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The Change in Low Power Steam Turbine Operating Parameters During Extractions Opening/Closing

Abstract

The paper presents steam turbine power, energy and exergy efficiencies and losses analysis during steam extractions opening/closing. The analyzed steam turbine can be used in steam power plant or in the marine steam propulsion system (low-power steam turbine). Steam extractions opening and closing can have a notable influence on various turbine operating parameters, what is currently purely exploited in the literature. Turbine developed power during steam extractions opening/closing is direct proportional to turbine energy and exergy losses and reverse proportional to turbine exergy efficiencies. Turbine energy efficiency is not affected by steam extractions opening/closing. Considering all the combinations of turbine steam extractions opening/closing, it is obtained that the range of real developed power is between 30612.91 kW and 34289.14 kW, while the range of turbine exergy efficiencies is between 85.65% and 86.08%. The range of turbine energy power losses in all possible observed combinations is between 5401.78 kW and 6050.30 kW, while the range of exergy destruction is between 4949.44 kW and 5746.81 kW.

Keywords: Steam turbine, Steam extraction, Power, Losses, Efficiency

1. Introduction

Steam turbines of any power range are nowadays widely used for electrical power production in cogeneration [1] and various kinds of thermal power plants [2, 3]. Many researchers and engineers investigated steam turbine efficiencies and losses in various operating conditions. For example, it is interesting to observe a change in efficiencies and losses of steam turbine during power plant repowering [4], in several load conditions [5] or when the steam turbine operates in the marine environment [6].

Recently used steam turbines usually have several steam extractions which ensure steam delivery to regenerative feed water heating system or to other steam consumers. Some examples of such steam turbines with several extractions can be found not only in thermal power plants [7], but also in various nuclear power plants [8, 9]. The feed water heating system increases the temperature of the feed water with the main goal of fuel consumption reducing [10]. The benefits of feed water heating system are widely exploited in [11] for various coal-fired thermal power plants and in [12] for many different energy processes.

Steam systems which include main low-power steam turbine [13] are still the dominant propulsion systems of LNG carriers [14]. Such low-power steam turbines also have several steam extractions to ensure feed water heating [15] or steam delivery to the various marine sub-systems [16].

Energy and exergy analyses proved to be safe and reliable methods in investigation of steam turbines and entire steam power systems. Some examples of mentioned analyses application can be found in the literature for the conventional steam power plant [17], auxiliary marine low-power steam turbines [18], combined cycle power plant [19] or in investigating various steam expansion processes of a conventional steam turbine [20]. These methods ensure that efficiencies and losses of any steam system component can be calculated in a short time period if required steam operating parameters (temperature, pressure and mass flow rate) are measured inside the plant [21, 22]. Energy and exergy analyses are black box methods, therefore they do not require knowledge of the inner structure of any analyzed component in the steam system [23].

In this paper is performed analysis of low-power steam turbine developed power, energy and exergy efficiencies as well as losses during steam extractions opening/closing. Steam extractions closing will surely increase turbine developed power, but in the literature is not found what will happen with turbine efficiencies and losses in such operating regimes. As each possible steam extractions opening/closing combination is investigated, it can be concluded that the base turbine operation (when all steam extractions are open) resulted with the lowest energy and exergy losses and with the highest exergy efficiency. Simultaneously, steam extractions closing enables a notable increase in turbine developed power.

2. Analyzed steam turbine characteristics and the principle of steam extractions opening/closing

Analyzed steam turbine operates in Zarand power plant southeast of Iran [24]. Its nominal power is around 30 MW (base state operation when all steam extractions are open). The turbine has four extractions as presented in Figure 1. The first, second and third steam extractions remove a certain steam mass flow rate from the turbine and delivered that steam (each extraction individually) to high-pressure regenerative feed water heaters [25]. Fourth steam extraction leads a certain steam mass flow rate from the steam turbine to the low-pressure feed water heater [26, 27]. Steam turbine is used for an electric generator drive. Similar low-power steam turbines can be found in several solar thermal steam power plants [28, 29], cogeneration power plants [1] or in various conventional [30] and marine [31, 32] steam power plants as main or auxiliary steam turbines [33].

Steam was delivered to the inlet of the analyzed low-power steam turbine directly from steam generator [34], while the steam mass flow rate at the turbine outlet, after expansion through the turbine was led to steam condenser [35, 36]. Steam condenser significantly influenced the operation of any, especially low-power steam turbines what is thoroughly investigated in the [37] for low-power steam turbines which operate in the phosphoric acid factory and in [38] for a variety of low-power steam turbines.

Turbine analyzed in this paper and presented schematically in Figure 1 can also be used in marine steam propulsion plants due to its acceptable nominal power (marine steam power plants usually had main steam turbine which nominal power is between 20 MW and 30 MW) [39, 40].

In performed research, the observed steam turbine is analyzed as an independent component, without investigating the influences of steam extractions opening/closing on other power plant elements or on the entire steam power plant. It is considered that each steam turbine extraction can be fully opened or fully closed (partially opened extractions are not analyzed).

