Isentropic analysis of the complex three cylinder steam turbine from municipal solid waste power plant

Mrzljak Vedran[1], Prpić-Oršić Jasna[1], Poljak Igor[2], Anđelić Nikola[1]
[1]Faculty of Engineering, University of Rijeka, Vukovarska 58, 51000 Rijeka, Croatia
[2]Department of maritime sciences, University of Zadar, Mihovila Pavlinovića 1, 23000 Zadar, Croatia
E-mail: vedran.mrzljak@riteh.uniri.hr, jasna.prpic.orsic@riteh.uniri.hr, ipoljak1@unizd.hr, nikola.andjelic@riteh.uniri.hr

Abstract: *In this paper are presented isentropic analysis results of a steam turbine and each of its cylinders which operate in Municipal Solid Waste (MSW) power plant. Low Pressure Cylinder (LPC) which produces the highest real mechanical power has the lowest isentropic loss of all cylinders equal to 4344.75 kW, while High Pressure Cylinder (HPC) which produces the lowest real mechanical power has the highest isentropic loss of all cylinders equal to 5204.54 kW. Isentropic losses and isentropic efficiencies are reverse proportional, because the cylinder with the lowest isentropic loss (LPC) has the highest isentropic efficiency equal to 88.92%, while the cylinder with the highest isentropic loss (HPC) has the lowest isentropic efficiency equal to 84.58%. Surprisingly, isentropic efficiency of the Intermediate Pressure Cylinder (IPC) is equal to 86.80% only, which is higher in comparison to HPC but notably lower than LPC. The observed turbine strongly differs from other comparable steam turbines from the literature where IPC has notably higher isentropic efficiencies than both HPC and LPC. Whole observed steam turbine produces real mechanical power equal to 97513 kW, while its isentropic efficiency is equal to 86.87%.*
KEYWORDS*: ISENTROPIC ANALYSIS, COMPLEX STEAM TURBINE, TURBINE CYLINDERS, MUNICIPAL SOLID WASTE (MSW)*

1. Introduction

Steam turbines are nowadays the dominant mechanical power producers worldwide [1, 2]. Produced mechanical power by the steam turbines is dominantly used for the electrical generators drive and electricity production [3, 4]. However, steam turbines can also be used in various power plants as auxiliary turbines for the direct mechanical power consumer's drive [5, 6].

High power steam turbines are dominantly composed of several cylinders (usually three to five cylinders) mounted on the same shaft [7, 8]. Medium and low power steam turbines are usually composed of two, or only one cylinder [9, 10].

In complex steam turbines, each cylinder usually has several steam extractions [11, 12]. Each steam extraction delivers a certain amount of steam to the components of condensate/feedwater heating system which increases water temperature before its entrance to the steam generator and in that way reduces fuel consumption [13, 14].

In addition, complex steam turbines dominantly possess steam re-heater which additionally increases steam temperature after its expansion in the first cylinder [15, 16]. Steam re-heater can be mounted in the power plant independently of steam generator, but the most usual arrangement is that steam re-heater is mounted inside steam generator and uses the same fuel as other steam generator components [17].

This paper presents an isentropic analysis of a complex three cylinder steam turbine which operates in Municipal Solid Waste (MSW) power plant. Isentropic analysis is simultaneously performed for the whole observed steam turbine as well as for each of its cylinders. The obtained results are compared to the isentropic analysis results of various similar steam turbines. It is concluded that isentropic efficiencies of the analyzed steam turbine cylinders show some notable differences in comparison to similar turbines from other power plants.

2. Description and characteristics of the analyzed steam turbine

Analyzed steam turbine operates in a power plant which uses Municipal Solid Waste (MSW) as a fuel [18]. Steam turbine consists of three cylinders (High Pressure Cylinder – HPC, Intermediate Pressure Cylinder – IPC and Low Pressure Cylinder – LPC) connected to the same shaft which drives an electric generator, Fig. 1. As can be seen from Fig. 1, HPC has only one steam extraction (at the end of the cylinder), IPC has four steam extractions, while LPC has three steam extractions. HPC extraction and first two steam extractions of the IPC deliver a certain steam mass flow rate to high pressure feedwater heating system [19, 20], while third IPC extraction delivers steam to the deaerator. Last IPC extraction and all three LPC extractions deliver a certain steam mass flow rate to low pressure condensate heating system [21, 22]. After expansion in LPC, the remaining steam mass flow rate is delivered to the main condenser. It should be highlighted that this power plant also possesses steam re-heater, traditionally mounted between HPC and IPC inside steam generator. Steam re-heater increases steam temperature and prepare it for the expansion in IPC and LPC. Steam re-heating process has many benefits not also in this, but also in many other steam power plants [23, 24].

