E_{SR} = \left(E_c + E_o\right) + \left(E_{pw} - E_b\right)\frac{1}{\eta_e} \tag{22}$$

$$E_{SR} = e_{c,st}\, t_{st} \tag{23}$$

After the losses E_{SR} are determined from the Equation (22) on the basis of the measurement data (Fig. 5 and 6) the sought coefficient is calculated as follows:

$$e_{c,st} = \frac{E_{SR}}{t_{st}} \tag{24}$$

The duration of the start-up t_{st} includes the periods when the rotation speed and load increase. The symbol E_o in Equation (22) stands for the energy supplied in the fuel oil. The energy supplied in the steam and water from the external sources is omitted here.

The terms in the Equation (22) are as follows:

- Energy supplied in the fuel oil (the energy supplied in the coal E_c may be determined in the same manner):

$$E_0 = \int_0^{t_r} M_0(t)\, W_{d,o}\, dt \tag{25}$$

where: M_o – amount of the fuel oil,
$W_{d,o}$ – lower heating value of the fuel oil,

Energy extracted in the generated electric power:

$$E_{out} = E_b - E_{pw} = \int_0^{t_r} \left[P_{el}(t) - P_{pw}(t)\right] dt \tag{26}$$

where: P_{el} – output electric power of the cycle measured at the electric generator,
P_{pw} – internal power

The integrals in (25) and (26) are calculated by numerical methods. For the measurement data, which dependency on time is shown in Figs. 5 and 6, the coefficient $e_{c,st}$ for the start-up of the 225 MW steam turbine from the cold initial thermal state equals:

$$e_{c,st} = 140.8 \text{ MW}$$

The same approach allows the determination of the coefficients for the start-ups from warm and hot initial thermal states.

6. Economic assessment of the modernisation of the start-up procedures for steam turbines

The economic assessment conducted for the analysed option of the modernisation of the start-up must regard the following facts:

- According to the comments listed in the Section 2.1 and the Equation (3), if the start-ups before the modernisation were conducted as time-optimal then the modernisation aimed to extend the residual time of operation extends this time by the value:

$$\Delta t_{st} = t_{st,1} - t_{st,0} \tag{27}$$

- The losses ΔE_S and start-up costs ΔK_S both increase:

$$\Delta K_S = K_S\,(t_{st,1}) - K_S\,(t_{st,0}) \tag{28}$$

After the duration of the start-up is extended, only the start-up costs increase - K_{SR}:

$$\Delta K_{SR} = K_{SR}\,(t_{st,1}) - K_{SR}\,(t_{st,0}) \tag{28.a}$$

Also assuming that the losses and costs depend linearly on the duration of the start-up gives

$$\Delta K_{SR} = k_{sr}\, N_{res}\,(\, t_{st,1} - t_{st,0}\,) \tag{28.b}$$

where: k_{sr} – start-up cost per unit of time [zł/h],
N_{res} – residual (future) number of start-ups.

- The turbine operates additional period of time $\Delta t_{res} = (t_{res} - t_{res,0})$
- During the additional time of operation an additional profit is generated from the production of the electric power

$$\Delta S = k_{el}\, P^{*}_{el}\, (t_{res} - t_{res,0}) \tag{29}$$

where: k_{el} – a profit from the sold electric power per unit of energy [zł/MWh]
P^{*}_{el} – average electric power of the cycle.

In the simplest form, the economic effect (ΔC) of the modernisation project is determined by the difference between the profit ΔS and losses ΔK_{SR}:

$$\Delta C = \Delta S - \Delta K_{SR} \tag{31}$$

The maximisation of the index ΔC for a modernisation project is taken as an objective function for the problems with the optimisation of the operating conditions of the steam turbines:

$$\Delta C \rightarrow MAX \tag{32}$$

7. The modernisation of the turbine start-up aimed to achieve the planned lifetime

The machine under analysis is a steam turbine, which has operated for a large number of hours and had several hundreds of start-ups. In order to simplify the calculations, it is assumed that all the start-ups were conducted from a cold initial thermal state and the stress amplitude was the same during all start-ups. Such an assumption does not change the essence of the problem.

