60 MW steam turbine conventional and segmental isentropic analyses comparison

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Abstract: *This paper presents results of two different isentropic analysis types: conventional isentropic analysis which considers the whole steam turbine cylinder and segmental isentropic analysis which considers all cylinder parts (segments). In conventional isentropic analysis is obtained that isentropic efficiency of the analyzed turbine is 73.39%, what is in a range of expected isentropic efficiencies for such steam turbines (in the mechanical power range around 60 MW). Segmental isentropic analysis shows that the last two segments (fifth and sixth segment) of the analyzed turbine did not show proper operation (especially the fifth turbine segment which isentropic efficiency is unacceptably low and equal to 26.73% only). Such isentropic efficiency results, related to the fifth and sixth turbine segment, indicate highly problematic operation, or the most likely malfunction of at least some turbine stages in these segments. For the analyzed steam turbine can be recommended that it should be stopped as soon as possible and that turbine stages mounted in the last two segments should be checked, repaired or replaced.*

KEYWORDS: STEAM TURBINE, TURBINE SEGMENTS, CONVENTIONAL ISENTROPIC ANALYSIS, SEGMENTAL ISENTROPIC ANALYSIS, LOSSES AND EFFICIENCIES

1. Introduction

The most of mechanical power used for the electric generators drive worldwide is produced by various kinds of steam turbines [1, 2]. Along with the mentioned, steam turbines have numerous other kinds of application, such as in marine power systems [3, 4], in cogeneration and combined cycle power plants [5, 6] as well as in various other plants or systems.

High power steam turbines are composed of several cylinders mounted on the same shaft [7, 8]. Medium or low power steam turbines can be composed of only one cylinder used for the drive of any mechanical power consumer or for various auxiliary purposes [9, 10].

Each steam turbine cylinder usually has at least few steam extractions which lead a certain amount of steam to the components of condensate/feedwater heating system [11, 12]. Extracted steam from the turbine cylinders in the condensate/feedwater heating system increases water temperature before its entrance to the steam generator and in that way reduces fuel consumption and harmful emissions. However, in the literature can also be found auxiliary steam turbines which did not possess any steam extractions [13] but such steam turbines are surely not the dominant ones.

Steam extractions (along with cylinder inlet and outlet) divide steam turbine cylinder to several segments. That division allows analysis of the whole cylinder, but also of various cylinder parts (cylinder segments). The conclusions derived in the analysis of the whole cylinder don't have to be identical as in the analysis of all segments from which the cylinder is composed.

For a 60 MW one-cylinder steam turbine, in this paper are performed two different isentropic analyses: conventional which consider whole cylinder and segmental which consider each cylinder segment. For the selected steam turbine, it will be very interesting to compare obtained conclusions and operating performances obtained in each of two used isentropic analyses.

2. Description of the analyzed 60 MW steam turbine

The analyzed steam turbine has a nominal power of 60 MW and is composed of only one cylinder, Fig. 1. Steam is delivered to the turbine from steam generator [14]. The observed steam turbine has five steam extractions: steam extractions the closest to the turbine inlet deliver steam with high pressure and temperature to high pressure feedwater heating system [15]. Third steam extraction delivers steam to the deaerator, while the last two steam extractions (fourth and five extraction) deliver a certain amount of steam to the low pressure condensate heating system [16]. Remaining steam which expands until the end of the turbine cylinder is delivered to the main condenser for condensation [17, 18]. As presented in Fig. 1, the analyzed steam turbine is used for the electric generator drive.

Steam inlet, outlet and extractions divide this steam turbine to six segments. The first segment is placed between turbine inlet and first steam extraction, inner segments are placed between two extractions, while the last segment is placed between last steam extraction and turbine outlet.

Isentropic analyses performed in this research will involve entire steam turbine (observed by conventional isentropic analysis) and will involve each of six steam turbine segments (what will be observed by segmental isentropic analysis). It will be interesting to present which conclusions will derive each of two used isentropic analyses.