The closing of one or more steam extractions (in Figure 1 steam extractions are marked with operating points 2, 3, 4 and 5) will surely increase turbine developed power because higher steam mass flow rate expands through the turbine and transfer its kinetic energy into the mechanical energy inside the turbine stages. Therefore, the highest turbine power will be developed when all steam extractions are closed. However, it will be interesting to observe which steam extractions opening/closing combination has the highest influence on the turbine power increase.

Energy and exergy analyses of the selected (or any other) steam turbine do not require knowledge of the turbine inner structure, they require only the knowledge of steam temperatures, pressures and mass flow rates in each turbine operating point presented in Figure 1 [41]. From the mentioned steam operating parameters can be calculated required steam specific enthalpies and specific exergies in each turbine operating point.

In the scientific and professional literature, the authors did not find analysis or conclusions related to the question: how steam extractions opening/closing influence energy and exergy efficiencies and losses of any turbine. Also, for the observed turbine it will be interesting to see which combination of steam extractions opening/closing have the highest influence on turbine losses, efficiencies and developed power because all possible combinations will be investigated.

From the viewpoint of the entire power plant in which analyzed turbine operates, steam extractions closing in any combination will surely result with lower feed water temperatures at the steam generator inlet [42, 43] and consequentially with higher fuel consumption.

Further analysis of the entire power plant in which investigated steam turbine operates can be profitability calculation. It will be interesting to observe did the increase in steam turbine power during the steam extractions closing can compensate an increase in steam generator fuel consumption, and if did - which steam extractions opening/ closing combination will be the most adequate.

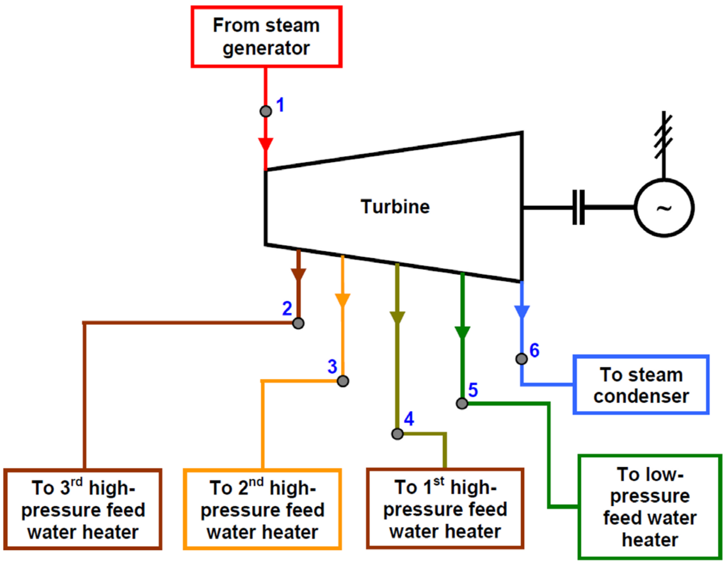

Figure 1 - Scheme of the investigated low-power steam turbine and marked operating points required in the analyses

Ideal (isentropic) and real (polytropic) steam expansion processes through the analyzed turbine are shown in Figure 2, according to operating points from Figure 1. Real (polytropic) steam expansion process is marked with numbers from 1 to 6, while ideal (isentropic) expansion process is marked with numbers from 1 to 6is.

Ideal (isentropic) steam expansion process assumes that steam specific entropy (*s*) during expansion remains constant [44]. Steam extractions are marked with red arrows (operating points 2, 3, 4 and 5). As can be seen from Figure 2, the last two operating points in the real (polytropic) expansion process (operating points 5 and 6) are under the saturation line (wet steam), according to Table 1. Exergy analysis of the turbine during the steam extractions opening/closing is performed by using real (polytropic) steam expansion process while turbine energy analysis is performed as a comparison between real (polytropic) and ideal (isentropic) expansion processes.

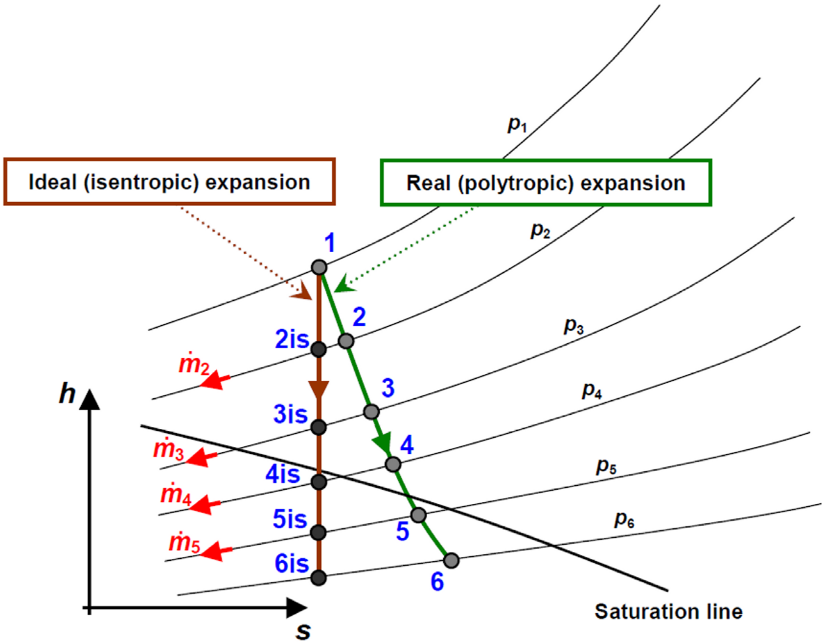

Figure 2 - Steam real (polytropic) and ideal (isentropic) expansion processes through the analyzed turbine in h-s diagram