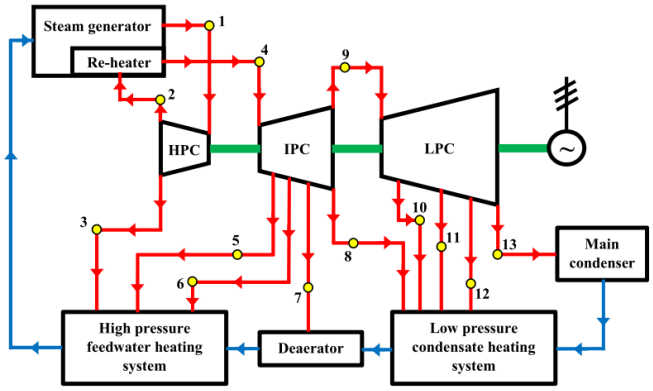

Fig. 1. *General scheme of the analyzed steam turbine along with operating points required for the isentropic analysis*

This paper presents the isentropic analysis results of the whole observed steam turbine and each of its three cylinders.

Isentropic analysis is based on a comparison of real (polytropic) and ideal (isentropic) steam expansion processes in each cylinder and whole turbine. Real (polytropic) steam expansion process is defined by operating points presented in Fig. 1 and Fig. 2 (points defined by numbers only) and its main characteristic is an increase in steam specific entropy during expansion. From Fig. 2 can be clearly seen that steam specific entropy increases from operating point 1 to 2 (HPC), from operating point 4 to 8 (IPC) and from operating point 9 to 13 (LPC). Increase in steam specific entropy during expansion is proportional to losses which occur in the turbine stages. Data in each operating point for real (polytropic) steam expansion process can be obtained only by the measurements during turbine exploitation.

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 in ideal process steam specific entropy remains constant during the expansion in each turbine cylinder. Ideal (isentropic) steam expansion process in each cylinder is defined using operating points with additional index – is, Fig. 2. Therefore, from Fig. 2 can be seen that steam specific entropy remains constant in the ideal expansion related to the HPC (operating points from 1 to 2is), IPC (operating points from 4 to 8is) and LPC (operating points from 9 to 13is). For each turbine cylinder, data related to the ideal (isentropic) steam expansion process are obtained mathematically, by knowing the steam

pressure in each operating point and by knowing steam specific entropy at the cylinder inlet. In comparison to real steam expansion process, ideal (isentropic) steam expansion process did not consider any losses which occur in turbine stages, what means that mechanical power developed in each turbine cylinder (as well as in the whole turbine) will always be higher in ideal than in real expansion process [25]. The ideal steam expansion actually represents maximal potential which can be used in any turbine cylinder and in the whole observed turbine.

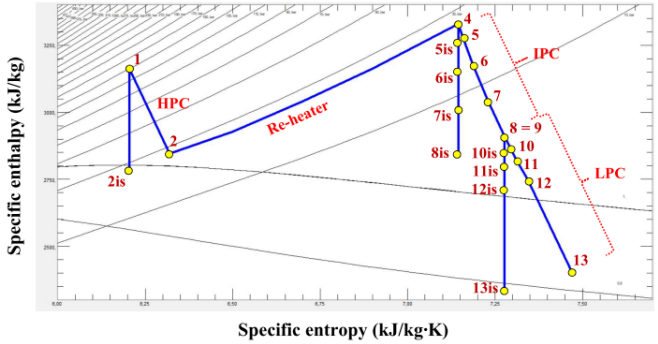

Fig. 2. *Specific enthalpy – Specific entropy (h-s) diagram of real (polytropic) and ideal (isentropic) steam expansion process through each cylinder of the observed turbine*

3. Isentropic analysis equations

Isentropic analysis of any steam turbine is actually a comparison of mechanical power developed during the real (polytropic) steam expansion process and mechanical power developed during the ideal (isentropic) steam expansion process. Ideal (isentropic) steam expansion process is theoretical one and it can be obtained if all the losses are neglected [26].

Isentropic analysis is a "black box" method because the inner structure of the whole turbine and each turbine cylinder is not known and it is not required. The required elements for this kind of analysis are all fluid flow streams to and from the observed component [27].

