EXERGY ANALYSIS OF STEAM TURBINE GOVERNING VALVE FROM A SUPER CRITICAL THERMAL POWER PLANT

PhD. Mrzljak Vedran[1], PhD. Orović Josip[2], PhD. Poljak Igor[2], PhD Student Lorencin Ivan[1]
[1]Faculty of Engineering, University of Rijeka, Vukovarska 58, 51000 Rijeka, Croatia
[2]University of Zadar, Maritime Department, M. Pavlinovića 1, 23000 Zadar, Croatia
E-mail: vedran.mrzljak@riteh.hr, jorovic@unizd.hr, ipoljak1@unizd.hr, ilorencin@riteh.hr

Abstract: *Exergy analysis of steam turbine governing valve from a super critical thermal power plant is presented in this paper. Governing valve was analyzed not only at the highest, but also on two partial steam system loads. The lowest valve exergy destruction is 3598 kW and is obtained at the highest steam system load, while at partial loads of 80% and 60% valve exergy destruction is 13550 kW and 21360 kW. Valve exergy efficiency increases with an increase in system load, from 95.58% at 60% of load to 97.87% at 80% of load. At the highest load, valve exergy efficiency is the highest and is 99.57%. Change in valve steam specific entropy increment (difference in steam specific entropy between valve outlet and inlet) can be used as a tool for quick assessment of valve losses change. The ambient temperature influence on governing valve exergy analysis is low, especially in the highest steam system load where the majority of valve operation can be expected.*

KEYWORDS: GOVERNING VALVE, EXERGY ANALYSIS, AMBIENT TEMPERATURE, SUPER CRITICAL POWER PLANT

1. Introduction

Governing valves were used in any type of power plants (land based or marine power plants) [1]. The main function of governing valves is to reduce pressure of operating medium [2]. When the governing valves are used in steam power plants (super critical or sub critical) their operating medium is superheated steam.

Main operating characteristics of superheated steam governing valves are that with the pressure reduction the steam temperature also reduces. During the superheated steam pressure and temperature reduction, steam specific entropy increases [3]. As the governing valves are mounted before the turbine housing, its operation allows obtaining the desired superheated steam operating parameters at the turbine entrance [4], what is necessary for safe and reliable turbine operation.

The essential rule for the governing valve operation is that before and after valve specific enthalpy of operating medium remains constant [5] (the negligible difference in specific enthalpy can occur only due to losses). In such way, operating medium pressure is reduced while the energy content remains unchanged [6].

It is irrelevant to investigate governing valves from the energy viewpoint, because without any operating medium mass flow leakage, governing valves have energy efficiency of 100 % and energy power losses equal to zero.

In the scientific and professional literature analysis of any valve type is rare. After an extensive search, papers were found about the investigation of steam turbine control valves [7], or analysis of steam turbine control valve along with its actuation system [8]. In [9] authors analyzed compressible superheated steam flow rate through pressure reduction valves.

This paper analyzed steam turbine governing valve mounted on the high pressure turbine inlet in a super critical thermal power plant, through three different steam system loads. Measurement results of governing valve operating parameters (steam pressures, temperatures and mass flow rates) at each steam system load enable calculation of valve exergy power inputs and outputs, as well as valve exergy destruction and exergy efficiency. At each steam system load the differences in steam specific entropy between governing valve outlet and inlet are also calculated and presented, which is a good indicator of system load and valve losses. Governing valve was also analyzed during the ambient temperature change.

2. Analyzed governing valve operating characteristics

The analyzed governing valve is mounted on the high pressure turbine inlet in a supercritical thermal power plant, Fig. 1. The main function of governing valve is steam pressure reducing before steam enters in the turbine. In the land-based steam power plant, steam generator (or more of them) will usually produce superheated steam with the highest possible pressure and temperature (defined by the steam generator producer) during the majority of plant operation. The changeable variable is usually the steam mass flow rate, which is the most important parameter for defining the power plant load.

Governing valves, which reduces steam pressure at the inlet of the first power plant turbine (high pressure turbine) are used for fine-tuning of power plant current load, while the steam energy content remains the same before and after the valve (the same steam specific enthalpy). Governing valves are important elements in any steam power plant, especially when plant operates at partial load.

