Isentropic analysis of entire intermediate pressure steam turbine cylinder and cylinder segments

Mrzljak Vedran[1], Prpić-Oršić Jasna[1], Senčić Tomislav[1], Anđelić Nikola[1]
[1]Faculty of Engineering, University of Rijeka, Vukovarska 58, 51000 Rijeka, Croatia
E-mail: vedran.mrzljak@riteh.uniri.hr, jasna.prpic.orsic@riteh.uniri.hr, tomislav.sencic@riteh.uniri.hr, nikola.andjelic@riteh.uniri.hr

Abstract: *In this paper is performed an isentropic analysis of the entire Intermediate Pressure Cylinder (IPC) and all of his four Segments. Obtained results show that the first Segment (Seg. 1) is the dominant mechanical power producer of all Segments and it produces 16816.70 kW of mechanical power in the real (polytropic) expansion process. Analyzed IPC produces more than half mechanical power of the entire turbine in which he operates (in real expansion process IPC produces mechanical power equal to 58499.48 kW). Isentropic loss and isentropic efficiency of IPC Segments are reverse proportional – Seg. 3 which has the highest isentropic loss simultaneously has the lowest isentropic efficiency (equal to 82.44%), while Seg. 4 which has the lowest isentropic loss has the highest isentropic efficiency (equal to 87.26%). Entire IPC has an isentropic efficiency equal to 87.78%. Any improvements and modifications which can potentially be performed in the observed IPC should firstly be based on the turbine stages mounted inside Seg. 3.*

KEYWORDS: *ISENTROPIC ANALYSIS, STEAM TURBINE, INTERMEDIATE PRESSURE CYLINDER (IPC), CYLINDER SEGMENTS, LOSSES AND EFFICIENCIES*

1. Introduction

In the electricity production worldwide, steam turbines are inevitable components [1, 2]. Steam turbines nowadays can be found in many systems and processes, such as conventional [3], supercritical [4], nuclear [5], cogeneration [6], combined [7], marine [8, 9] and other power plants. In all mentioned power plants, steam turbines can be composed of only one or more cylinders.

High power steam turbines are dominantly composed of several cylinders mounted on the same shaft, while medium and low power steam turbines can be composed of only one cylinder [10, 11]. In addition, low power steam turbines are usually used for the auxiliary equipment drive [12].

Steam turbine cylinders can be single flow or dual flow cylinders. In single flow cylinders, steam expands throughout the cylinder in one direction only (from cylinder inlet to outlet), while in dual flow cylinders steam enters in the cylinder at the cylinder midpoint and simultaneously expands in two directions. Dual flow cylinders have many benefits, so they are dominantly used as the last (low pressure) cylinders before main condenser [13].

Steam turbine cylinders usually have several steam extractions. Each steam extraction from the turbine cylinder lead a certain amount of steam mass flow rate to the components of condensate/feedwater heating system, or for auxiliary heating purposes [14].

Steam inlet, steam outlet and all extractions of the same turbine cylinder defines cylinder Segments and make a clear division of the entire cylinder into several parts. Cylinder Segments allow analysis of the steam expansion processes not only in the entire cylinder, but also in (at least) several cylinder parts [15]. Analysis of the process inside each Segment of the same turbine cylinder allows more precise detection of potentially problematic parts which cannot be obtained considering entire cylinder as a whole.

In this paper is performed isentropic analysis of the entire Intermediate Pressure Cylinder (IPC) and all of his four Segments. Such analysis allows detection of the Segment with the lowest isentropic efficiency and the highest isentropic loss, which should be a baseline for any improvements and modifications.

2. Description and operating characteristics of the analyzed IPC

The analyzed Intermediate Pressure Cylinder (IPC) is a part of a complex three cylinder steam turbine from Kolubara A5 steam power plant. All the cylinders of this turbine are connected to the same shaft which drives an Electric Generator (EG). The entire turbine has a nominal power of 110 MW [16].