All equations presented is this section are related to turbine operating points presented in Fig. 1 and Fig. 2. Equations used in the isentropic analysis are composed according to the recommendations from the literature [28, 29]. Developed mechanical power (both real and ideal) of each cylinder and whole turbine are calculated according to the following equations:

HPC

$$P_{re,HPC}=\dot{m}_1\cdot(h_1-h_2) \quad (1)$$

$$P_{id,HPC}=\dot{m}_1\cdot(h_1-h_{2is}) \quad (2)$$

IPC

$$P_{re,IPC}=\dot{m}_4\cdot(h_4-h_5)+(\dot{m}_4-\dot{m}_5)\cdot(h_5-h_6)+(\dot{m}_4-\dot{m}_5-\dot{m}_6)\cdot(h_6-h_7)+(\dot{m}_4-\dot{m}_5-\dot{m}_6-\dot{m}_7)\cdot(h_7-h_8) \quad (3)$$

$$P_{id,IPC}=\dot{m}_4\cdot(h_4-h_{5is})+(\dot{m}_4-\dot{m}_5)\cdot(h_{5is}-h_{6is})+(\dot{m}_4-\dot{m}_5-\dot{m}_6)\cdot(h_{6is}-h_{7is})+(\dot{m}_4-\dot{m}_5-\dot{m}_6-\dot{m}_7)\cdot(h_{7is}-h_{8is}) \quad (4)$$

LPC

$$P_{re,LPC}=\dot{m}_9\cdot(h_9-h_{10})+(\dot{m}_9-\dot{m}_{10})\cdot(h_{10}-h_{11})+(\dot{m}_9-\dot{m}_{10}-\dot{m}_{11})\cdot(h_{11}-h_{12})+(\dot{m}_9-\dot{m}_{10}-\dot{m}_{11}-\dot{m}_{12})\cdot(h_{12}-h_{13}) \quad (5)$$

$$P_{id,LPC}=\dot{m}_9\cdot(h_9-h_{10is})+(\dot{m}_9-\dot{m}_{10})\cdot(h_{10is}-h_{11is})+(\dot{m}_9-\dot{m}_{10}-\dot{m}_{11})\cdot(h_{11is}-h_{12is})+(\dot{m}_9-\dot{m}_{10}-\dot{m}_{11}-\dot{m}_{12})\cdot(h_{12is}-h_{13is}) \quad (6)$$

WT (Whole Turbine)

$$P_{re,WT}=P_{re,HPC}+P_{re,IPC}+P_{re,LPC} \quad (7)$$

$$P_{id,WT}=P_{id,HPC}+P_{id,IPC}+P_{id,LPC} \quad (8)$$

The isentropic loss of each cylinder and whole turbine is calculated according to the equation:

$$IS_{L,(i)}=P_{id,(i)}-P_{re,(i)} \quad (9)$$

while isentropic efficiency (again of each cylinder and whole turbine) is calculated by using an equation:

$$\eta_{IS,(i)}=\frac{P_{re,(i)}}{P_{id,(i)}} \quad (10)$$

In Eq. 9 and Eq. 10 index i is related to each turbine cylinder and to whole turbine (i = HPC; IPC; LPC; WT).

4. Steam operating parameters

Steam operating parameters of the real (polytropic) steam expansion process, which are obtained by the measurements during the turbine exploitation, are found in [18] and presented in Table 1. Other steam operating parameters presented in Table 1 which are not found in the literature, are calculated from known data in each operating point by using NIST-REFPROP 9.0 software [30].

Parameters of the ideal (isentropic) steam expansion process in each cylinder of the observed turbine are obtained by the calculations, according to previously described procedure, Fig. 2. Along with steam mass flow rates, in ideal (isentropic) mechanical power calculation the most important steam parameters are isentropic specific enthalpies, which are presented for each cylinder of the observed turbine in Table 2.

Table 1. *Steam operating parameters required for the isentropic analysis of the observed steam turbine and each turbine cylinder – 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	440.0	130.00	90.20	3162.2	6.2047	Sh.**
2	240.5	26.50	88.22	2845.8	6.3190	Sh.
3	240.5	26.50	1.98	2845.8	6.3190	Sh.
4	440.0	25.00	88.22	3329.3	7.1458	Sh.
5	415.2	20.83	3.38	3280.5	7.1581	Sh.
6	360.8	13.66	3.88	3174.1	7.1872	Sh.
7	290.8	7.52	3.76	3038.7	7.2306	Sh.
8	224.4	4.00	0.92	2911.7	7.2770	Sh.
9	224.4	4.00	76.28	2911.7	7.2770	Sh.
10	206.4	3.33	1.40	2877.5	7.2901	Sh.
11	178.6	2.48	1.90	2824.7	7.3106	Sh.
12	138.7	1.57	7.15	2749.3	7.3436	Sh.
13	51.03	0.13	65.83	2402.8	7.4698	0.92