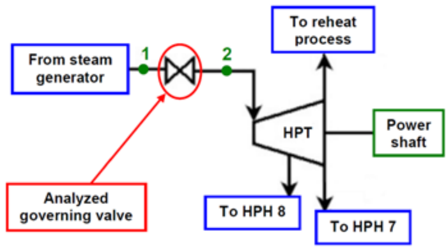

Fig. 1. *Analyzed governing valve position with marked inlet (1) and outlet (2) at the entrance of high pressure turbine from a super critical thermal power plant [10]*

Steam turbine governing valves in thermal power plants are usually of Venturi type. Cross-section of the turbine steam chest along with governing valves and its main bar is presented in Fig. 2. The main bar mechanism is used for raising and lowering of the governing valves. All governing valves are not lifted at the same time equally, but periodically, one by one. Such opening regime is allowable by different lengths of each governing valve stem. The main bar lifting mechanism is usually driven by servomotor, as presented in Fig. 2.

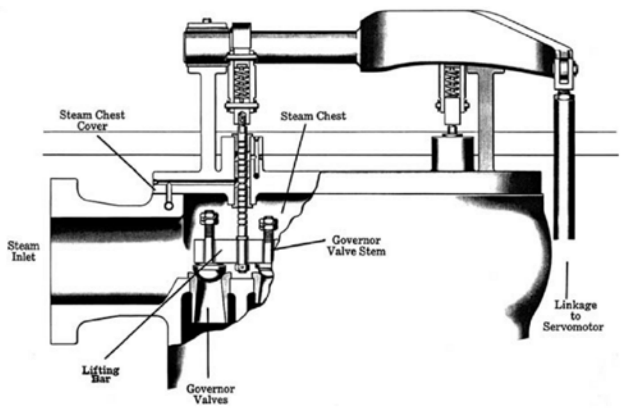

Fig. 2. *Venturi governing valves and bar lift mechanism [11]*

3. Exergy analysis of a control volume

3.1. Governing equations for exergy analysis

Mass flow balance for a control volume in steady state disregarding potential and kinetic energy is defined according to [12] by an equation:

$$\sum \dot{m}_{\mathrm{IN}} = \sum \dot{m}_{\mathrm{OUT}} \quad (1)$$

Exergy analysis is based on the second law of thermodynamics [13]. The main exergy balance equation for a control volume in steady state [14] is:

$$\dot{X}_{\mathrm{heat}} - P = \sum \dot{m}_{\mathrm{OUT}} \cdot \varepsilon_{\mathrm{OUT}} - \sum \dot{m}_{\mathrm{IN}} \cdot \varepsilon_{\mathrm{IN}} + \dot{E}_{\mathrm{ex,D}} \quad (2)$$

where the net exergy transfer by heat ($\dot{X}_{\mathrm{heat}}$) at the temperature T can be defined, according to [15], by an following equation:

$$\dot{X}_{\mathrm{heat}} = \sum (1 - \frac{T_0}{T}) \cdot \dot{Q} \quad (3)$$

Specific exergy is defined [16] by an equation:

$$\varepsilon = (h - h_0) - T_0 \cdot (s - s_0) \quad (4)$$

The exergy power of any flow stream [17,18] is defined as:

$$\dot{E}_{\mathrm{ex}} = \dot{m} \cdot \varepsilon = \dot{m} \cdot \left[(h - h_0) - T_0 \cdot (s - s_0) \right] \quad (5)$$

The definition of control volume exergy efficiency depends on a control volume type and operation principle. In general, exergy efficiency of any control volume can be defined, according to [19,20], by an equation:

$$\eta_{\mathrm{ex}} = \frac{\text{Exergy output}}{\text{Exergy input}} \quad (6)$$

3.2. Exergy analysis of governing valve from a super critical thermal power plant

Necessary operating points for steam turbine governing valve exergy analysis are presented in Fig. 1. The required steam specific enthalpies and specific entropies are calculated by using measured steam pressures and temperatures from Table 1 with Nist-REFPROP 9.0 software [21].

Steam temperature and pressure change through the governing valve resulted with the change in steam specific entropy. Change in steam specific entropy resulted with a significant change of steam specific exergy, equation (4) and steam exergy power, equation (5). Change of governing valve outlet exergy power, in comparison with valve inlet, resulted with the change in the governing valve exergy destruction and exergy efficiency.