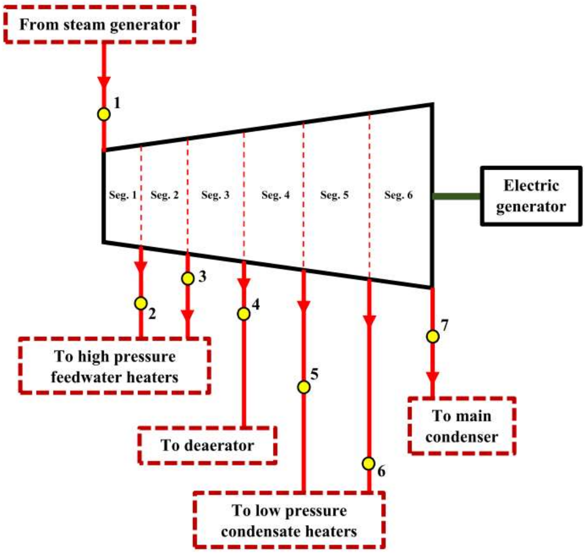

Fig. 1. *General scheme of the analyzed 60 MW steam turbine along with operating points necessary for the isentropic analyses (both conventional and segmental)*

In this research will be performed two different kinds of the isentropic analysis: conventional and segmental. For both kinds of the isentropic analysis, relevant steam specific enthalpy drops are presented in Fig. 2.

The conventional isentropic analysis considers specific enthalpy drops (ideal and real) in the entire turbine cylinder, or entire turbine (the analyzed turbine is one-cylinder steam turbine). Conventional isentropic analysis is based on a comparison of real (polytropic) steam expansion process in the whole cylinder (represented in Fig. 2 with operating points 1-2-3-4-5-6-7) and ideal (isentropic) steam expansion process in the whole cylinder (represented in Fig. 2 with operating points 1-2IS-3IS,C-4IS,C-5IS,C-6IS,C-7IS,C).

Segmental isentropic analysis is based on a comparison of real (polytropic) steam expansion process in each turbine segment (represented in Fig. 2 with operating points 1-2 for the first segment, 2-3 for the second segment, 3-4 for the third segment, etc.) and ideal (isentropic) steam expansion process in each turbine segment (represented in Fig. 2 with operating points 1-2IS for the first segment, 2-3IS,S for the second segment, 3-4IS,S for the third segment, 4-5IS,S for the fourth segment, etc.).

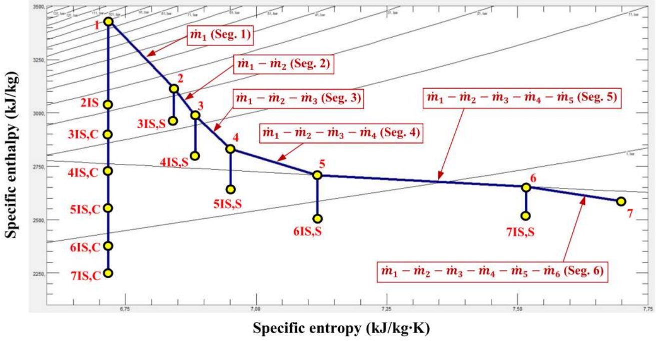

Fig. 2. *Specific enthalpy – specific entropy (h-s) diagram of real (polytropic) and ideal (isentropic) steam expansion processes through turbine and segments*

3. Equations for the conventional and segmental isentropic analyses

Isentropic analysis related to any steam turbine is based on a comparison of mechanical power developed during the real (polytropic) steam expansion process and mechanical power developed during the ideal (isentropic) steam expansion process which can theoretically be obtained if all the losses are neglected [19]. Ideal (isentropic) steam expansion process is the process between the same pressures and it uses the same steam mass flow rates as real (polytropic) process, but during the ideal steam expansion all the losses are neglected which means that steam specific entropy remains always constant. In the real (polytropic) steam expansion process steam specific entropy continuously increases what represent losses which occur in such process. Isentropic loss is the difference between ideal and real developed mechanical power, while the isentropic efficiency is the ratio between real and ideal mechanical power. Isentropic analysis can be conventional (performed for the turbine cylinder or the whole turbine) or segmental (performed for each steam turbine segment). All the equations presented is this section will be related to turbine operating points presented in Fig. 1 and Fig. 2 and are composed according to the recommendations from the literature [20, 21].

