ENERGY AND EXERGY ANALYSIS OF DEAERATOR FROM COMBINED-CYCLE POWER PLANT

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Abstract: *Energy and exergy analysis of deaerator from combined-cycle power plant is presented in this paper. The deaerator is analyzed in three operating regimes and in various ambient conditions. The lowest deaerator energy loss of 525.60 kW and the highest energy efficiency of 78.21 % are obtained for the lowest water temperature at the deaerator outlet - in the same operating regime is obtained the lowest deaerator exergy efficiency. Decrease in the ambient temperature resulted simultaneously with an increase in deaerator exergy destruction and with increase in exergy efficiency. Deaerator exergy efficiency in each operating regime and for each observed ambient temperature significantly varies (from 13.82 % to 45.94 %). From the efficiency aspect, deaerator energy and exergy analysis show diametrically opposed results in two observed operating regimes.*

KEYWORDS: DEAERATOR, COMBINED-CYCLE POWER PLANT, ENERGY ANALYSIS, EXERGY ANALYSIS

1. Introduction

Steam power plants (independent plants [1] or part of some complex plants [2]) have regenerative condensate/feed water heating system which is used for condensate/feed water heating before its return to steam generator (or more of them) [3, 4]. Condensate/feed water heating resulted with a fuel savings and with increasing of steam power plant efficiency [5]. Such heating system consists of many components which exact number and the complexity of the entire system depends on many parameters.

An inevitable component of condensate/feed water heating system is a deaerator which has two functions: function of deaerating (removing of dissolved gasses from condensate/feed water to prevent erosion of heat exchangers, pipelines and steam generator parts) and function of condensate/feed water heating. Deaerator divides regenerative heating system in two parts - low pressure part between steam condenser and deaerator and high pressure part between deaerator and steam generator, as can be seen for example in [6].

This paper presents an energy and exergy analysis of deaerator which is part of a regenerative heating system in combined-cycle power plant. Analyzed deaerator is investigated in three operating regimes and at three different ambient temperatures in order to obtain a complete picture of its operation. It is interesting that energy and exergy efficiencies in two of three deaerator operating regimes show diametrically opposed results, what will be explained and discussed in detail.

2. Description and main characteristics of the analyzed deaerator from combined-cycle power plant

In this analysis is observed the deaerator from combined-cycle power plant, which is used in water/steam part of a combined system [7]. General deaerator scheme and operating points required for the analysis are presented in Fig. 1. Condensate from the main steam condenser [8] is delivered to the analyzed deaerator by using a condensate pump (operating point 1, Fig. 1) [9]. Another input into the analyzed deaerator is steam extracted from the steam turbine (operating point 2, Fig. 1). As presented in Fig. 1, one part of steam extracted from the turbine is used for deaerating and the rest of extracted steam is used for water heating. Analyzed deaerator has only one major fluid stream outlet - it is water stream which is delivered to the main feed water pump (operating point 3, Fig. 1). Due to deaerating and heating processes into the analyzed deaerator, water at the deaerator outlet (in operating point 3) has higher temperature in comparison with condensate at the deaerator inlet (in operating point 1). Another fluid stream outlet from the analyzed deaerator is a stream of gases (which cannot be condensed) and which are released after the deaerating process. Due to low mass flow rate of gasses released after deaerating process (in comparison to other deaerator fluid streams), its stream can be neglected in the deaerator energy and exergy analysis, as shown in the literature [10].

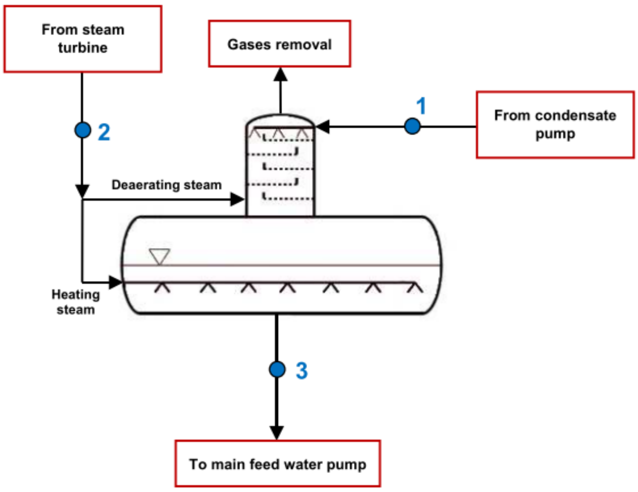

Fig. 1. *Main scheme and required operating points of the analyzed deaerator*

3. Energy and exergy analysis equations

3.1. Overall equations for the energy and exergy analysis of any control volume

The first law of thermodynamics defines energy [11], while the second law of thermodynamics defines exergy analysis [12] of any control volume. Energy analysis of control volume is completely independent of the ambient conditions in which control volume operates [13], while the exergy analysis is significantly influenced by the ambient conditions [14].