General scheme of the IPC analyzed in this paper, along with operating points necessary for his isentropic analysis is presented in Fig. 1. IPC gets steam from steam Re-Heater (Re-Heater is mounted inside the steam generator), operating point 1, Fig. 1. Analyzed IPC is a single flow cylinder which means that steam expands through the cylinder in only one direction – from the inlet until the outlet. IPC has four steam extractions. The first steam extraction (operating point 2, Fig. 1) delivers a certain amount of steam to High Pressure Feedwater Heating System, second steam extraction (operating point 3, Fig. 1) delivers a certain amount of steam to Deaerator, while the last two extractions (operating points 4 and 5, Fig. 1) deliver a certain amount of steam to the components of Low Pressure Condensate Heating System. The remaining steam mass flow rate at the IPC outlet (operating point 6, Fig. 1) is delivered to the Low Pressure Cylinder (LPC).

Steam inlet, outlet and extractions divide analyzed IPC into four Segments. As presented in the Fig. 1, the first Segment is IPC part between steam inlet and first extraction, second Segment is defined between first and second steam extraction, third Segment is defined between second and third steam extraction, while the last fourth Segment is defined between the last two (third and fourth) steam extractions. Isentropic analysis performed in this paper will be related to each of four IPC Segments as well as to the entire cylinder (EC).

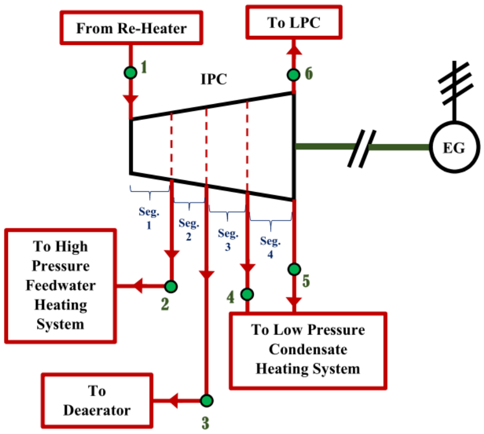

Fig. 1. *General scheme of the Intermediate Pressure Cylinder (IPC) along with operating points necessary for the isentropic analysis*

Isentropic analysis of the entire IPC (EC) and each of his Segments strongly differs. The most notable differences between these two isentropic analyses are graphically presented in a specific enthalpy/specific entropy (h/s) diagram which shows the difference between real (polytropic) and ideal (isentropic) steam expansion processes, Fig. 2.

It should be highlighted that real (polytropic) steam expansion process in any Segment or in the EC is characterized by an increase in steam specific entropy, which is related to losses during the expansion process. In ideal (isentropic) steam expansion process, all the losses which occur during the expansion are neglected, so steam specific entropy remains unchanged. Therefore, in ideal (isentropic) steam expansion process, any Segment or EC will develop the highest possible mechanical power.

Isentropic analysis of the entire IPC is based on a comparison of real (polytropic) and ideal (isentropic) steam expansion processes in the entire cylinder. In Fig. 2, real (polytropic) steam expansion process of the EC is represented with operating points 1 – 2 – 3 – 4 – 5, while ideal (isentropic) steam expansion process of the entire IPC is represented with operating points 1 – 2is,EC – 3is,EC – 4is,EC – 5is,EC.

Isentropic analysis of each IPC Segment is based on a comparison of real (polytropic) and ideal (isentropic) steam expansion processes in each IPC Segment. For the first IPC Segment, real steam expansion is represented with operating points 1 and 2, while ideal steam expansion is represented with operating points 1 and 2is,Seg. In second IPC Segment, real expansion is represented with operating points 2 and 3, while ideal steam expansion is represented with operating points 2 and 3is,Seg. In third IPC Segment, real expansion is represented with operating points 3 and 4, while ideal steam expansion is represented with operating points 3 and 4is,Seg. In the last, fourth IPC Segment, real expansion is represented with operating points 4 and 5, while ideal steam expansion is represented with operating points 4 and 5is,Seg. Finally, it should be highlighted that, due to steam extractions, steam mass flow rate through each Segment differs, what must be considered in the equations for the real (polytropic) and ideal (isentropic) mechanical power calculation of each Segment. The operating points of the real (polytropic) steam expansion process throughout the observed IPC in Fig. 2 are marked in accordance to Fig. 1.