It should be highlighted that an isentropic analysis of any kind is actually a "black box" method. In any isentropic analysis (conventional or segmental), the inner structure of the whole turbine or the inner structure of each turbine segment is not required (number, arrangement or type of turbine stages, inner leakages inside the whole turbine or segment, steam flow characteristics, etc.) [22].

3.1. Equations for the conventional isentropic analysis of the observed 60 MW steam turbine

Observed turbine is single flow steam turbine and it consists of only one cylinder. Therefore, the equations for the developed mechanical power calculation (both ideal and real) are the same for the whole observed turbine as for one cylinder.

Real (polytropic) mechanical power of the whole observed turbine is calculated by using an equation:

$$P_{\mathrm{re,WT,C}}=\dot{m}_1\cdot(h_1-h_2)+(\dot{m}_1-\dot{m}_2)\cdot(h_2-h_3)+(\dot{m}_1-\dot{m}_2-\dot{m}_3)\cdot(h_3-h_4)+(\dot{m}_1-\dot{m}_2-\dot{m}_3-\dot{m}_4)\cdot(h_4-h_5)+(\dot{m}_1-\dot{m}_2-\dot{m}_3-\dot{m}_4-\dot{m}_5)\cdot(h_5-h_6)+(\dot{m}_1-\dot{m}_2-\dot{m}_3-\dot{m}_4-\dot{m}_5-\dot{m}_6)\cdot(h_6-h_7), \quad (1)$$

while ideal (isentropic) mechanical power of the whole observed turbine can be calculated by using an equation:

$$P_{\mathrm{id,WT,C}}=\dot{m}_1\cdot(h_1-h_{2\mathrm{IS}})+(\dot{m}_1-\dot{m}_2)\cdot\left(h_{2\mathrm{IS}}-h_{3\mathrm{IS,C}}\right)+(\dot{m}_1-\dot{m}_2-\dot{m}_3)\cdot\left(h_{3\mathrm{IS,C}}-h_{4\mathrm{IS,C}}\right)+(\dot{m}_1-\dot{m}_2-\dot{m}_3-\dot{m}_4)\cdot\left(h_{4\mathrm{IS,C}}-h_{5\mathrm{IS,C}}\right)+(\dot{m}_1-\dot{m}_2-\dot{m}_3-\dot{m}_4-\dot{m}_5)\cdot\left(h_{5\mathrm{IS,C}}-h_{6\mathrm{IS,C}}\right)+(\dot{m}_1-\dot{m}_2-\dot{m}_3-\dot{m}_4-\dot{m}_5-\dot{m}_6)\cdot\left(h_{6\mathrm{IS,C}}-h_{7\mathrm{IS,C}}\right). \quad (2)$$

Isentropic loss of the whole observed turbine is:

$$IS_{\mathrm{L,WT,C}} = P_{\mathrm{id,WT,C}} - P_{\mathrm{re,WT,C}}, \quad (3)$$

while whole turbine isentropic efficiency is:

$$\eta_{\mathrm{IS,WT,C}} = \frac{P_{\mathrm{re,WT,C}}}{P_{\mathrm{id,WT,C}}}. \quad (4)$$

In the above equations and throughout the paper, P is mechanical power, $\dot{m}$ is fluid mass flow rate, h is fluid specific enthalpy, index re is related to real (polytropic) process, index id is related to ideal (isentropic) process, index WT is related to the whole turbine, while indexes C and L are related to the conventional isentropic analysis and isentropic loss, respectively.