* O. P. = Operating Point (in accordance to Fig. 1)
** Sh. = Superheated

Table 2. *Steam operating parameters required for the isentropic analysis of the observed steam turbine and each turbine cylinder – ideal (isentropic) steam expansion process*

O. P.*	Pressure (bar)	Isentropic specific enthalpy (kJ/kg)
1	130.00	3162.2
2is	26.50	2788.1
3	26.50	-
4	25.00	3329.3
5is	20.83	3272.0
6is	13.66	3148.1
7is	7.52	2991.9
8is	4.00	2848.5
9	4.00	2911.7
10is	3.33	2871.2
11is	2.48	2809.7
12is	1.57	2722.3
13is	0.13	2340.3

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

5. Results and discussion

Ideal (isentropic) and real (polytropic) mechanical power of each cylinder and whole analyzed turbine are presented in Fig. 3.

From Fig. 3 is clear that for each cylinder and whole turbine ideal (isentropic) mechanical power is higher than real (polytropic) one due to neglecting all losses which occur in the real steam expansion process. Observing all cylinders, it can be concluded that the dominant mechanical power producer is LPC which produces real mechanical power equal to 34875.23 kW. However, real mechanical power produced in LPC is only slightly higher than real mechanical power produced in IPC (which is equal to 34098.50 kW). The lowest real mechanical power is produced in HPC (28539.28 kW), which is notably lower in comparison to both IPC and LPC.

Whole observed steam turbine (WT) produces real mechanical power equal to 97513 kW, while its potential in mechanical power production (in ideal, isentropic scenario) is equal to 112246.91 kW. Whole turbine will never be able to produce ideal (isentropic) mechanical power in real exploitation, but ideal mechanical power can be used as a guideline (not only for the whole turbine, but also for each cylinder) for any improvements.

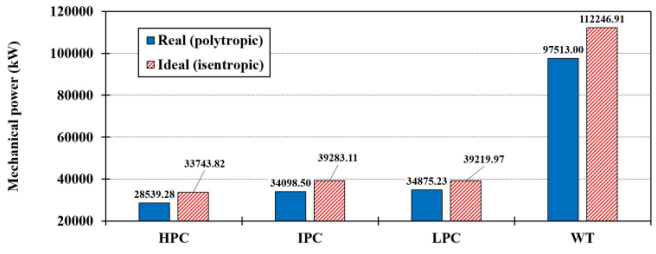

Fig. 3. *Ideal (isentropic) and real (polytropic) mechanical power of each cylinder and whole analyzed turbine*

Isentropic losses of each turbine cylinder and whole observed turbine are presented in Fig. 4.

Observing turbine cylinders, from Fig. 4 can be seen interesting fact related to this steam turbine – LPC which produces the highest real mechanical power has the lowest isentropic loss of all cylinders equal to 4344.75 kW, while HPC which produces the lowest real mechanical power has the highest isentropic loss of all cylinders equal to 5204.54 kW. It is also interesting that IPC which real mechanical power is very close to one produced in LPC has isentropic loss only slightly lower than HPC (IPC isentropic loss is equal to 5184.62 kW), Fig. 3 and Fig. 4.

Isentropic loss of the whole observed steam turbine is equal to 14733.90 kW.

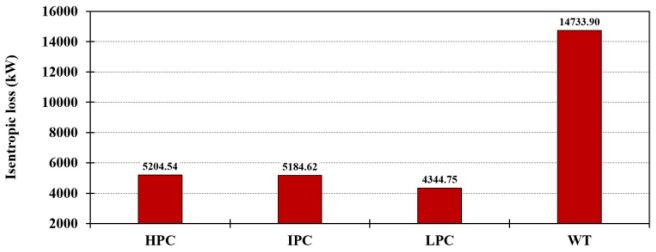

Fig. 4. *Isentropic loss of each cylinder and whole analyzed turbine*

Isentropic efficiencies of each cylinder and whole observed steam turbine are presented in Fig. 5.