Control volume energy analysis

For control volume in steady state, mass flow rate and energy balances, according to [15, 16], can be defined by Eq. 1 and Eq. 2. It should be noted that mass flow rate balance (Eq. 1) assumes no leakage throughout control volume, while in energy balance (Eq. 2) potential and kinetic energies are disregarded:

$$\sum \dot{m}_{\text{in}} = \sum \dot{m}_{\text{out}} \,, \tag{1}$$

$$\sum \dot{m}_{\text{in}} \cdot h_{\text{in}} + \dot{Q} = \sum \dot{m}_{\text{out}} \cdot h_{\text{out}} + P \,. \tag{2}$$

The energy of any fluid flow can be calculated as presented in [17]:

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

Overall control volume energy efficiency, according to [18], can be defined as:

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

Control volume exergy analysis

Control volume exergy balance is defined by Eq. 5. Again, identical to control volume energy balance, potential and kinetic energy can be disregarded [19]:

$$\sum \dot{m}_{in} \cdot \varepsilon_{in} + \dot{X}_{heat} = \sum \dot{m}_{out} \cdot \varepsilon_{out} + P + \dot{E}_{ex,D} . \quad (5)$$

Two components of the Eq. 5 should be additionally defined. The first is specific exergy (ε), which is defined according to [20] as:

$$\varepsilon = (h - h_0) - T_0 \cdot (s - s_0) , \quad (6)$$

while the second is the net exergy transfer by heat at the temperature T ($\dot{X}_{heat}$), which can be defined as:

$$\dot{X}_{heat} = \sum (1 - \frac{T_0}{T}) \cdot \dot{Q} . \quad (7)$$

The exergy of any fluid flow is:

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

Overall definition of control volume exergy efficiency, according to [21] is:

$$\eta_{ex} = \frac{\text{Exergy output}}{\text{Exergy input}} . \quad (9)$$

3.2. Energy and exergy analysis equations of the investigated deaerator from combined-cycle power plant

Energy and exergy analysis equations of the investigated deaerator from combined-cycle power plant [22] are based on deaerator operating points presented in Fig. 1. Both analyses (energy and exergy) are of “black box” type, which means that in such analyses deaerator inner structure is irrelevant, it is important only fluid flow streams to and from the deaerator.

Energy analysis of a deaerator

- Deaerator energy power input:

$$\dot{E}_{en,in} = \dot{m}_1 \cdot h_1 + \dot{m}_2 \cdot h_2 . \quad (10)$$

- Deaerator energy power output:

$$\dot{E}_{en,out} = \dot{m}_3 \cdot h_3 . \quad (11)$$

- Deaerator energy power loss (deaerator energy destruction):

$$\dot{E}_{en,D} = \dot{E}_{en,in} - \dot{E}_{en,out} = \dot{m}_1 \cdot h_1 + \dot{m}_2 \cdot h_2 - \dot{m}_3 \cdot h_3 . \quad (12)$$

- Deaerator energy efficiency:

$$\eta_{en} = \frac{\dot{E}_{en,out}}{\dot{E}_{en,in}} = \frac{\dot{m}_3 \cdot h_3}{\dot{m}_1 \cdot h_1 + \dot{m}_2 \cdot h_2} . \quad (13)$$

Exergy analysis of a deaerator

- Deaerator exergy power input:

$$\dot{E}_{ex,in} = \dot{m}_1 \cdot \varepsilon_1 + \dot{m}_2 \cdot \varepsilon_2 . \quad (14)$$

- Deaerator exergy power output:

$$\dot{E}_{ex,out} = \dot{m}_3 \cdot \varepsilon_3 . \quad (15)$$

- Deaerator exergy power loss (deaerator exergy destruction):

$$\dot{E}_{ex,D} = \dot{E}_{ex,in} - \dot{E}_{ex,out} = \dot{m}_1 \cdot \varepsilon_1 + \dot{m}_2 \cdot \varepsilon_2 - \dot{m}_3 \cdot \varepsilon_3 . \quad (16)$$