3.2. Equations for the segmental isentropic analysis of the observed 60 MW steam turbine

Analyzed steam turbine, Fig. 1, has six segments. Equations for the real (polytropic) and ideal (isentropic) developed mechanical power calculation of each observed turbine segment are presented in Table 1 (the equations are arranged by using operating points from Fig. 2). In Table 1 and throughout the paper, index S is related to the segmental isentropic analysis.

Table 1. *Equations for the real (polytropic) and ideal (isentropic) developed mechanical power calculation of each turbine segment*

Seg.	Real (polytropic) mechanical power	Eq.
1	$P_{\mathrm{re,Seg.1,S}}=\dot{m}_1\cdot(h_1-h_2)$	(5)
2	$P_{\mathrm{re,Seg.2,S}}=(\dot{m}_1-\dot{m}_2)\cdot(h_2-h_3)$	(6)
3	$P_{\mathrm{re,Seg.3,S}}=(\dot{m}_1-\dot{m}_2-\dot{m}_3)\cdot(h_3-h_4)$	(7)
4	$P_{\mathrm{re,Seg.4,S}}=(\dot{m}_1-\dot{m}_2-\dot{m}_3-\dot{m}_4)\cdot(h_4-h_5)$	(8)
5	$P_{\mathrm{re,Seg.5,S}}=(\dot{m}_1-\dot{m}_2-\dot{m}_3-\dot{m}_4-\dot{m}_5)\cdot(h_5-h_6)$	(9)
6	$P_{\mathrm{re,Seg.6,S}}=(\dot{m}_1-\dot{m}_2-\dot{m}_3-\dot{m}_4-\dot{m}_5-\dot{m}_6)\cdot(h_6-h_7)$	(10)

Seg.	Ideal (isentropic) mechanical power	Eq.
1	$P_{\mathrm{id,Seg.1,S}}=\dot{m}_1\cdot(h_1-h_{2\mathrm{IS}})$	(11)
2	$P_{\mathrm{id,Seg.2,S}}=(\dot{m}_1-\dot{m}_2)\cdot\left(h_2-h_{3\mathrm{IS,S}}\right)$	(12)
3	$P_{\mathrm{id,Seg.3,S}}=(\dot{m}_1-\dot{m}_2-\dot{m}_3)\cdot\left(h_3-h_{4\mathrm{IS,S}}\right)$	(13)
4	$P_{\mathrm{id,Seg.4,S}}=(\dot{m}_1-\dot{m}_2-\dot{m}_3-\dot{m}_4)\cdot\left(h_4-h_{5\mathrm{IS,S}}\right)$	(14)
5	$P_{\mathrm{id,Seg.5,S}}=(\dot{m}_1-\dot{m}_2-\dot{m}_3-\dot{m}_4-\dot{m}_5)\cdot\left(h_5-h_{6\mathrm{IS,S}}\right)$	(15)
6	$P_{\mathrm{id,Seg.6,S}}=(\dot{m}_1-\dot{m}_2-\dot{m}_3-\dot{m}_4-\dot{m}_5-\dot{m}_6)\cdot\left(h_6-h_{7\mathrm{IS,S}}\right)$	(16)

For each segment from the observed steam turbine, isentropic loss is the difference between ideal (isentropic) and real (polytropic) developed mechanical power, while isentropic efficiency of each segment is a ratio of real and ideal developed mechanical power.

4. Steam operating parameters

Observed steam turbine data of the real (polytropic) steam expansion process are obtained by measurements, found in [23] and presented in Table 2. Steam parameters in each operating point from Table 2, which are not found in the literature, are calculated by using NIST-REFPROP 9.0 software [24].

Ideal (isentropic) steam specific enthalpies, required for the calculation of ideal mechanical power, are not obtained by the measurements – they are obtained by numerical calculations.

In conventional isentropic analysis, each operating point on the main turbine isentrope, Fig. 2, has the same steam specific entropy as an operating point at the turbine inlet (operating point 1). Along with known steam pressure in each operating point on the main isentrope, these two parameters (pressure and specific entropy) were sufficient to calculate all other steam parameters on the main isentrope. Steam specific enthalpies of ideal (isentropic) steam expansion process in the conventional isentropic analysis are presented in Table 3.