3. Energy and exergy analysis equations

In this section are firstly presented general energy and exergy analysis equations valid for any control volume after which follows equations for the energy and exergy analyses of investigated low-power steam turbine in any combination of steam extractions opening/closing.

3.1. General equations for the energy and exergy analyses of any control volume

Energy conservation, which is defined by the first law of thermodynamics [45], represents the baseline for the energy analysis of any control volume [46]. Disregarding potential and kinetic energy, for any control volume in steady state, mass flow rate balance equation can be defined according to [47] as:

$$\sum \dot{m}_{\mathrm{IN}} = \sum \dot{m}_{\mathrm{OUT}} \ , \tag{1}$$

while the energy balance equation for the same control volume, according to [48, 49], is:

$$\dot{Q} - P = \sum \dot{m}_{\mathrm{OUT}} \cdot h_{\mathrm{OUT}} - \sum \dot{m}_{\mathrm{IN}} \cdot h_{\mathrm{IN}} \ . \tag{2}$$

The total energy (energy power) of any fluid flow is defined according to [50, 51] as:

$$\dot{E}_{\mathrm{en}} = \dot{m} \cdot h \ . \tag{3}$$

The energy efficiency of a control volume is defined by its type and characteristics [52]. Therefore, energy efficiency can take many different forms [53]. The most usual definition of energy efficiency of any control volume is:

$$\eta_{\mathrm{en}} = \frac{\text{Energy output}}{\text{Energy input}} \ . \tag{4}$$

The second law of thermodynamics defines exergy analysis of any control volume [54, 55]. The exergy balance equation for control volume in steady state is, according to [56, 57]:

$$\dot{X}_{\mathrm{heat}} - P = \sum \dot{m}_{\mathrm{OUT}} \cdot \varepsilon_{\mathrm{OUT}} - \sum \dot{m}_{\mathrm{IN}} \cdot \varepsilon_{\mathrm{IN}} + \dot{E}_{\mathrm{ex,D}} \ , \tag{5}$$

where the exergy transfer by heat ($\dot{X}_{\mathrm{heat}}$) at temperature T is defined according to [58] as:

$$\dot{X}_{\mathrm{heat}} = \sum (1 - \frac{T_0}{T}) \cdot \dot{Q} \ . \tag{6}$$

The definition of specific exergy for any fluid flow can be found in [59, 60]. Equation for specific exergy calculation is:

$$\varepsilon = (h - h_0) - T_0 \cdot (s - s_0)\,. \tag{7}$$

The total exergy (exergy power) of any fluid flow, according to [61] is:

$$\dot{E}_{\mathrm{ex}} = \dot{m} \cdot \varepsilon = \dot{m} \cdot \left[(h - h_0) - T_0 \cdot (s - s_0) \right]. \tag{8}$$

Similar to energy efficiency, exergy efficiency of a control volume is defined by its type and operating characteristics. The general exergy efficiency definition of any control volume, according to [62] is:

$$\eta_{\mathrm{ex}} = \frac{\text{Exergy output}}{\text{Exergy input}}\,. \tag{9}$$

3.2. Energy and exergy analysis equations for the investigated low-power steam turbine

Equations for the energy and exergy analyses of the investigated low-power steam turbine will be presented in this section within a situation when all of the steam extractions are open (base turbine operation). Equations for the turbine energy and exergy analyses when one or more steam extractions are closed will be defined by using the same equations.

Equations for the energy analysis of investigated low-power steam turbine with all steam extractions open, as presented in Figure 1, are:

MASS FLOW RATE BALANCE:

$$\dot{m}_1 = \dot{m}_2 + \dot{m}_3 + \dot{m}_4 + \dot{m}_5 + \dot{m}_6\,. \tag{10}$$

ENERGY BALANCE:

- Turbine real (polytropic) developed power (according to Figure 2):

$$\begin{aligned} P_{\mathrm{re}} = {} & \dot{m}_1 \cdot (h_1 - h_2) + (\dot{m}_1 - \dot{m}_2) \cdot (h_2 - h_3) + (\dot{m}_1 - \dot{m}_2 - \dot{m}_3) \cdot (h_3 - h_4) + \\ & + (\dot{m}_1 - \dot{m}_2 - \dot{m}_3 - \dot{m}_4) \cdot (h_4 - h_5) + (\dot{m}_1 - \dot{m}_2 - \dot{m}_3 - \dot{m}_4 - \dot{m}_5) \cdot (h_5 - h_6)\,. \end{aligned} \tag{11}$$