By observing results related to all three cylinders, it can be concluded that isentropic losses, Fig. 4, and isentropic efficiencies, Fig. 5, are reverse proportional, because the cylinder with the lowest isentropic loss (LPC) has the highest isentropic efficiency equal to 88.92%, while the cylinder with the highest isentropic loss (HPC) has simultaneously the lowest isentropic efficiency equal to 84.58%. Surprisingly, isentropic efficiency of the IPC is equal to 86.80%, which is higher in comparison to HPC but simultaneously lower than LPC. Finally, isentropic efficiency of the whole analyzed steam turbine is equal to 86.87%.

In the literature can be found many comparisons of a various steam turbines. Observing literature [31], it can be stated that this steam turbine shows some differences related to isentropic performance in comparison to the steam turbines from marine, conventional and ultra-supercritical steam power plants. For steam turbine analyzed in this paper can be seen that LPC has higher isentropic efficiency in comparison to IPC, while for other comparable steam turbines IPC has notably higher isentropic efficiencies than both HPC and LPC. Also, while observing isentropic efficiencies of all cylinders and whole steam turbine analyzed in this paper, it can be concluded that they show isentropic performance very close to the turbine from the conventional steam power plant. Obtained isentropic efficiencies of the cylinders and whole turbine in this analysis are higher in comparison to steam turbine from marine propulsion steam power plant, but still lower in comparison to steam turbine from ultra-supercritical power plant.

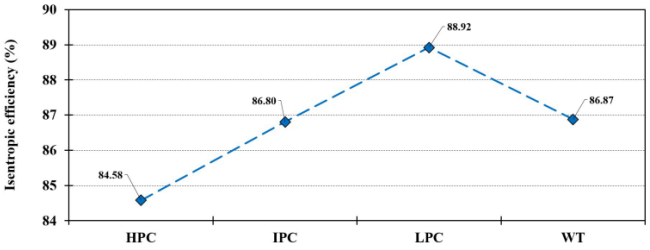

Fig. 5. *Isentropic efficiency of each cylinder and whole analyzed turbine*

Further analysis of this steam turbine will be based on the investigation of its improvement possibilities and possible optimization (for each cylinder and whole turbine) using various conventional [32] and machine learning methods and techniques which are often used for similar kind of problems [33-36].

6. Conclusions

In this paper is presented an isentropic analysis of a steam turbine and each of three turbine cylinders from Municipal Solid Waste (MSW) power plant. Obtained results lead to several interesting conclusions:

- The dominant mechanical power producer in the observed turbine is LPC which produces real mechanical power equal to 34875.23 kW. Whole observed steam turbine produces real mechanical power equal to 97513 kW.
- LPC which produces the highest real mechanical power has the lowest isentropic loss of all cylinders equal to 4344.75 kW, while HPC which produces the lowest real mechanical power has the highest isentropic loss of all cylinders equal to 5204.54 kW.
- Isentropic losses and isentropic efficiencies are reverse proportional, because the cylinder with the lowest isentropic loss (LPC) has the highest isentropic efficiency equal to 88.92%, while the cylinder with the highest isentropic loss (HPC) has the lowest isentropic efficiency equal to 84.58%.
- Surprisingly, isentropic efficiency of the IPC is equal to 86.80%, which is higher in comparison to HPC but notably lower than LPC. The isentropic efficiency of the whole analyzed steam turbine is equal to 86.87%.
- For the steam turbine analyzed in this paper can be seen that LPC has higher isentropic efficiency in comparison to IPC, while for other comparable steam turbines from the literature IPC has notably higher isentropic efficiencies than both HPC and LPC.
- Isentropic performance of the observed steam turbine and its cylinders is very close to the turbines from conventional steam power plants. Obtained isentropic efficiencies of the turbine and cylinders in this analysis are higher in comparison to steam turbines from marine propulsion power plants, but still lower in comparison to steam turbines from ultra-supercritical power plants.

7. Acknowledgment

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

8. References

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

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

[3] 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)

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

[5] 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)

[6] 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)

[7] Adibhatla, S., & Kaushik, S. C. (2014). Energy and exergy analysis of a super critical thermal power plant at various load conditions under constant and pure sliding pressure operation. Applied thermal engineering, 73(1), 51-65. (doi:10.1016/j.applthermaleng.2014.07.030)

[8] 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)

[9] 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)

[10] Anđelić, N., Lorencin, I., Mrzljak, V., & Car, Z. (2024). On the application of symbolic regression in the energy sector: Estimation of combined cycle power plant electrical power output using genetic programming algorithm. Engineering applications of artificial intelligence, 133, 108213. (doi:10.1016/j.engappai.2024.108213)