Mass and exergy balances for the analyzed steam turbine governing valve, according to Fig. 1, are:

Governing valve mass flow balance:

$$\dot{m}_1 = \dot{m}_2 \quad (7)$$

Governing valve exergy balance:

- Exergy power input:

$$\dot{E}_{\mathrm{ex,IN}} = \dot{m}_1 \cdot \varepsilon_1 \quad (8)$$

- Exergy power output:

$$\dot{E}_{\mathrm{ex,OUT}} = \dot{m}_2 \cdot \varepsilon_2 \quad (9)$$

- Exergy destruction (exergy power loss):

$$\dot{E}_{\mathrm{ex,D}} = \dot{E}_{\mathrm{ex,IN}} - \dot{E}_{\mathrm{ex,OUT}} = \dot{m}_1 \cdot \varepsilon_1 - \dot{m}_2 \cdot \varepsilon_2 \quad (10)$$

- Exergy efficiency:

$$\eta_{\mathrm{ex}} = \frac{\dot{E}_{\mathrm{ex,OUT}}}{\dot{E}_{\mathrm{ex,IN}}} = \frac{\dot{m}_2 \cdot \varepsilon_2}{\dot{m}_1 \cdot \varepsilon_1} \quad (11)$$

The ambient state in the plant during the measurements was:
- pressure: p_0 = 1 bar = 0.1 MPa,
- temperature: T_0 = 25 °C = 298 K.

4. Measurement of governing valve flow streams

Measurement results of governing valve flow streams (at valve inlet and outlet) were presented in [10] for three different thermal power plant loads (load of 60%, 80% and full load – 100%), Table 1. From Table 1 it can be seen that at any load steam pressure and temperature remain constant at governing valve inlet, while steam mass flow rates at valve inlet decreases with a decrease in plant load. The steam temperature at governing valve outlet depends on the pressure reduction. Higher pressure reduction (lower steam pressure at valve outlet) will result with lower steam temperature at the valve outlet.

Table 1. *Measured data of steam flow streams at the governing valve inlet and outlet [10]*

Load (%)	INLET (1*)			OUTLET (2*)		
	Temp. (K)	Press. (bar)	Steam mass flow rate (kg/s)	Temp. (K)	Press. (bar)	Steam mass flow rate (kg/s)
100	810.1	242.2	562.2	805.1	229.2	562.2
80	810.1	242.2	435.7	787.0	183.0	435.7
60	810.1	242.2	327.6	766.5	138.1	327.6

* Streams numeration refers to Fig. 1

From Table 1 it can be seen that power plant (steam system) load is mostly influenced with steam mass flow rate, which is the lowest at the lowest load and then increases up to the highest load.

Analyzed governing valve parameter which can also determine steam system load is the pressure reduction. The highest pressure reduction occurs at the lowest steam system load and for the analyzed valve it is 104.1 bar (reduction from 242.2 bar to 138.1 bar - load of 60%). Governing valve pressure reduction decreases with an increase in steam system load.

It can be concluded that governing valve pressure reduction and steam system load are reverse proportional, while the steam mass flow rate and steam system load are directly proportional.

5. Governing valve exergy analysis results with the discussion

5.1. Governing valve exergy analysis - based on the measurement results

Analyzed governing valve exergy power input and output change during the change in steam system load is presented in Fig. 3. An increase in steam mass flow rate, according to Table 1 and equations (8) and (9), is the most important reason for the increase of valve exergy power input and output during the increase in steam system load.

Governing valve exergy power input increases from 483538 kW at steam system load of 60%, to 643093 kW at a load of 80% and finally to 829807 kW at the highest steam system load of 100%, Fig. 3. Between the same steam system loads, valve exergy power output increases from 462178 kW to 629543 kW and finally it is 826209 kW at the highest steam system load.

The difference between valve exergy power input and output at each load represents valve exergy destruction (valve exergy power losses). From Fig. 3 and from presented values of valve exergy power input and output at each load it can be seen that those differences become lower and lower as steam system load increases. Governing valve has an operation principle as the most of other steam power plant components - the lowest exergy destruction will be obtained at the highest system load.

Exergy destruction of the analyzed governing valve, as a difference between exergy power input and output - equation (10), is the lowest at the highest steam system load and is 3598 kW, Fig. 4. As the steam system load decreases, valve exergy destruction increases and is 13550 kW at steam system load of 80%, while at the lowest observed steam system load of 60% governing valve exergy destruction amounts 21360 kW.

Governing valve exergy efficiency, calculated according to equation (11) is the highest at the highest steam system load (99.57%) and then decreases with a decrease in steam system load. At partial steam system load of 80% valve exergy efficiency is 97.87%, while at the lowest load valve exergy efficiency is equal to 95.58%. It should be concluded that governing valve exergy efficiency has a very high values, even at a partial steam system loads.