- Turbine ideal (isentropic) developed power (according to Figure 2):

$$\begin{aligned} P_{\mathrm{is}} = {} & \dot{m}_1 \cdot (h_1 - h_{2\mathrm{is}}) + (\dot{m}_1 - \dot{m}_2) \cdot (h_{2\mathrm{is}} - h_{3\mathrm{is}}) + (\dot{m}_1 - \dot{m}_2 - \dot{m}_3) \cdot (h_{3\mathrm{is}} - h_{4\mathrm{is}}) + \\ & + (\dot{m}_1 - \dot{m}_2 - \dot{m}_3 - \dot{m}_4) \cdot (h_{4\mathrm{is}} - h_{5\mathrm{is}}) + (\dot{m}_1 - \dot{m}_2 - \dot{m}_3 - \dot{m}_4 - \dot{m}_5) \cdot (h_{5\mathrm{is}} - h_{6\mathrm{is}}) \end{aligned} . \quad (12)$$

- Turbine energy power losses (energy destruction):

$$\dot{E}_{\mathrm{en,D}} = P_{\mathrm{is}} - P_{\mathrm{re}} . \quad (13)$$

- Turbine energy efficiency:

$$\eta_{\mathrm{en}} = \frac{P_{\mathrm{re}}}{P_{\mathrm{is}}} . \quad (14)$$

Exergy analysis of any control volume (as well as of the analyzed low-power steam turbine) depends on the ambient conditions. The ambient conditions (dead state conditions) in this analysis are taken as: pressure of 1 bar (0.1 MPa) and a temperature of 25 °C (298 K). For the steam turbine exergy analysis, the relevant turbine developed power is real (polytropic) power, calculated by using an Eq. (11) for the situation when all steam extractions are open (base turbine operation). The change in ambient conditions for the analyzed steam turbine is not investigated, because as presented in [63, 64], steam turbines are not significantly influenced by the ambient conditions change.

Equations for the exergy analysis of investigated low-power steam turbine with all steam extractions open (Figure 1), are:

<u>EXERGY BALANCE:</u>

- Turbine exergy input:

$$\dot{E}_{\mathrm{ex,IN}} = \dot{m}_1 \cdot \varepsilon_1 . \quad (15)$$

- Turbine exergy output:

$$\dot{E}_{\mathrm{ex,OUT}} = \dot{m}_2 \cdot \varepsilon_2 + \dot{m}_3 \cdot \varepsilon_3 + \dot{m}_4 \cdot \varepsilon_4 + \dot{m}_5 \cdot \varepsilon_5 + \dot{m}_6 \cdot \varepsilon_6 + P_{\mathrm{re}} . \quad (16)$$

- Turbine exergy destruction:

$$\dot{E}_{\mathrm{ex,D}} = \dot{E}_{\mathrm{ex,IN}} - \dot{E}_{\mathrm{ex,OUT}} = \dot{m}_1 \cdot \varepsilon_1 - \dot{m}_2 \cdot \varepsilon_2 - \dot{m}_3 \cdot \varepsilon_3 - \dot{m}_4 \cdot \varepsilon_4 - \dot{m}_5 \cdot \varepsilon_5 - \dot{m}_6 \cdot \varepsilon_6 - P_{\mathrm{re}} . \quad (17)$$

- Turbine exergy efficiency:

$$\eta_{\mathrm{ex}} = \frac{P_{\mathrm{re}}}{\dot{E}_{\mathrm{ex,IN}} - \dot{E}_{\mathrm{ex,OUT}} + P_{\mathrm{re}}} = \frac{P_{\mathrm{re}}}{\dot{m}_1 \cdot \varepsilon_1 - \dot{m}_2 \cdot \varepsilon_2 - \dot{m}_3 \cdot \varepsilon_3 - \dot{m}_4 \cdot \varepsilon_4 - \dot{m}_5 \cdot \varepsilon_5 - \dot{m}_6 \cdot \varepsilon_6}. \quad (18)$$

Equations for the analyzed turbine developed power calculation (ideal or real), energy and exergy losses and efficiencies during one or more steam extractions closing remains the same as presented above, equations from (10) to (18). The closing of one or more steam turbine extractions means that steam mass flow rate through closed steam extraction is equal to zero. Steam operating parameters (steam temperature, pressure and mass flow rate) for each open steam extraction remains the same as in the situation when all steam turbine extractions are open. The calculation principle is always the same, regardless of observed steam turbine extractions opening/closing combination.

4. Steam operating parameters of the analyzed low-power steam turbine

Required data (steam temperature, pressure and mass flow rate) in each operating point of the analyzed low-power turbine (according to Figure 1) are found in [24] for a base turbine operation. These data are obtained in real (polytropic) steam expansion process and presented in Table 1. In Table 1 are also presented steam specific enthalpies, specific entropies, specific exergies and steam quality in each turbine operating point. Calculation of all required operating parameters is performed by using NIST REFPROP 9.0 software [65].