In segmental isentropic analysis, ideal steam expansions must be defined from the inlet until the outlet of each turbine segment. From Fig. 2 can be observed that in the ideal (isentropic) steam expansion process related to each turbine segment, operating point at the end of such expansion has the same steam specific entropy as at the segment inlet. Again, by knowing steam pressures at each segment inlet and outlet (as well as steam specific entropy), required data for each operating point are known and other parameters for the ideal expansion in each segment can be calculated. Steam specific enthalpies of ideal (isentropic) steam expansion process in the segmental analysis are presented in Table 4.

Table 2. *Steam operating parameters of real (polytropic) steam expansion process*

O. P.*	Temperature (°C)	Pressure (bar)	Mass flow rate (kg/s)	Specific enthalpy (kJ/kg)	Specific entropy (kJ/kg·K)	Quality
1	520.00	91.233	76.39	3436.3	6.7168	Superheated
2	345.40	24.231	4.94	3118.1	6.8419	Superheated
3	274.70	13.244	4.14	2986.9	6.8835	Superheated
4	190.50	5.690	4.56	2831.4	6.9510	Superheated
5	121.20	2.060	3.88	2707.7	7.1173	Superheated
6	87.30	0.628	1.78	2655.2	7.5168	Superheated
7	66.86	0.272	57.09	2585.6	7.6979	0.985

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

Table 3. *Steam specific enthalpies of ideal (isentropic) steam expansion process in the conventional analysis*

Operating Point*	Isentropic specific enthalpy (kJ/kg)
1	3436.3
2IS	3042.8
3IS,C	2898.8
4IS,C	2727.9
5IS,C	2549.8
6IS,C	2367.0
7IS,C	2252.0

* According to Fig. 2.

Table 4. *Steam specific enthalpies of ideal (isentropic) steam expansion process in the segmental analysis*

Operating Point*	Isentropic specific enthalpy (kJ/kg)
1	3436.3
2IS	3042.8
2	3118.1
3IS,S	2964.3
3	2986.9
4IS,S	2800.6
4	2831.4
5IS,S	2642.1
5	2707.7
6IS,S	2511.3
6	2655.2
7IS,S	2524.0
7	2585.6

* According to Fig. 2.

5. Results and discussion

The results of conventional isentropic analysis related to the whole observed steam turbine are presented in Table 5.

Conventional isentropic analysis of the observed steam turbine shows that this turbine produces 58.97 MW of real mechanical power (used for the electric generator drive), while in an ideal situation this turbine can produce mechanical power of 80.35 MW. Therefore, improvement potential of observed turbine related to the mechanical power is equal to 21.38 MW (isentropic loss in conventional isentropic analysis). The isentropic efficiency of the analyzed turbine is 73.39%, what is in a range of expected isentropic efficiencies for such steam turbines [25, 26]. Therefore, it can be concluded that conventional isentropic analysis shows proper and expected operation of the whole observed turbine. However, conventional isentropic analysis cannot answer to the question did all segments of this steam turbine operate properly, it can show only general picture valid for the whole turbine.

Table 5. *Results of the conventional isentropic analysis*

Real (polytropic) mechanical power	58971.17 kW
Ideal (isentropic) mechanical power	80349.75 kW
Isentropic loss	21378.58 kW
Isentropic efficiency	73.39 %

The results of segmental isentropic analysis are presented in Fig. 3, Fig. 4 and Fig. 5.

From Fig. 3 can be observed that in each turbine segment ideal (isentropic) mechanical power must be higher in comparison to real (polytropic) one, due to neglecting all the losses in ideal expansion. However, for the analyzed turbine, produced mechanical power is not proportionally distributed to each segment. The first segment of the analyzed steam turbine produces notably higher mechanical power (both real and ideal) in comparison to all other segments. The last two segments (Seg. 5 and Seg. 6) produces very low real mechanical power. Also, from Fig. 3 is clear that the differences between ideal and real mechanical power of each segment notably vary, therefore, isentropic losses will also notably vary from one turbine segment to another.