For the above assumptions, the relations (7) and (16) take the following forms respectively:

$$\frac{N_{res}}{t_{res}} = \frac{N_0}{t_0} \tag{33}$$

$$t_{res} = \frac{1 - Z_0}{\dfrac{1}{t_f} + \dfrac{N_0}{C\, t_0}\left(\dfrac{\Delta\sigma}{E}\right)^D} \tag{34}$$

Equation (34) also integrates the approximation (17). Inserting (33) with (28.b) and (29) into (31) gives the following:

$$\Delta C = k_{el}\ P_{el}^{*}\left(t_{res} - t_{res,0}\right) - k_{sr} t_{res} \frac{N_0}{t_0}\left(t_{st,1} - t_{st,0}\right) \tag{35}$$

or in a dimensionless form:

$$\frac{\Delta C}{k_{el} P_{el}^{*} t_{res,0}} = \frac{t_{res}}{t_{res,0}}\left[1 - \frac{k_{sr} N_0}{k_{el} P_{el}^{*}}\ \frac{t_{st,1} - t_{st,0}}{t_0}\right] - 1 \tag{36}$$

Using the following symbols:

$$\Delta C_{rel} = \frac{\Delta C}{K_{el} P_{el}^{*} t_{res,0}} \tag{37}$$

$$A_{\cos t} = \frac{k_{sr} N_0}{k_{el} P_{el}^{*}} \tag{38}$$

the dimensionless equation may be rewritten as

$$\Delta C_{rel} = \frac{t_{res}}{t_{res,0}}\left[1 - A_{\cos t}\ \frac{t_{st,1} - t_{st,0}}{t_0}\right] - 1 \tag{39}$$

The economic effectiveness of the modernisation of the turbine start-ups is shown in Figs. 8 and 9. The calculations are for the following input data:

- The total time of operation prior to the analysis t_0 = 150 000 h,
- The total number of start-ups prior to the analysis N_0 = 1200,
- The start-up duration prior to the analysis $t_{st,0}$ = 100 min.

The maximal reduced stress operation and the temperature of the component A (Figs. 3 and 4) in a steady state equal

$$\sigma^c = 90 \text{ MPa}$$
$$T = 530\ ^{o}\text{C}$$

The dependency between the stress amplitude $\Delta\sigma$ and the duration of the start-up t_{st} for the component A is assumed according to Fig. 3.

Figure 7 shows the increase of the relative net profit ΔC_{rel} in a relation to the duration of the start-up. Depending on the value of the coefficient $A_{cost,}$ this function reaches a maximum value and then drops down to the negative values. This means that the modernisation through the change of the start-ups duration is not always profitable. Figure 4 presents two sample variants of the modernisation of the turbine start-ups.

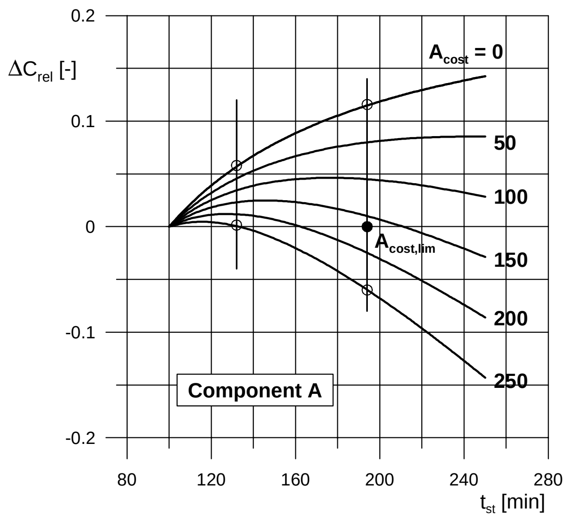

Fig. 7. The dependency between the ΔC_{rel} and the duration of the turbine start-up and coefficient A_{cost}

Rys. 7. Zależność względnego przyrostu zysku netto od czasu trwania rozruchu i współczynnika A_{cost}

Variant I

The turbine may operate in the same regime as before the analysis during next the 165 000 hours (point 0 in Fig. 4) - with respect to the durability of the component A.

The task is to adjust the duration of the start-ups in order to extend the residual time of operation up to t_{res} = 175 000 hours.

Figure 4 suggests that the duration t_{st} = 132 minutes (point 1' in Fig. 4) is the solution. Within the range of possible variations of the coefficient $A_{cost,}$ such modernisation is always profitable (line 1' in Fig. 7).