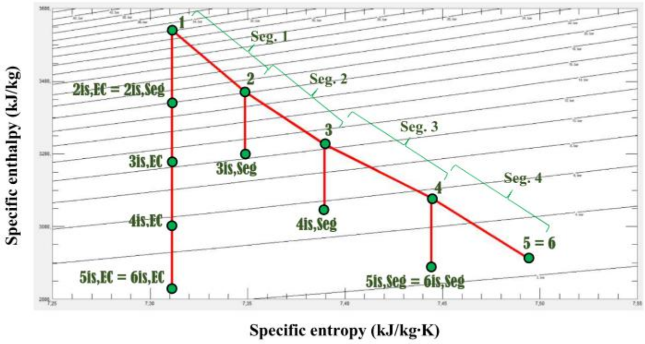

Fig. 2. *Steam expansion process (ideal and real) throughout entire IPC and all his Segments in specific enthalpy/specific entropy (h/s) diagram*

3. Isentropic analysis equations of the entire IPC and his Segments

In an isentropic analysis of any steam turbine, turbine cylinder and cylinder Segment are compared real (polytropic) and ideal (isentropic) steam expansion processes [17], as presented in Fig. 2. Steam operating parameters in real (polytropic) expansion process are obtained by measurements during the turbine (and each turbine cylinder) exploitation in the power plant. Steam operating parameters in ideal (isentropic) expansion are obtained mathematically. The ideal 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 expansion steam specific entropy remains always constant.

The baseline for isentropic analysis is calculation of real and ideal mechanical power (for the entire turbine, cylinder or cylinder Segment). Isentropic loss is the difference between ideal and real mechanical power, while the isentropic efficiency is the ratio between real and ideal mechanical power.

It should also be highlighted that isentropic analysis must be performed in a different manner for the entire turbine cylinder and for the cylinder Segments [18]. For the cylinder Segments must be used ideal (isentropic) specific heat drop from the Segment inlet until the Segment outlet. Parts of the main isentrope (which is used for the entire IPC) cannot be used in the isentropic analysis of cylinder Segments (for all Segments except the first one) due to isobars spread during the increase in steam specific entropy.

Equations for the isentropic analysis of the entire observed IPC and all his Segments are composed according to the recommendations from the literature [19, 20]. Operating points used in the equations through this Section are related to Fig. 1 and Fig. 2.

3.1. Isentropic analysis equations of the entire IPC

Real (polytropic) mechanical power of the entire observed IPC is calculated according to the equation:

$$P_{\mathrm{re,EC}}=\dot{m}_1\cdot(h_1-h_2)+(\dot{m}_1-\dot{m}_2)\cdot(h_2-h_3)+(\dot{m}_1-\dot{m}_2-\dot{m}_3)\cdot(h_3-h_4)+(\dot{m}_1-\dot{m}_2-\dot{m}_3-\dot{m}_4)\cdot(h_4-h_5). \quad (1)$$

Ideal (isentropic) mechanical power of the entire IPC is calculated by using an equation:

$$P_{\mathrm{id,EC}}=\dot{m}_1\cdot(h_1-h_{\mathrm{2is.EC}})+(\dot{m}_1-\dot{m}_2)\cdot(h_{\mathrm{2is.EC}}-h_{\mathrm{3is.EC}})+(\dot{m}_1-\dot{m}_2-\dot{m}_3)\cdot(h_{\mathrm{3is.EC}}-h_{\mathrm{4is.EC}})+(\dot{m}_1-\dot{m}_2-\dot{m}_3-\dot{m}_4)\cdot(h_{\mathrm{4is.EC}}-h_{\mathrm{5is.EC}}). \quad (2)$$