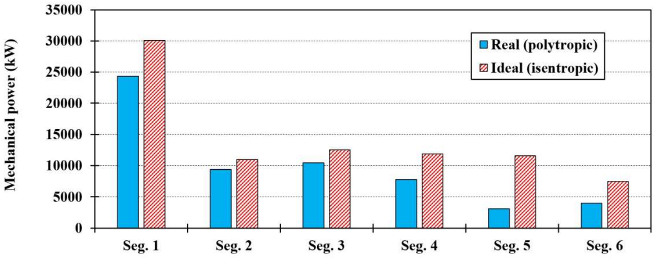

Fig. 3. *Ideal (isentropic) and real (polytropic) mechanical power of each turbine segment in the segmental analysis*

Isentropic losses of each turbine segment are presented in Fig. 4. It is clear that Seg. 5 has notably higher isentropic loss (equal to 8470.91 kW) in comparison to all other turbine segments. High isentropic loss in the first turbine segment (Seg. 1), equal to 5752.08 kW, can be explained with a fact that the first turbine segment produces high mechanical power, notably higher than other turbine segments, Fig. 3 and Fig. 4.

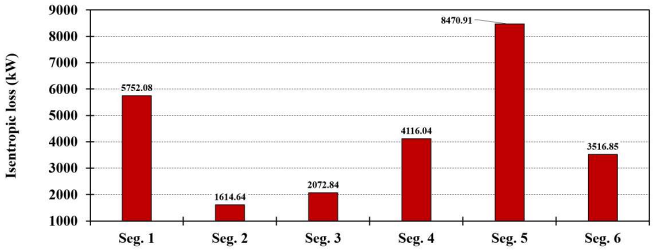

Fig. 4. *Isentropic loss of each turbine segment in the segmental analysis*

Isentropic efficiencies of each segment from the observed steam turbine are presented in Fig. 5.

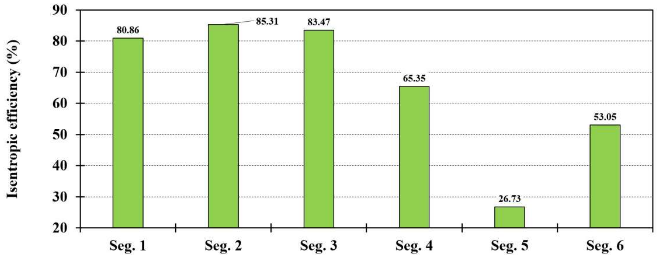

Fig. 5. *Isentropic efficiency of each turbine segment in the segmental analysis*

From Fig. 5 can be clearly seen that the first three segments of the analyzed turbine operate very well with isentropic efficiencies higher than 80%. Fourth turbine segment can obviously be improved, because its isentropic efficiency is quite low, equal to 65.35% only. The fifth and sixth segment of the analyzed turbine did not show proper operation (especially the fifth turbine segment which isentropic efficiency is unacceptably low and equal to 26.73% only). Such isentropic efficiency results, related to the fifth and sixth turbine segment, indicate highly problematic operation, or the most likely malfunction of at least some turbine stages in these segments.

Final conclusion which can be derived from the performed isentropic analyses is that conventional isentropic analysis shows global operating parameters related to the entire cylinder which cannot indicate problematic cylinder parts. So, it is necessary to perform segmental isentropic analysis to observe operation of each turbine segment. For the analyzed steam turbine can be recommended that it should be stopped as soon as possible and that turbine stages mounted in the last two segments should be checked, repaired or completely replaced.