- Deaerator exergy efficiency:

$$\eta_{ex} = \frac{\dot{E}_{ex,out}}{\dot{E}_{ex,in}} = \frac{\dot{m}_3 \cdot \varepsilon_3}{\dot{m}_1 \cdot \varepsilon_1 + \dot{m}_2 \cdot \varepsilon_2} . \quad (17)$$

4. Analyzed deaerator steam/water parameters in three operating regimes

Steam/water parameters (pressures, temperatures and mass flow rates) in each operating point of the analyzed deaerator (Fig. 1) are found in [7] and presented in Table 1 for the first deaerator operating regime, in Table 2 for the second deaerator operating regime and in Table 3 for the third deaerator operating regime. Deaerator operating regimes are related to the water temperature at the deaerator outlet – the highest water temperature at the deaerator outlet denotes first operating regime (Table 1), while the lowest water temperature at the deaerator outlet denotes last (third) operating regime, Table 3.

Steam/water specific enthalpies, specific entropies and specific exergies are calculated by using NIST-REFPROP 9.0 software [23]. Steam/water specific exergies presented in Table 1, Table 2 and Table 3 are calculated for the following ambient state: temperature of 15 °C = 288 K and a pressure of 1 bar.

Table 1. *Steam/water parameters of the analyzed deaerator – Operating regime 1 [7]*

O.P.*	Temperature (K)	Pressure (bar)	Mass flow rate (kg/s)	Specific enthalpy (kJ/kg)	Specific entropy (kJ/kg·K)	Specific exergy (kJ/kg)
1	362.16	10	12.90	373.60	1.1807	35.116
2	453.03	10	1.04	2777.10	6.5850	882.190
3	368.45	10	13.94	400.05	1.2531	40.713

* O.P. = Operating Point; Operating points refer to Fig. 1.

Table 2. *Steam/water parameters of the analyzed deaerator – Operating regime 2 [7]*

O.P.*	Temperature (K)	Pressure (bar)	Mass flow rate (kg/s)	Specific enthalpy (kJ/kg)	Specific entropy (kJ/kg·K)	Specific exergy (kJ/kg)
1	354.07	10	5.93	339.63	1.0859	28.467
2	453.03	10	0.40	2777.10	6.5850	882.190
3	359.36	10	6.33	361.84	1.1481	32.744

* O.P. = Operating Point; Operating points refer to Fig. 1.

Table 3. *Steam/water parameters of the analyzed deaerator – Operating regime 3 [7]*

O.P.*	Temperature (K)	Pressure (bar)	Mass flow rate (kg/s)	Specific enthalpy (kJ/kg)	Specific entropy (kJ/kg·K)	Specific exergy (kJ/kg)
1	293.15	10	9.12	84.85	0.2963	1.091
2	453.03	10	0.59	2777.10	6.5850	882.190
3	319.35	10	9.71	194.31	0.6539	7.551

* O.P. = Operating Point; Operating points refer to Fig. 1.

5. The results of deaerator energy and exergy analyses with discussion

5.1. The results of deaerator energy analysis

The results of deaerator energy analysis in each observed operating regime remains the same regardless of the conditions of the ambient in which deaerator operates. According to Eq. 12, in each deaerator operating regime energy power input is the sum of the deaerator energy power output and energy power loss (energy destruction) – which are presented in Fig. 2.

From Fig. 2 can be observed that in Operating regime 1 deaerator has the highest energy power output (5576.70 kW) and simultaneously the highest energy power loss (2130.93 kW). In comparison with Operating regime 1, in deaerator Operating regime

2 energy power output and energy power loss significantly decreases, while in Operating regime 3 deaerator has the lowest energy power output (1886.75 kW) and the lowest energy power loss (525.60 kW).

It can be concluded that the decrease in temperature of water at deaerator outlet (operating point 3, Fig. 1) resulted with a decrease in deaerator energy power output and simultaneously with decrease in deaerator energy power loss (energy destruction).