Isentropic loss of the entire IPC is:

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

Entire IPC isentropic efficiency is:

$$\eta_{\mathrm{is,EC}}=\frac{P_{\mathrm{re,EC}}}{P_{\mathrm{id,EC}}}. \quad (4)$$

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 EC is related to the entire IPC, while index L is related to isentropic loss.

3.2. Isentropic analysis equations of the IPC Segments

Real (polytropic) and ideal (isentropic) mechanical power of the first IPC Segment (Seg. 1) are:

$$P_{\mathrm{re,Seg.1}}=\dot{m}_1\cdot(h_1-h_2), \quad (5)$$
$$P_{\mathrm{id,Seg.1}}=\dot{m}_1\cdot(h_1-h_{\mathrm{2is,Seg}}). \quad (6)$$

Real (polytropic) and ideal (isentropic) mechanical power of the second IPC Segment (Seg. 2) are:

$$P_{\mathrm{re,Seg.2}}=(\dot{m}_1-\dot{m}_2)\cdot(h_2-h_3), \quad (7)$$
$$P_{\mathrm{id,Seg.2}}=(\dot{m}_1-\dot{m}_2)\cdot(h_2-h_{\mathrm{3is,Seg}}). \quad (8)$$

Real (polytropic) and ideal (isentropic) mechanical power of the third IPC Segment (Seg. 3) are:

$$P_{\mathrm{re,Seg.3}}=(\dot{m}_1-\dot{m}_2-\dot{m}_3)\cdot(h_3-h_4), \quad (9)$$
$$P_{\mathrm{id,Seg.3}}=(\dot{m}_1-\dot{m}_2-\dot{m}_3)\cdot(h_3-h_{\mathrm{4is,Seg}}). \quad (10)$$

Real (polytropic) and ideal (isentropic) mechanical power of the fourth IPC Segment (Seg. 4) are:

$$P_{\mathrm{re,Seg.4}}=(\dot{m}_1-\dot{m}_2-\dot{m}_3-\dot{m}_4)\cdot(h_4-h_5), \quad (11)$$
$$P_{\mathrm{id,Seg.4}}=(\dot{m}_1-\dot{m}_2-\dot{m}_3-\dot{m}_4)\cdot(h_4-h_{\mathrm{5is,Seg}}). \quad (12)$$

The isentropic loss of each IPC Segment is:

$$IS_{\mathrm{L,Seg.(i)}}=P_{\mathrm{id,Seg.(i)}}-P_{\mathrm{re,Seg.(i)}}, \quad (13)$$

while isentropic efficiency of each IPC Segment is:

$$\eta_{\mathrm{is,Seg.(i)}}=\frac{P_{\mathrm{re,Seg.(i)}}}{P_{\mathrm{id,Seg.(i)}}}. \quad (14)$$

In Eq. 13 and Eq. 14, index i is equal from 1 to 4 and is related to the IPC Segments numeration (according to Fig. 1 and Fig. 2).

4. Steam operating parameters required for the isentropic analysis

The IPC operating parameters, obtained by the measurements, are related to the real (polytropic) steam expansion process – they are found in the literature [16] and presented in Table 1. It should be highlighted that all operating points presented in Table 1 contained superheated steam. In the literature [20, 21] can be found that IPC has optimal operating conditions in a three cylinder steam turbine, because he is not influenced by the steam of the highest pressure and temperature (as the High Pressure Cylinder) and simultaneously, it is not influenced by additional losses related to wet steam (as the last stages of Low Pressure Cylinder).