Table 1 - Steam operating parameters (base turbine operation) at each operating point of the analyzed turbine – real (polytropic) steam expansion

O.P.*	Temperature (°C)	Pressure (bar)	Mass flow rate (kg/s)	Specific enthalpy (kJ/kg)	Specific entropy (kJ/kg·K)	Specific exergy (kJ/kg)	Quality
1	482.01	43.00	33.194	3400.96	7.009	1318.20	Superheated
2	314.61	11.72	1.945	3078.73	7.100	966.45	Superheated
3	232.52	5.29	1.147	2923.57	7.174	789.05	Superheated
4	184.84	3.09	2.028	2834.16	7.231	682.63	Superheated
5	92.81	0.78	2.641	2637.28	7.369	444.70	0.9882
6	40.79	0.08	25.433	2367.97	7.582	112.08	0.9139

** O. P. = Operating Point (according to Figure 1 and Figure 2)*

In order to calculate turbine ideal (isentropic) developed power, it was necessary to calculate steam specific enthalpies for the ideal (isentropic) expansion. The isentropic expansion process assumes that steam specific entropy remains unchanged.

For the ideal (isentropic) expansion, steam pressures and mass flow rates in each turbine operating point remain the same as for the real (polytropic) steam expansion (base turbine operation). The steam temperature at the steam expansion beginning (operating point 1, Figure 1 and Figure 2) is the same for real and ideal expansion process. Knowledge of steam temperature and pressure at the beginning of the expansion process allows steam specific entropy calculation. At other turbine operating points, steam operating parameters for ideal (isentropic) expansion process are calculated by knowing the steam pressure in each operating point and steam specific entropy, which is always the same as at the beginning of the expansion process. Data in each turbine operating point for the ideal (isentropic) steam expansion are presented in Table 2, according to Figure 2.

Comparing steam specific enthalpies in each turbine operating point for the real (polytropic) expansion – Table 1 and for the ideal (isentropic) expansion – Table 2, it could be noted that steam specific enthalpies are lower for the ideal process in each operating point except at the expansion beginning [66].

Table 2 - Steam operating parameters (base turbine operation) at each operating point of the analyzed turbine – ideal (isentropic) steam expansion

O.P.*	Pressure (bar)	Mass flow rate (kg/s)	Isentropic specific enthalpy (kJ/kg)
1	43.00	33.194	3400.96
2is	11.72	1.945	3021.90
3is	5.29	1.147	2839.30
4is	3.09	2.028	2734.10
5is	0.78	2.641	2502.50
6is	0.08	25.433	2185.70

** O. P. = Operating Point (according to Figure 2)*

Steam operating parameters in each analyzed turbine operating point found in [24] were presented in a situation when all steam extractions were open (base turbine operation). Steam extractions closing do not affected steam operating parameters; they remain the same as presented in Table 1 and Table 2.

Analyzed low-power steam turbine has four steam extractions (operating points 2, 3, 4 and 5, Figure 1). All possible combinations of the steam extractions opening/closing are presented in Table 3. Analysis of turbine developed power (ideal and real) as well as analysis of turbine energy and exergy efficiencies and losses were investigated for each possible combination.

From Table 3 can be seen that the first combination is when all steam turbine extractions were open while the last combination is when all steam turbine extractions were closed. There are four possible combinations when one turbine extraction is closed and all the others are open (combinations from 2 to 5 – Table 3) and six possible combinations when two turbine extractions were open and two were closed (combinations from 6 to 11 – Table 3). Finally, there are four possible combinations when three steam extractions were closed with only one open (combinations from 12 to 15). So, the analyzed low-power turbine has sixteen possible steam extractions opening/closing combinations.

Table 3 - Steam extractions opening/closing combinations

Steam extractions combination number	**Steam extractions* (2-3-4-5)**
1	o-o-o-o
2	c-o-o-o
3	o-c-o-o
4	o-o-c-o
5	o-o-o-c
6	c-c-o-o
7	o-c-c-o
8	o-o-c-c
9	c-o-c-o
10	c-o-o-c
11	o-c-o-c
12	c-c-c-o
13	o-c-c-c
14	c-o-c-c
15	c-c-o-c
16	c-c-c-c

** o = extraction open, c = extraction closed*

5. The results of the turbine analysis during steam extractions opening/closing

The change in ideal (isentropic) and real (polytropic) power of the analyzed turbine for all steam extractions opening/closing combinations is presented in Figure 3. In each combination of steam extractions opening/closing ideal (isentropic) turbine power is higher than the real (polytropic) power.

Steam extractions closing in any combination allows that additional steam mass flow rate expand through the turbine, so the lowest ideal and real turbine power is developed when all steam extractions are open (combination 1, Figure 3).

Closing of only one steam extraction while all the others are open is presented in Figure 3 with combinations from 2 to 5, according to Table 3. The highest ideal and real turbine power with only one steam extraction closed is obtained when the first steam extraction is closed (in this situation obtained ideal turbine power is 37640.92 kW, while real turbine power is equal to 31995.20 kW - combination 2, Figure 3). Therefore, in such operating regime can be concluded that the steam mass flow rate from the first turbine extraction (when the first extraction is open) have the highest contribution in turbine power increasing.