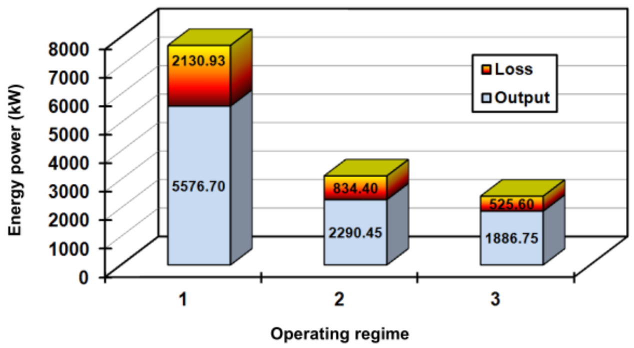

Fig. 2. Change in energy power output and energy power loss of the analyzed deaerator in three operating regimes

From Operating regime 1 to Operating regime 3 deaerator energy efficiency continuously increases (from 72.35 % in Operating regime 1 to 78.21 % in Operating regime 3), Fig. 3. This trend of deaerator energy efficiency is reverse proportional to deaerator energy power loss (energy destruction) which continuously decreases from Operating regime 1 to Operating regime 3, Fig. 2 and Fig. 3.

Furthermore, it can be concluded that analyzed deaerator has the highest energy efficiency (and the lowest energy power loss) at the lowest temperature of water at the deaerator outlet, Fig. 3 and Table 3.

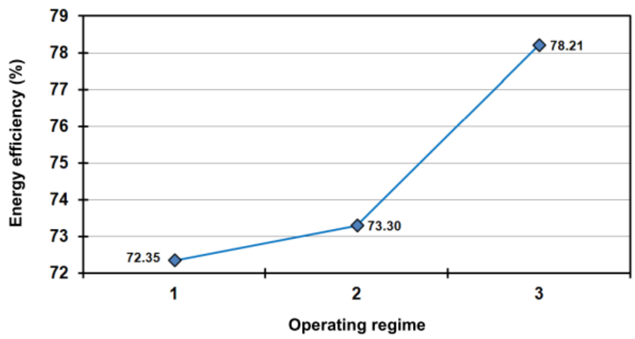

Fig. 3. Change in energy efficiency of the analyzed deaerator in three operating regimes

5.2. The results of deaerator exergy analysis

Deaerator exergy analysis is performed in all three operating regimes and for three different ambient temperatures (5 °C, 10 °C and 15 °C) in order to investigate the deaerator exergy destruction and efficiency in different states of the ambient.

From Fig. 4 can be seen that analyzed deaerator has different trends when compared exergy and energy destructions (Fig. 2). Both energy and exergy destructions (losses) are the highest for deaerator Operating regime 1, but the lowest deaerator exergy destruction occurs in Operating regime 2, regardless of the observed ambient temperature (the lowest deaerator energy destruction occurs in Operating regime 3 – Fig. 2).

Decrease in the ambient temperature resulted with an increase in deaerator exergy destruction, regardless of observed operating regime. Deaerator exergy destruction in Operating regime 1 is the highest influenced with the change in the ambient temperature, while deaerator exergy destruction in Operating regime 3 is the lowest influenced with the change in the ambient temperature, Fig. 4.

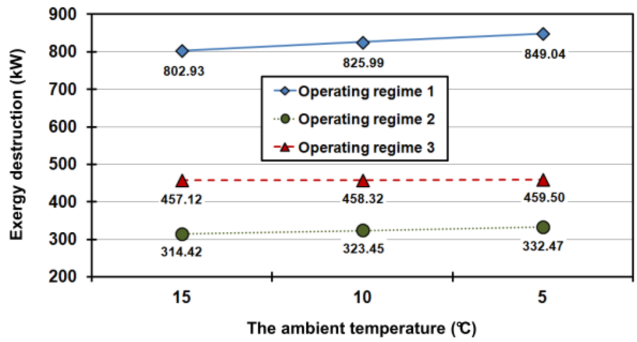

Fig. 4. Change in the exergy destruction of the analyzed deaerator in three operating regimes and at three ambient temperatures

Decrease of the ambient temperature increases deaerator exergy destruction (Fig. 4) and simultaneously increases deaerator exergy efficiency, regardless of the observed operating regime, Fig. 5.

In Operating regime 1 analyzed deaerator has the highest exergy efficiencies which vary from 41.41 % at the ambient temperature of 15 °C to 45.94 % at the ambient temperature of 5 °C. In the same operating regime, the deaerator has the lowest energy efficiency (72.35 %, Fig. 3).

In Operating regime 2, at the same ambient temperature, deaerator exergy efficiency is slightly lower in comparison with Operating regime 1.