6. Conclusions

In this paper are presented results of two different isentropic analysis types: conventional isentropic analysis which considers the whole steam turbine cylinder and segmental isentropic analysis which considers all cylinder parts (segments). In each analysis are obtained produced mechanical power (ideal and real) as well as isentropic losses and efficiencies. The most important conclusions obtained from the performed research are:

- Conventional isentropic analysis shows that isentropic efficiency of the analyzed turbine is 73.39%, what is in a range of expected isentropic efficiencies for such steam turbines. Therefore, conventional isentropic analysis shows proper and expected operation of the whole observed turbine.
- Segmental isentropic analysis shows that produced mechanical power in the observed steam turbine is not proportionally distributed to each segment. The first segment of the analyzed turbine produces notably higher mechanical power in comparison to all other segments.
- The fifth and sixth segment of the analyzed turbine did not show proper operation (especially the fifth turbine segment which isentropic efficiency is unacceptably low and equal to 26.73% only). Such isentropic efficiency results, related to the fifth and sixth turbine segment, indicate highly problematic operation, or the most likely malfunction of at least some turbine stages in these segments.
- For the analyzed steam turbine can be recommended that it should be stopped as soon as possible and that turbine stages mounted in the last two segments should be checked, repaired or replaced.

7. Acknowledgment

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8. References

[1] Elhelw, M., & Al Dahma, K. S. (2019). Utilizing exergy analysis in studying the performance of steam power plant at two different operation mode. Applied Thermal Engineering, 150, 285-293. (doi:10.1016/j.applthermaleng.2019.01.003)

[2] Tanuma, T. (Ed.). (2022). Advances in steam turbines for modern power plants. Woodhead Publishing.

[3] Koroglu, T., & Sogut, O. S. (2018). Conventional and advanced exergy analyses of a marine steam power plant. Energy, 163, 392-403. (doi:10.1016/j.energy.2018.08.119)

[4] Poljak, I., & Mrzljak, V. (2023). Thermodynamic Analysis and Comparison of Two Marine Steam Propulsion Turbines. NAŠE MORE: znanstveni časopis za more i pomorstvo, 70(2), 0-0. (doi:10.17818/NM/2023/2.2)

[5] Burin, E. K., Vogel, T., Multhaupt, S., Thelen, A., Oeljeklaus, G., Görner, K., & Bazzo, E. (2016). *Thermodynamic and economic evaluation of a solar aided sugarcane bagasse cogeneration power plant.* Energy, 117, 416-428. (doi:10.1016/j.energy.2016.06.071)

[6] Lorencin, I., Anđelić, N., Mrzljak, V., & Car, Z. (2019). Genetic Algorithm Approach to Design of Multi-Layer Perceptron for Combined Cycle Power Plant Electrical Power Output Estimation. Energies, 12(22), 4352. (doi:10.3390/en12224352)

[7] Ahmadi, G. R., & Toghraie, D. (2016). Energy and exergy analysis of Montazeri steam power plant in Iran. Renewable and Sustainable Energy Reviews, 56, 454-463. (doi:10.1016/j.rser.2015.11.074)

[8] Mrzljak, V., Jelić, M., Poljak, I., & Prpić-Oršić, J. (2023). Analysis and Comparison of Main Steam Turbines from Four Different Thermal Power Plants. Pomorstvo, 37(1), 58-74. (doi:10.31217/p.37.1.6)

[9] Behrendt, C., & Stoyanov, R. (2018). Operational Characteristic of Selected Marine Turbounits Powered by Steam from Auxiliary Oil-Fired Boilers. New Trends in Production Engineering, 1(1), 495-501. (doi:10.2478/ntpe-2018-0061)

[10] Mrzljak, V., Senčić, T., & Žarković, B. (2018). Turbogenerator steam turbine variation in developed power: Analysis of exergy efficiency and exergy destruction change. Modelling and Simulation in Engineering, 2018. (doi:10.1155/2018/2945325)

[11] Kostyuk, A., & Frolov, V. (Eds.). (1988). Steam and gas turbines. Mir Pub.