Option when two turbine steam extractions are open and two extractions are closed can be seen in Figure 3 as combinations from 6 to 11. In this operating regime, the highest turbine power (ideal and real) will be developed for a combination 9 when the first and third steam extractions are closed while second and fourth steam extractions are open, Table 3. In observed combination 9 turbine ideal power is 38753.19 kW, while turbine real power is equal to 32940.71 kW.

Closing of three steam turbine extractions, while only one steam extraction remains open, is presented in Figure 3 with combinations from 12 to 15. In this operating regime the highest ideal and real turbine power will be developed for combination 14 when only the second steam extraction is open and all the others are closed. In combination 14, ideal turbine power is 39589.83 kW, while real turbine power is equal to 33651.92 kW.

The highest turbine power (ideal and real) is obtained when all steam extractions were closed (combination 16, Figure 3). In this situation the entire steam mass flow rate delivered to the turbine inlet expand through the turbine. For this operating regime turbine ideal power is 40339.44 kW, while the real power is equal to 34289.14 kW.

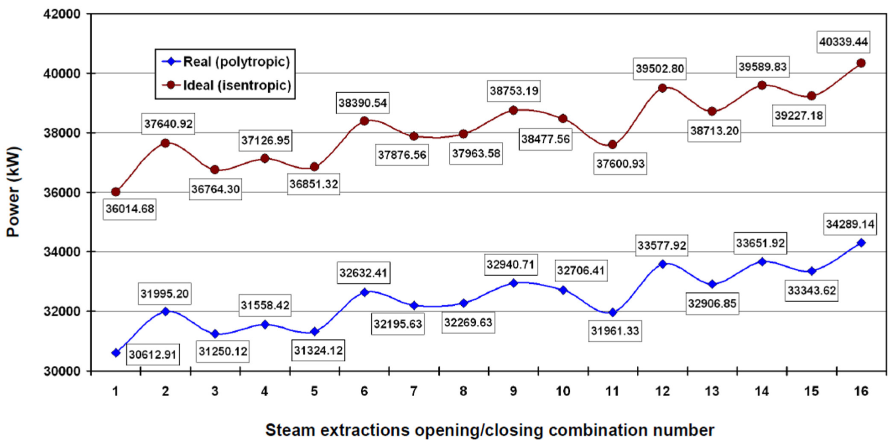

Figure 3 - The change in real (polytropic) and ideal (isentropic) turbine power during steam extractions opening/closing

Developed turbine power (ideal and real) during steam extractions opening/closing is directly proportional to turbine energy power losses, Figure 4. The lowest turbine energy power losses of 5401.78 kW can be observed when all steam extractions are open - in that operating regime turbine develop the lowest power (combination 1, Figure 3 and Figure 4). Simultaneously, the highest turbine energy power losses of 6050.30 kW are obtained when all steam extractions are closed - in that operating regime turbine develops the highest power (combination 16, Figure 3 and Figure 4).

For all observed steam extractions opening/closing combinations (one, two or three steam extractions closed), the highest turbine power (ideal or real) resulted also with the highest energy power losses.

A turbine operating regime with only one steam extraction closed and all the other open has the highest energy power losses of 5645.73 kW in combination 2, Figure 4, where the turbine power is the highest, Figure 3.

The highest turbine energy power losses in operating regime when two steam extractions were open and two steam extractions were closed are equal to 5812.48 kW - combination 9, while the highest turbine energy power losses in operating regime when only one steam extraction is open and all the others are closed are 5937.90 kW and can be seen in combination 14, Figure 4. Again, in combinations 9 and 14 can be noticed the highest turbine power for described operating regimes, Figure 3.

For all steam extractions opening/closing combinations presented in Figure 4 and Table 3 (from combination 1 up to combination 16), analyzed steam turbine energy efficiency is the same and equal to 85.00%.

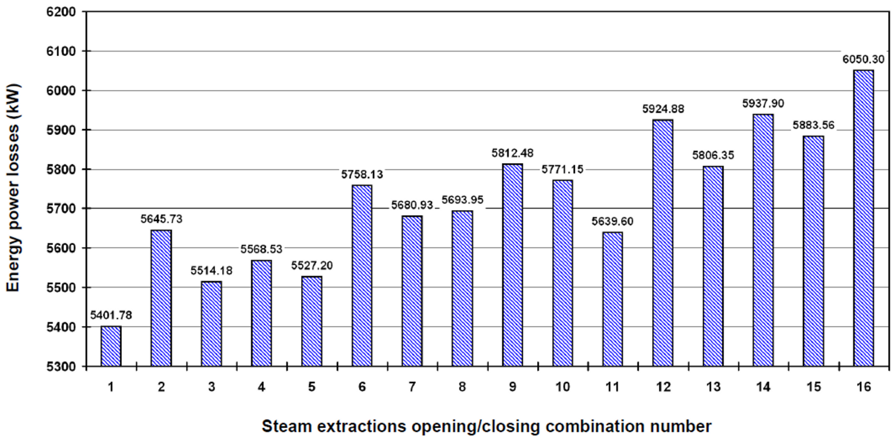

Figure 4 - Change in analyzed turbine energy power losses during steam extractions opening/closing

For all observed combinations of steam turbine extractions opening/closing (Table 3), turbine exergy input, calculated according to Eq. (15), is the same and equal to

43756.33 kW. The reason of such occurrence is that the steam mass flow rate at the turbine inlet, as well as steam temperature and pressure at the turbine inlet are the same regardless of steam extractions opening/closing combination.