Steam specific enthalpies related to the ideal (isentropic) steam expansion processes (for entire IPC and each of his Segments) are obtained by numerical calculations, according to the previously described procedure. For the entire IPC, steam operating parameters in the ideal (isentropic) expansion process are presented in Table 2, while for each IPC Segment, steam operating parameters in the ideal (isentropic) expansion process are presented in Table 3. Steam parameters in each operating point from Table 2 and Table 3, are calculated by using NIST-REFPROP 9.0 software [22].

Table 1. *Steam operating parameters in the real (polytropic) expansion process*

O. P.*	Temperature (°C)	Pressure (bar)	Mass flow rate (kg/s)	Specific enthalpy (kJ/kg)	Specific entropy (kJ/kg·K)
1	538.70	32.2	98.98	3542.1	7.3111
2	455.31	18.2	5.23	3372.2	7.3486
3	383.07	10.5	1.80	3227.6	7.3893
4	307.92	5.5	4.70	3079.7	7.4442
5	222.13	2.5	4.33	2913.2	7.4939
6	222.13	2.5	82.92	2913.2	7.4939

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

Table 2. *Steam operating parameters in the ideal (isentropic) expansion process for the Entire Cylinder*

Isentropic - Entire Cylinder			
O. P.*	**Pressure (bar)**	**Specific entropy (kJ/kg·K)**	**Isentropic specific enthalpy-Entire Cylinder (kJ/kg)**
1	32.2	7.3111	3542.1
2is,EC = 2is,Seg	18.2	7.3111	3345.1
3is,EC	10.5	7.3111	3177.2
4is,EC	5.5	7.3111	3004.8
5is,EC = 6is,EC	2.5	7.3111	2826.6

* O. P. = Operating Point (in accordance to Fig. 2)

Table 3. *Steam operating parameters in the ideal (isentropic) expansion process for the cylinder Segments*

Isentropic - Segments			
O. P.*	**Pressure (bar)**	**Specific entropy (kJ/kg·K)**	**Isentropic specific enthalpy-Segments (kJ/kg)**
3is,Seg	10.5	7.3486	3201.2
4is,Seg	5.5	7.3893	3048.2
5is,Seg = 6is,Seg	2.5	7.4442	2888.9

* O. P. = Operating Point (in accordance to Fig. 2)

5. Results and discussion

Real (polytropic) and ideal (isentropic) mechanical power of the entire IPC (EC) and each of his Segments is presented in Fig. 3.

Due to neglecting all the losses during the expansion process, ideal (isentropic) mechanical power of the EC and each Segment must be higher in comparison to real (polytropic) one, what is confirmed in Fig. 3. Observation of all Segments shows that the first Segment (Seg. 1) is the dominant mechanical power producer which produces 16816.70 kW of mechanical power in the real expansion process and his potential in mechanical power production (ideal expansion process) is equal to 19499.06 kW.

Entire IPC produces 58499.48 kW of mechanical power in real (polytropic) steam expansion process, while it can produce mechanical power equal to 66639.82 kW if the expansion process through this cylinder is ideal (isentropic).

The entire turbine, which observed IPC is a constituent part, produces nominal power equal to 110 MW, so it can be concluded that IPC is the dominant mechanical power producer of all cylinders, and that this cylinder produces more than half mechanical power of the entire turbine in the real expansion process.

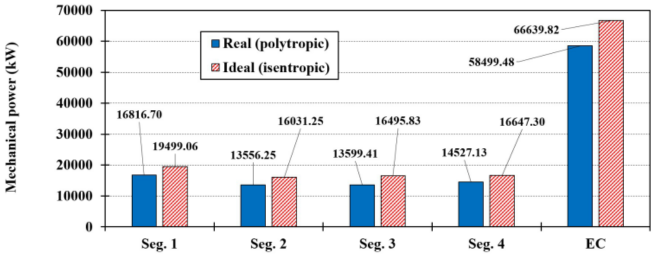

Fig. 3. *Mechanical power (ideal and real) produced in the entire IPC and each cylinder Segment*

Isentropic loss of the entire IPC and each of his Segments is presented in Fig. 4.