Deaerator Operating regime 3 is the most interesting to observe (in this operating regime the water temperature at the deaerator outlet is the lowest, Table 3). In Operating regime 3, analyzed deaerator has the highest energy efficiency (78.21 %, Fig. 3), while its exergy efficiency does not exceed 21.03 %, even at the lowest ambient temperature, Fig. 5. Such low exergy efficiency of deaerator in Operating regime 3 is the result of low fluid temperatures (water inlet and outlet), which are very close to the ambient temperature – Table 3.

Deaerator Operating regimes 1 and 3 are the best example of one control volume operating regimes in which energy and exergy analysis gives totally opposed results from the efficiency aspect, Fig. 3 and Fig. 5.

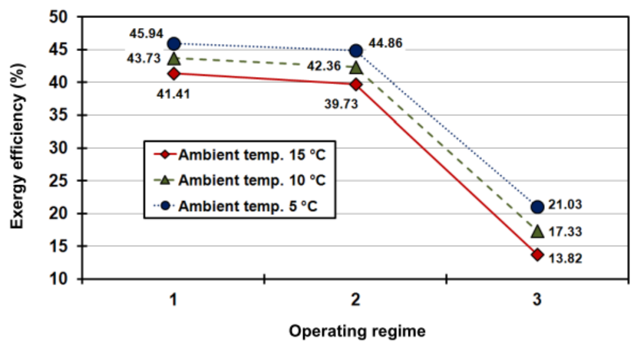

Fig. 5. Change in exergy efficiency of the analyzed deaerator in three operating regimes and at three ambient temperatures

6. Conclusions

In this paper is presented energy and exergy analysis of deaerator from combined-cycle power plant. It is analyzed the change in energy and exergy losses and efficiencies in three deaerator operating regimes and for three different ambient temperatures. The most important conclusions of the analysis are:

- Deaerator energy analysis shows that a decrease in the water temperature at deaerator outlet resulted with simultaneous decrease of deaerator energy loss and increase in energy efficiency. The lowest deaerator energy loss and the highest energy efficiency (525.60 kW and 78.21 %) are obtained for the lowest water temperature at the deaerator outlet of 319.35 K (Operating regime 3).

- The highest deaerator exergy destruction (exergy loss), regardless of the ambient temperature, is obtained for the highest water temperature at the deaerator outlet (Operating regime 1).
- Decrease in the ambient temperature resulted with an increase in deaerator exergy destruction for all observed operating regimes. Change in the ambient temperature has the highest influence on deaerator exergy destruction in Operating regime 1 (where the water temperature at the deaerator outlet is the highest).
- Decrease in the ambient temperature resulted with an increase in deaerator exergy efficiency in all observed operating regimes.
- The highest deaerator exergy efficiencies (between 41.41 % and 45.94 %) are obtained for the highest water temperature at the deaerator outlet (Operating regime 1), while the lowest deaerator exergy efficiencies (between 13.82 % and 21.03 %) are obtained for the lowest water temperature at the deaerator outlet (Operating regime 3).
- Analyzed deaerator Operating regimes 1 and 3 are the best example of how energy and exergy analysis (from the efficiency aspect) can result with diametrically opposed results. In Operating regime 1 deaerator has the lowest energy and the highest exergy efficiency, while in Operating regime 3 deaerator has the highest energy and the lowest exergy efficiency.

7. Acknowledgment

This research has been supported by the Croatian Science Foundation under the project IP-2018-01-3739, CEEPUS network CIII-HR-0108, European Regional Development Fund under the grant KK.01.1.1.01.0009 (DATACROSS), University of Rijeka scientific grant uniri-tehnic-18-275-1447 and University of Rijeka scientific grant uniri-tehnic-18-18-1146.

NOMENCLATURE		**Greek symbols:**	
		ε	specific exergy, kJ/kg
Latin Symbols:		η	efficiency, %
$\dot{E}$	energy/exergy of a fluid flow, kW		
h	specific enthalpy, kJ/kg	**Subscripts:**	
$\dot{m}$	mass flow rate, kg/s	0	ambient state
p	pressure, bar	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, K or °C	out	outlet (output)
$\dot{X}_{\mathrm{heat}}$	exergy transfer by heat, kW		

8. References

[1] Ahmadi, G. R., Toghraie, D.: *Energy and exergy analysis of Montazeri Steam Power Plant in Iran*, Renewable and Sustainable Energy Reviews 56, p. 454–463, 2016. (doi:10.1016/j.rser.2015.11.074)

[2] Kostyuk, A., Frolov, V.: *Steam and gas turbines*, Mir Publishers, Moscow, 1988.