Analyzed steam turbine exergy output, calculated by using Eq. (16), varies during steam turbine extractions opening/closing, Figure 5. From Figure 3 and Figure 5 can be concluded that turbine developed power (ideal or real) is reverse proportional to exergy output.

The highest turbine exergy output (38806.39 kW) is obtained when all steam turbine extractions are open - in that operating regime turbine developed the lowest power (combination 1, Figure 3 and Figure 5). The lowest turbine exergy output (38009.52 kW) is obtained when all steam extractions are closed - in that operating regime turbine developed the highest power (combination 16, Figure 3 and Figure 5).

A turbine operating regime with only one steam extraction closed and all the other open has the lowest exergy output equal to 38527.60 kW in combination 2, Figure 5, where the turbine power is the highest in such operating regime, Figure 3.

The lowest turbine exergy output in operating regime when two steam extractions were open and two steam extractions were closed is 38315.93 kW - combination 9, while the lowest turbine exergy output in operating regime when only one steam extraction is open and all the others are closed is 38148.72 kW and can be seen in combination 14, Figure 5. Again, in combinations 9 and 14 can be noticed the highest turbine power for mentioned operating regimes, Figure 3.

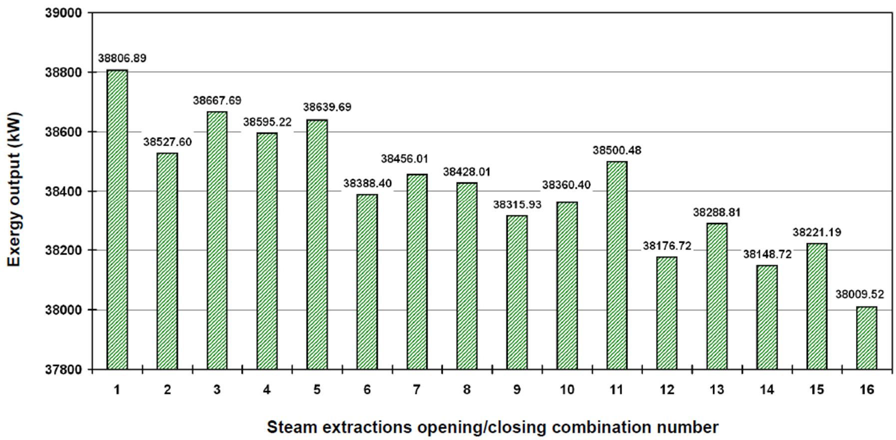

Figure 5 - Change in analyzed turbine exergy output during steam extractions opening/closing

Comparison of the analyzed turbine power (ideal or real) and turbine exergy destruction and exergy efficiency, Figure 3 and Figure 6, leads to a conclusion that for various steam extractions opening/closing combinations turbine exergy destruction is directly proportional to turbine power, while the change in turbine exergy efficiency is reverse proportional to turbine power.

When all steam turbine extractions are open (combination 1) - turbine will develop the lowest power and have the lowest exergy destruction (4949.44 kW) with simultaneously the highest exergy efficiency (86.08%), Figure 6. All steam extractions closing (combination 16) result with the highest turbine power and with the highest exergy destruction (5746.81 kW) - simultaneously turbine exergy efficiency will be the lowest (85.65%).

Only one turbine steam extraction closing (with other extractions open) result in the highest turbine exergy destruction of 5228.73 kW and with almost the lowest turbine exergy efficiency of 85.95% in combination 2 (only the first steam extraction closed). In such operating regime, for combination 2, turbine developed power (ideal and real) will be the highest, Figure 3 and Figure 6.

Two turbine extractions closing (with other extractions opened) result with the highest turbine developed power (ideal and real) in such operating regime for combination 9, Figure 3. For combination 9, turbine has the highest exergy destruction (5440.40 kW) and the lowest exergy efficiency (85.83%) in that operating regime, Figure 6.

Three steam turbine extractions closing (with only one extraction opened) result in the highest turbine exergy destruction (5607.61 kW) and the lowest turbine exergy efficiency (85.72%) for combination 14, Figure 6. Combination 14 in this turbine operating regime (with only one steam extraction open) develops the highest power.

Comparison of Figure 4 and Figure 6 leads to conclusion that during steam extractions opening/closing, turbine energy and exergy losses have the same proportional trends - the same conclusions valid for turbine energy power losses are also valid for turbine exergy destruction (exergy losses).