The first Segment (Seg. 1) which produces the highest mechanical power (both ideal and real) did not have the highest isentropic loss. The highest isentropic loss of all Segments has Seg. 3, equal to 2896.43 kW. On the other side, the last, fourth Segment (Seg. 4) has the lowest isentropic loss equal to 2120.17 kW.

Entire IPC isentropic loss is equal to 8140.33 kW, Fig. 4.

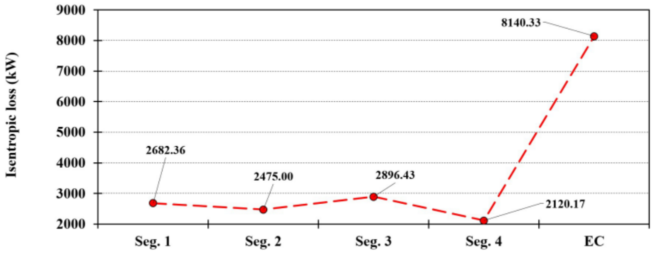

Fig. 4. *Isentropic loss of the entire IPC and each cylinder Segment*

Comparison of Fig. 4 and Fig. 5 shows that isentropic loss and isentropic efficiency of IPC Segments are reverse proportional – Seg. 3 which has the highest isentropic loss simultaneously has the lowest isentropic efficiency (equal to 82.44%), while Seg. 4 which has the lowest isentropic loss has the highest isentropic efficiency (equal to 87.26%). It should be highlighted that Seg. 1 which has higher isentropic loss also has higher isentropic efficiency in comparison to Seg. 2. Entire IPC has isentropic efficiency equal to 87.78%, Fig. 5.

Entire IPC has very high isentropic efficiency, while Seg. 3 can be further improved with an aim to increase his isentropic efficiency. Any improvements and modifications which should potentially be performed in the observed IPC should firstly be based on the turbine stages mounted inside Seg. 3.

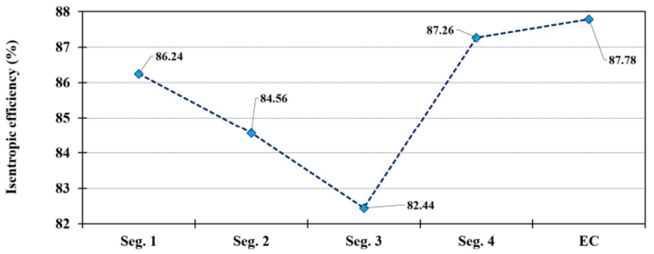

Fig. 5. *Isentropic efficiency of the entire IPC and each Segment*

Further analysis of the observed IPC will be based on the results of this research. It can (and it will) be used various conventional [23, 24] and artificial intelligence [25-27] methods and techniques to find optimal operating regimes of this cylinder, in which the efficiencies will be the highest (for the entire cylinder and each his Segment).

6. Conclusions

This paper presents isentropic analysis results of the entire Intermediate Pressure Cylinder (IPC) and all of four his Segments. The most important conclusions and obtained findings are:

- The first Segment (Seg. 1) is the dominant mechanical power producer of all Segments and it produces 16816.70 kW of mechanical power in the real (polytropic) expansion process.
- Entire IPC produces 58499.48 kW of mechanical power in real (polytropic) steam expansion process. Analyzed IPC produces more than half mechanical power of the entire turbine in which he operates.
- The highest isentropic loss of all Segments has Seg. 3, equal to 2896.43 kW, while the last, fourth Segment (Seg. 4) has the lowest isentropic loss equal to 2120.17 kW. Entire IPC isentropic loss is equal to 8140.33 kW.
- Isentropic loss and isentropic efficiency of IPC Segments are reverse proportional – Seg. 3 which has the highest isentropic loss simultaneously has the lowest isentropic efficiency (equal to 82.44%), while Seg. 4 which has the lowest isentropic loss has the highest isentropic efficiency (equal to 87.26%). Entire IPC has an isentropic efficiency equal to 87.78%.
- Any improvements and modifications which can potentially be performed in the observed IPC should firstly be based on the turbine stages mounted inside Seg. 3.