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

[4] Mrzljak, V., Poljak, I., Medica-Viola, V.: *Thermodynamical analysis of high-pressure fed water heater in steam propulsion system during exploitation*, Shipbuilding 68 (2), p. 45-61, 2017. (doi:10.21278/brod68204)

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

[6] Adibhatla, S., Kaushik, S. C.: *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, p. 49-63, 2014. (doi:10.1016/j.applthermaleng.2014.07.030)

[7] Stradioto, D. A., Seelig, M. F., Schneider, P. S.: *Performance analysis of a CCGT power plant integrated to a LNG regasification process*, Journal of Natural Gas Science and Engineering 23, p. 112-117, 2015. (doi:10.1016/j.jngse.2015.01.032)

[8] Medica-Viola, V., Pavković, B., Mrzljak, V.: *Numerical model for on-condition monitoring of condenser in coal-fired power plants*, International Journal of Heat and Mass Transfer 117, p. 912–923, 2018. (doi:10.1016/j.ijheatmasstransfer.2017.10.047)

[9] Poljak, I., Orović, J., Mrzljak, V.: *Energy and Exergy Analysis of the Condensate Pump During Internal Leakage from the Marine Steam Propulsion System*, Scientific Journal of Maritime Research 32 (2), p. 268-280, 2018. (doi:10.31217/p.32.2.12)

[10] Koroglu, T., Sogut, O. S.: *Conventional and Advanced Exergy Analyses of a Marine Steam Power Plant*, Energy 163, p. 392-403, 2018. (doi:10.1016/j.energy.2018.08.119)

[11] Mrzljak, V., Poljak, I.: *Energy Analysis of Main Propulsion Steam Turbine from Conventional LNG Carrier at Three Different Loads*, International Journal of Maritime Science & Technology "Our Sea" 66 (1), p. 10-18, 2019. (doi:10.17818/NM/2019/1.2)

[12] Lorencin, I., Anđelić, N., Mrzljak, V., Car, Z.: *Exergy analysis of marine steam turbine labyrinth (gland) seals*, Scientific Journal of Maritime Research 33 (1), p. 76-83, 2019. (doi:10.31217/p.33.1.8)

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

[14] Mrzljak, V., Blecich, P., Anđelić, N., Lorencin, I.: *Energy and Exergy Analyses of Forced Draft Fan for Marine Steam Propulsion System during Load Change*, Journal of Marine Science and Engineering 7 (11), 381, 2019. (doi:10.3390/jmse7110381)

[15] Mrzljak, V., Poljak, I., Žarković, B.: *Exergy Analysis of Steam Pressure Reduction Valve in Marine Propulsion Plant on Conventional LNG Carrier*, International Journal of Maritime Science & Technology "Our Sea" 65(1), p. 24-31, 2018. (doi:10.17818/NM/2018/1.4)

[16] Baldi, F., Ahlgren, F., Van Nguyen, T., Thern, M., Andersson, K.: *Energy and Exergy Analysis of a Cruise Ship*, Energies 2018, 11, 2508. (doi:10.3390/en11102508)

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

[18] Mrzljak, V., Prpić-Oršić, J., Senčić, T.: *Change in Steam Generators Main and Auxiliary Energy Flow Streams During the Load Increase of LNG Carrier Steam Propulsion System*, Scientific Journal of Maritime Research 32 (1), p. 121-131, 2018. (doi:10.31217/p.32.1.15)

[19] Mrzljak, V., Poljak, I., Prpić-Oršić, J.: *Exergy analysis of the main propulsion steam turbine from marine propulsion plant*, Shipbuilding 70 (1), p. 59-77, 2019. (doi:10.21278/brod70105)

[20] Tan, H., Shan, S., Nie, Y., Zhao, Q.: *A new boil-off gas re-liquefaction system for LNG carriers based on dual mixed refrigerant cycle*, Cryogenics 92, p. 84–92, 2018. (doi:10.1016/j.cryogenics.2018.04.009)

[21] Dincer, I., Midilli, A., Kucuk, H.: *Progress in Exergy, Energy and the Environment*, Springer International Publishing, 2014. (doi:10.1007/978-3-319-04681-5)

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

[23] Lemmon, E.W., Huber, M.L., McLinden, M.O.: *NIST reference fluid thermodynamic and transport properties-REFPROP*, version 9.0, User's guide, Colorado, 2010.