Variant II

The task is now to adjust the duration of the start-ups in order to extend the residual time of operation up to t_{res} = 185 000 hours.

Figure 4 suggests that the duration t_{st} = 194 minutes (point 1” in Fig. 4) is the solution. This variant is not always profitable (line 1” in Fig. 7). It is possible to find a limiting value $A_{cost,lim}$ in Fig. 7, above which the modernisation is not profitable ($\Delta C < 0$).

The economic effectiveness of the analysed variants may also be assessed on the basis of the Fig. 8. This figure presents the dependency between the increase of the relative net profit ΔC_{rel} and the coefficient A_{cost} for two durations of the turbine start-ups. The first variant (duration t_{st} = 132 min) the relative net profit ΔC_{rel} is positive for all values of the A_{cost}.

The profit from the second variant (duration t_{st} = 194 min) depends on the value of the coefficient A_{cost}. The boundary of the positive profit area is defined by the limiting value $A_{cost,lim,}$ similarly, as in Fig. 7.

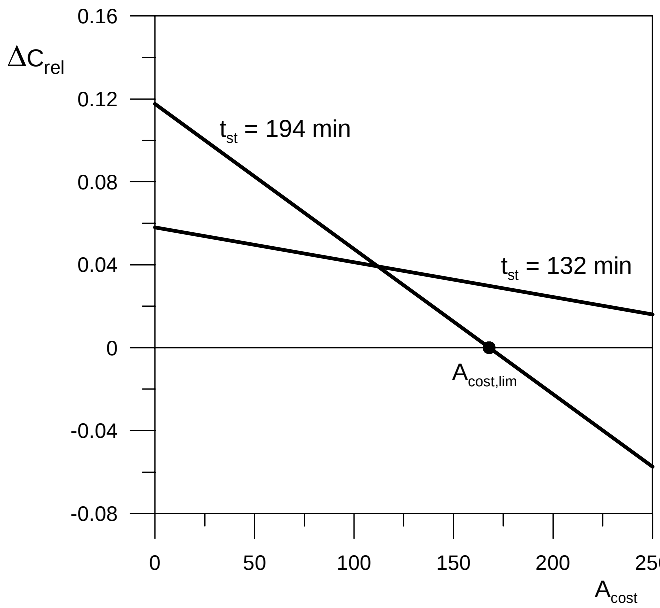

Fig. 8. The dependency between the ΔC_{rel} and coefficient A_{cost} for two start-ups durations
Rys. 8. Zależność względnego przyrostu zysku netto ΔC_{rel} od współczynnika A_{cost} dla dwóch czasów rozruchu turbiny

8. Conclusions

In the conducted research, a problem of the modernisation of steam turbine start-ups conditions was formulated. The aim of the modernisation is to expand the time of the operation. The research analysed the possibilities to decrease the wear rate of the main components through the modernisation of the conditions of the operation. The adjustments may concern the change of the start-up processes or the decrease in the live steam parameters in the steady states of the operation.

For the turbines with high degree of the component wear, the decrease in the live steam parameters does not always guarantee the extension of the future time of operation. The change of the start-up process provides more possibilities to achieve the desired result.

The theoretical considerations as well as numerical simulations indicate that the extension of the time of operation requires the extension of the start-up durations.

Before the final decision is made concerning the application of the analysed modernisation of turbine start-up conditions, there has to be an assessment of the increased operation costs caused by the increased start-up costs. An economic assessment is therefore required for the proposed modernisation.

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Opłacalność modernizacji procedur eksploatacji turbin parowych w celu osiągnięcia oczekiwanego czasu dalszej pracy

S t r e s z c z e n i e

W pracy analizowano zadanie modernizacji procesów rozruchowych turbin parowych w celu przedłużenia całkowitego czasu pracy. Przedstawiono metodologię doboru nowych warunków rozruchu turbin z uwzględnieniem aktualnego zużycia eksploatacyjnego elementów. Omówiono zakres prowadzonych badań i uzyskane wyniki. O wyborze konkretnego wariantu optymalizacji rozruchu powinien decydować rachunek ekonomiczny. W związku z tym w rozwiązaniu sformułowanego zagadnienia uwzględniono kryterium minimalizacji kosztów w dłuższych okresach.