7. Acknowledgment

This research has been fully supported by the Croatian Science Foundation under the project IP-2022-10-2821.

8. References

[1] Rosen, M. A. (2001). Energy-and exergy-based comparison of coal-fired and nuclear steam power plants. Exergy, An International Journal, 1(3), 180-192. (doi:10.1016/S1164-0235(01)00024-3)

[2] 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)

[3] Noroozian, A., Mohammadi, A., Bidi, M., & Ahmadi, M. H. (2017). Energy, exergy and economic analyses of a novel system to recover waste heat and water in steam power plants. Energy conversion and management, 144, 351-360. (doi:10.1016/j.enconman.2017.04.067)

[4] Tontu, M., Sahin, B., & Bilgili, M. (2019). Using energy and exergy analysis to compare different coal-fired power plants. Energy Sources, Part A: Recovery, Utilization, and Environmental Effects, 1-16. (doi:10.1080/15567036.2019.1696429)

[5] 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)

[6] 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)

[7] 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)

[8] 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)

[9] 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)

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

[11]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)

[12]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)

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

[14]Uysal, C., Kurt, H., & Kwak, H. Y. (2017). Exergetic and thermoeconomic analyses of a coal-fired power plant. International Journal of Thermal Sciences, 117, 106-120. (doi:10.1016/j.ijthermalsci.2017.03.010)

[15]Mrzljak, V., & Poljak, I. (2019). Energy analysis of main propulsion steam turbine from conventional LNG carrier at three different loads. NAŠE MORE: znanstveni časopis za more i pomorstvo, 66(1), 10-18. (doi:10.17818/NM/2019/1.2)

[16]Djordjevic, M., Mančić, M., & Mitrović, D. (2015). ENERGY AND EXERGY ANALYSIS OF COAL FIRED POWER PLANT. Facta Universitatis, Series: Working and Living Environmental Protection, 163-175.

[17]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)

[18]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)

[19]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)

[20]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)

[21]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.

[22]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.

[23]Mrzljak, V., Poljak, I., Jelić, M., & Prpić-Oršić, J. (2023). Thermodynamic Analysis and Improvement Potential of Helium Closed Cycle Gas Turbine Power Plant at Four Loads. Energies, 16(15), 5589. (doi:10.3390/en16155589)

[24]Entezari, A., Bahari, M., Aslani, A., Ghahremani, S., & Pourfayaz, F. (2021). Systematic analysis and multi-objective optimization of integrated power generation cycle for a thermal power plant using Genetic algorithm. Energy Conversion and Management, 241, 114309. (doi:10.1016/j.enconman.2021.114309)

[25]Baressi Šegota, S., Mrzljak, V., Anđelić, N., Poljak, I., & Car, Z. (2023). Use of Synthetic Data in Maritime Applications for the Problem of Steam Turbine Exergy Analysis. Journal of Marine Science and Engineering, 11(8), 1595. (doi:10.3390/jmse11081595)

[26]Babatunde, D. E., Anozie, A., & Omoleye, J. (2020). Artificial neural network and its applications in the energy sector: An overview. International Journal of Energy Economics and Policy, 10(2), 250-264. (doi:10.32479/ijeep.8691)

[27]Baressi Šegota, S., Lorencin, I., Anđelić, N., Mrzljak, V., & Car, Z. (2020). Improvement of marine steam turbine conventional exergy analysis by neural network application. Journal of Marine Science and Engineering, 8(11), 884. (doi:10.3390/jmse8110884)