[11] Si, N., Zhao, Z., Su, S., Han, P., Sun, Z., Xu, J., ... & Xiang, J. (2017). Exergy analysis of a 1000 MW double reheat ultra-supercritical power plant. Energy Conversion and Management, 147, 155-165. (doi:10.1016/j.enconman.2017.05.045)

[12] Poljak, I., Mrzljak, V., Senčić, T., & Pastorčić, D. (2024). Isentropic and exergy analyses of marine steam turbine segments at several loads. Scientific Journal of Maritime Research-Pomorstvo, 38(1). (doi:10.31217/p.38.1.8)

[13] 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)

[14] 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)

[15] Adibhatla, S., & Kaushik, S. C. (2017). Energy, exergy, economic and environmental (4E) analyses of a conceptual solar aided coal fired 500 MWe thermal power plant with thermal energy storage option. Sustainable Energy Technologies and Assessments, 21, 89-99. (doi:10.1016/j.seta.2017.05.002)

[16] Kopac, M., & Hilalci, A. (2007). Effect of ambient temperature on the efficiency of the regenerative and reheat Çatalağzı power plant in Turkey. Applied Thermal Engineering, 27(8-9), 1377-1385. (doi:10.1016/j.applthermaleng.2006.10.029)

[17] Khanmohammadi, S., Azimian, A. R., & Khanmohammadi, S. (2013). Exergy and exergo–economic evaluation of Isfahan steam power plant. International Journal of Exergy, 12(2), 249-272. (doi:10.1504/IJEX.2013.053386)

[18] Esmaeilion, F., Ahmadi, A., & Dashti, R. (2021). Exergy-economic-environment optimization of the waste-to-energy power plant using multi-objective particle-swarm optimization (MOPSO). Scientia Iranica, 28(5), 2733-2750. (doi:10.24200/sci.2021.55633.4323)

[19] Mohammed, M. K., Al Doori, W. H., Jassim, A. H., Ibrahim, T. K., & Al-Sammarraie, A. T. (2019). Energy and exergy analysis of the steam power plant based on effect the numbers of feed water heater. Journal of Advanced Research in Fluid Mechanics and Thermal Sciences, 56(2), 211-222.

[20] Mrzljak, V., Poljak, I., & Medica-Viola, V. (2017). Thermodynamical analysis of high-pressure feed water heater in steam propulsion system during exploitation. Brodogradnja: Teorija i praksa brodogradnje i pomorske tehnike, 68(2), 45-61. (doi:10.21278/brod68204)

[21] Espatolero, S., Romeo, L. M., & Cortés, C. (2014). Efficiency improvement strategies for the feedwater heaters network designing in supercritical coal-fired power plants. Applied Thermal Engineering, 73(1), 449-460. (doi:10.1016/j.applthermaleng.2014.08.011)

[22] Mrzljak, V., Poljak, I., & Medica-Viola, V. (2016). Efficiency and losses analysis of low-pressure feed water heater in steam propulsion system during ship maneuvering period. Pomorstvo, 30(2), 133-140. (doi:10.31217/p.30.2.6)

[23] 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)

[24] Leyzerovich, A. S. (2021). Steam turbines for modern fossil-fuel power plants. River Publishers.

[25] 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.

[26] 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)

[27] 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)

[28] Kanoğlu, M., Çengel, Y. A. & Dincer, I. (2012). Efficiency Evaluation of Energy Systems. Springer Briefs in Energy. (doi:10.1007/978-1-4614-2242-6)

[29] Blažević, S., Mrzljak, V., Anđelić, N., & Car, Z. (2019). Comparison of energy flow stream and isentropic method for steam turbine energy analysis. Acta Polytechnica, 59(2), 109-125. (doi:10.14311/AP.2019.59.0109)

[30] 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.

[31] 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)

[32] 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)

[33] Ebrahimgol, H., Aghaie, M., Zolfaghari, A., & Naserbegi, A. (2020). A novel approach in exergy optimization of a WWER1000 nuclear power plant using whale optimization algorithm. Annals of Nuclear Energy, 145, 107540. (doi:10.1016/j.anucene.2020.107540)

[34] 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)

[35] Talebi, S., & Norouzi, N. (2020). Entropy and exergy analysis and optimization of the VVER nuclear power plant with a capacity of 1000 MW using the firefly optimization algorithm. Nuclear Engineering and Technology, 52(12), 2928-2938. (doi:10.1016/j.net.2020.05.011)

[36] 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)