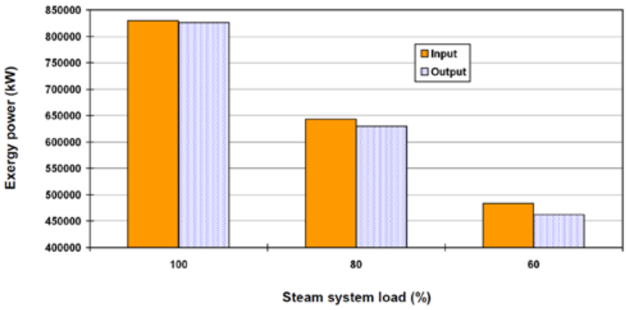

Fig. 3. *Change of governing valve exergy power input and output during the change in steam system load*

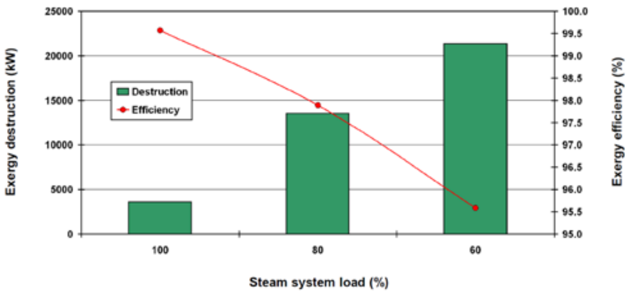

Fig. 4. *Change of the governing valve exergy destruction and exergy efficiency during the change in steam system load*

As mentioned before from the presented measurement results, pressure reduction on the analyzed governing valve and steam system load are reverse proportional. Additional operating parameter of the analyzed governing valve can be used for detecting the change in steam plant load. This operating parameter is steam specific entropy difference between valve outlet and inlet. Steam specific entropy at the governing valve outlet is higher than steam specific entropy at valve inlet due to pressure reduction and losses which can occur during this process. Pressure reduction on the governing valve and specific entropy difference (increment) on the same governing valve are directly proportional - they increase during the decrease in steam system load, Fig. 5.

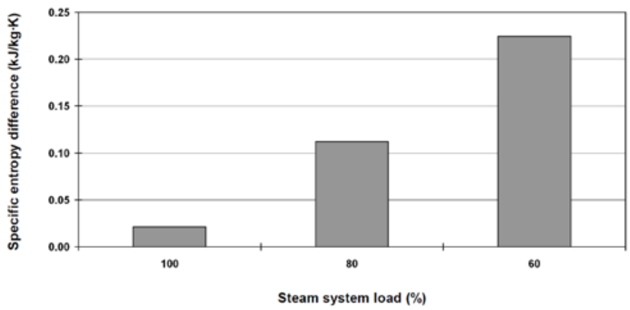

Fig. 5. *Change of steam specific entropy increment between governing valve outlet and inlet during the change in system load*

Specific entropy increment of any steam plant component represents losses which occur during the component operation and therefore, it can also be the real indicator of the analyzed component operation. When comparing Fig. 4 and Fig. 5 it can be concluded that calculation of exergy destruction is not necessary for governing valve loss assessment at different steam system loads - it is enough to calculate steam specific entropy increment. So, steam specific entropy increment can be used as a tool for quick assessment of valve losses, while a detailed analysis require calculation of valve exergy destruction.

From Fig. 5 it can be seen that analyzed valve specific entropy increment decreases with an increase in steam system load from 0.224 kJ/kg·K at 60% of load to 0.112 kJ/kg·K at 80% of load. At the highest load, valve specific entropy increment amounts only 0.021 kJ/kg·K.

5.2. Governing valve exergy analysis - the ambient temperature variation

As for the most other steam plant components [22], it can be expected that the influence of the ambient temperature change on exergy analysis of governing valve will also have low impact. In this analysis, the ambient temperature was varied from 283 K to 313 K in the steps of 10 K, while the ambient pressure remains constant at the measurement state (1 bar) in each observed system load.

The change in analyzed governing valve exergy destruction for all observed steam system loads during the ambient temperature variation is presented in Fig. 6. It can clearly be seen that the ambient temperature change has as higher impact on valve exergy destruction as the steam system load decreases.

At the highest steam system load, valve exergy destruction is the lowest and increase in the ambient temperature for 10 K causes a slight increase in valve exergy destruction for only 120 kW in average. The same increase in the ambient temperature resulted in an increase in valve exergy destruction for 500 kW in average at the steam system load of 80%. At the lowest steam system load of 60% increase in the ambient temperature for 10 K causes the highest increase in valve exergy destruction which is 740 kW in average.

Several conclusions can be derived from Fig. 6. First of all, governing valve exergy destruction (exergy power losses) significantly increases during the decrease in steam system load. Second, the change in the ambient temperature more and more affects the valve exergy destruction as steam system load decreases.