It should be noted that during steam extractions opening/closing exergy efficiency of the analyzed low-power steam turbine increases and decreases in a small range - between 85.65% and 86.08%, Figure 6. This fact leads to a conclusion that the increase in power by steam extractions closing will not cause significant change in turbine exergy efficiency, regardless of extractions opening/closing combination. However, steam extractions closing in any combination will result with notable change in turbine energy and exergy losses.

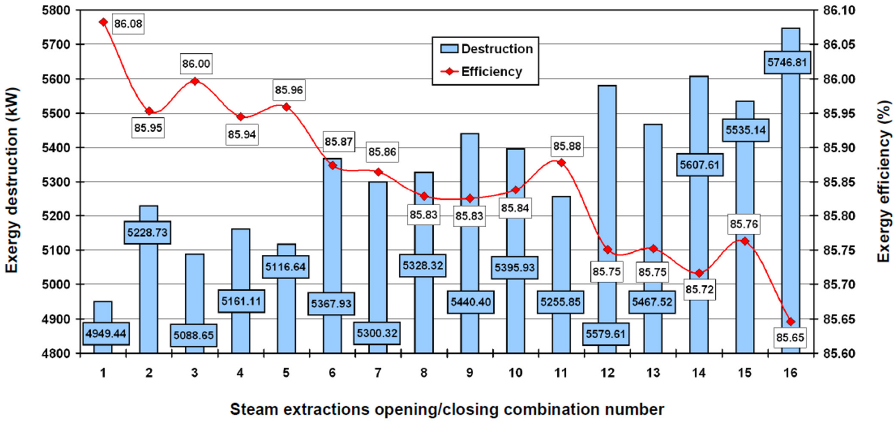

Figure 6 - Change in analyzed turbine exergy destruction and exergy efficiency during steam extractions opening/closing

6. Conclusions

In this paper is analyzed low-power steam turbine with four steam extractions. The turbine is analyzed as an independent component of steam power plant. It was investigated how turbine steam extractions opening/closing in each possible combination affect turbine developed power (ideal or real) as well as turbine energy and exergy efficiencies and losses. In base operation, turbine delivers a certain steam mass flow rate through each extraction to regenerative feed water heaters. One or more steam extractions closing will surely increase fuel consumption in steam generator and simultaneously will cause an increase in analyzed steam turbine power. The most important conclusions obtained from the presented analysis are:

Turbine developed power (ideal or real) during steam extractions opening/closing is direct proportional to turbine energy and exergy losses and reverse proportional to turbine exergy efficiencies.

Analyzed turbine energy efficiency and exergy input are not affected by steam extractions opening/closing. The turbine energy efficiency is 85.00% and exergy input is 43756.33 kW in any combination of turbine steam extractions opening/closing.

Turbine operation regime when all of steam extractions are open resulted with the lowest developed power (36014.68 kW for ideal and 30612.91 kW for real power), with the lowest energy power losses (5401.78 kW) and the lowest exergy destruction (4949.44 kW). In such operating regime turbine exergy efficiency is the highest and equal to 86.08%.

Closing of all analyzed steam turbine extractions resulted with the highest developed power (40339.44 kW for ideal and 34289.14 kW for real power), with the highest energy power losses (6050.30 kW) and the highest exergy destruction (5746.81 kW). In such operating regime turbine exergy efficiency is the lowest and equal to 85.65%.

In turbine operating regime when one steam extraction is closed and the other steam extractions are open - the highest turbine power (ideal and real) is obtained when the closed steam extraction is the first one.

Operating regime with two steam extractions open and two steam extractions closed gives the highest turbine ideal and real power when closed steam extractions are first and third.

The highest turbine ideal and real power in the operating regime with only one open steam extraction are obtained when open steam extraction is the second one.

During steam extractions opening/closing exergy efficiency of the analyzed low-power steam turbine increases and decreases in a small range - between 85.65% and 86.08%, while the change of turbine energy and exergy losses are much more intensive.

Further investigation of this low-power steam turbine will be based on steam turbine optimization by using various artificial intelligence methods and techniques such as neural networks [67-69], genetic programming [70] or various optimization algorithms [71]. The main aim will be to increase turbine power and (if possible) simultaneously decrease fuel consumption in the steam generator.

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NOMENCLATURE		***Greek symbols:***	
		ε	specific exergy, kJ/kg
Latin Symbols:		η	efficiency, -
$\dot{E}$	power of a flow, kW		
h	specific enthalpy, kJ/kg	***Subscripts:***	
$\dot{m}$	mass flow rate, kg/s	0	ambient conditions (dead state)
p	pressure, bar or MPa	D	destruction (loss)
P	power, kW	en	energy
$\dot{Q}$	heat transfer, kW	ex	exergy
s	specific entropy, kJ/kg·K	IN	inlet (input)
T	temperature, °C or K	is	isentropic (ideal steam expansion)
$\dot{X}_{\text{heat}}$	exergy transfer by heat, kW	OUT	outlet (output)
		re	real (polytropic steam expansion)

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