[12] Mrzljak, V., Anđelić, N., Lorencin, I., & Sandi Baressi Šegota, S. (2021). The influence of various optimization algorithms on nuclear power plant steam turbine exergy efficiency and destruction. Pomorstvo, 35(1), 69-86. (doi:10.31217/p.35.1.8)

[13] Mrzljak, V., Prpić-Oršić, J., & Poljak, I. (2018). Energy power losses and efficiency of low power steam turbine for the main feed water pump drive in the marine steam propulsion system. Pomorski zbornik, 54(1), 37-51. (doi:10.18048/2018.54.03)

[14] Mrzljak, V., Poljak, I., & Medica-Viola, V. (2017). Dual fuel consumption and efficiency of marine steam generators for the propulsion of LNG carrier. Applied Thermal Engineering, 119, 331-346. (doi:10.1016/j.applthermaleng.2017.03.078)

[15] Mrzljak, V., Lorencin, I., Anđelić, N., & Car, Z. (2021). Thermodynamic Analysis of a Condensate Heating System from a Marine Steam Propulsion Plant with Steam Reheating. Journal of Marine Science and Application, 20, 117-127. (doi:10.1007/s11804-021-00191-5)

[16] Jiping, L., Wei, H., Xin, W., Xiaoqu, H., Daotong, C., & Junjie, Y. (2015). Theoretical investigation on the partial load feedwater heating system with thermal vapor compressor in a coal-fired power unit. Energy Procedia, 75, 1102-1107. (doi:10.1016/j.egypro.2015.07.500)

[17] Škopac, L., Medica-Viola, V., & Mrzljak, V. (2020). Selection Maps of Explicit Colebrook Approximations according to Calculation Time and Precision. Heat Transfer Engineering, 1-15. (doi:10.1080/01457632.2020.1744248)

[18] Pattanayak, L., Padhi, B. N., & Kodamasingh, B. (2019). Thermal performance assessment of steam surface condenser. Case Studies in Thermal Engineering, 14, 100484. (doi:10.1016/j.csite.2019.100484)

[19] Mrzljak, V., Šegota, S. B., Kocijel, L., & Prpić-Oršić, J. (2020). Energy (isentropic) analysis of three-cylinder steam turbine with re-heating. Innovations, 8(1), 37-40.

[20] Hafdhi, F., Khir, T., Yahyia, A. B., & Brahim, A. B. (2015). Energetic and exergetic analysis of a steam turbine power plant in an existing phosphoric acid factory. Energy Conversion and Management, 106, 1230-1241. (doi:10.1016/j.enconman.2015.10.044)

[21] Medica-Viola, V., Baressi Šegota, S., Mrzljak, V., & Štifanić, D. (2020). Comparison of conventional and heat balance based energy analyses of steam turbine. Pomorstvo, 34(1), 74-85. (doi:10.31217/p.34.1.9)

[22] Mrzljak, V., Kudláček, J., Baressi Šegota, S., & Medica-Viola, V. (2021). Energy and Exergy Analysis of Waste Heat Recovery Closed-Cycle Gas Turbine System while Operating with Different Medium. Pomorski zbornik, 60(1), 21-48. (doi:10.18048/2021.60.02)

[23] Aljundi, I. H. (2009). Energy and exergy analysis of a steam power plant in Jordan. Applied thermal engineering, 29(2-3), 324-328. (doi:10.1016/j.applthermaleng.2008.02.029)

[24] Lemmon, E. W., Huber, M. L., & McLinden, M. O. (2010). NIST Standard Reference Database 23, Reference Fluid Thermodynamic and Transport Properties (REFPROP), version 9.0, National Institute of Standards and Technology. R1234yf. fld file dated December, 22, 2010.

[25] Mrzljak, V., Poljak, I., & Mrakovčić, T. (2017). Energy and exergy analysis of the turbo-generators and steam turbine for the main feed water pump drive on LNG carrier. Energy conversion and management, 140, 307-323. (doi:10.1016/j.enconman.2017.03.007)

[26] Elčić, Z. (1995). Steam turbines. ABB, Karlovac, National and University Library Zagreb.