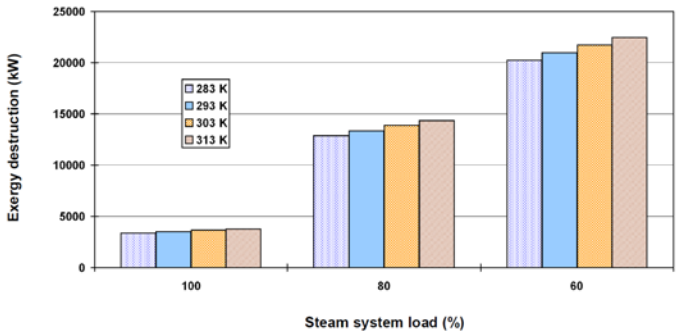

Fig. 6. *Change of governing valve exergy destruction during the variation in the ambient temperature*

Analyzed governing valve exergy efficiency change during the ambient temperature variation is presented in Table 2. The ambient temperature increase causes decrease in governing valve exergy efficiency, but that decrease is low at all steam system loads. Still, the highest decrease in governing valve exergy efficiency during the ambient temperature increase is notable at the lowest system load.

Table 2. *Governing valve exergy efficiency change during the ambient temperature variation*

Load (%)	Exergy efficiency at the ambient temperature			
	283 K	293 K	303 K	313 K
100	99.62%	99.59%	99.55%	99.52%
80	98.11%	97.97%	97.80%	97.63%
60	96.05%	95.75%	95.42%	95.07%

6. Conclusion

The paper presents exergy analysis of steam turbine governing valve mounted on the high pressure turbine inlet in a super critical thermal power plant. Governing valve was analyzed through three different steam system loads. Measurement results of steam operating parameters (pressures, temperatures and mass flow rates) at governing valve inlet and outlet enables calculation of valve exergy power inputs and outputs, as well as valve exergy destruction and exergy efficiency at each steam system load.

Increase in steam mass flow rate is the most important reason for the increase of valve exergy power input and output during the increase in steam system load. The difference between valve exergy power input and output becomes lower as steam system load increases. That difference represents valve exergy destruction (valve exergy power losses) at each steam system load.

The lowest valve exergy destruction which amounts 3598 kW and the highest valve exergy efficiency (99.57%) was obtained at the highest steam system load. Decrease in steam system load resulted in an increase in valve exergy destruction which is 13550 kW at 80% of load and 21360 kW at 60% of load, while at the same time valve exergy efficiency decreases (97.87% - 80% of load and 95.58% - 60% of load).

Steam specific entropy difference (increment) between valve outlet and inlet is an additional operating parameter which can be used for detecting the change in steam plant load. Steam specific entropy increment of the analyzed valve can also be used as a tool for quick assessment of valve losses.

The conclusion which follows from the ambient temperature variation is that the ambient temperature influence on analyzed governing valve exergy analysis is low, especially at the highest steam system load where the majority of valve operation can be expected.

7. Acknowledgment

This work has been fully supported by the Croatian Science Foundation under the project IP-2018-01-3739.

8. Nomenclature

Latin Symbols:		***Greek symbols:***	
$\dot{E}$	stream flow power, kW	ε	specific exergy, kJ/kg
h	specific enthalpy, kJ/kg	η	efficiency, -
$\dot{m}$	mass flow rate, kg/s		
p	pressure, bar	***Subscripts:***	
P	power, kW	0	ambient state
$\dot{Q}$	heat transfer, kW	D	destruction
s	specific entropy, kJ/kg·K	ex	exergy
T	temperature, K	IN	inlet (input)
$\dot{X}_{\text{heat}}$	heat exergy transfer, kW	OUT	outlet (output)

9. References

[1] 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)

[2] Kitto, J. B., Stultz, S. C.: *Steam/its generation and use*, 41st edition, The Babcock & Wilcox Company, Ohio, 2005.

[3] 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)

[4] Mrzljak, V.: *Low power steam turbine energy efficiency and losses during the developed power variation*, Technical Journal 12 (3), p. 174-180, 2018. (doi:10.31803/tg-20180201002943)

[5] 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)

[6] Cengel Y., Boles M.: *Thermodynamics an engineering approach*, Eighth edition, McGraw-Hill Education, 2015.

[7] Wang, P., Liu, Y.: *Influence of a circular strainer on unsteady flow behavior in steam turbine control valves*, Applied Thermal Engineering, 115, p. 463–476, 2017. (doi:10.1016/j.applthermaleng.2016.12.073)

[8] Pondini, M., Colla, V., Signorini, A.: *Models of control valve and actuation system for dynamics analysis of steam turbines*, Applied Energy 207, p. 208-217 , 2017. (doi:10.1016/j.apenergy.2017.05.117)

[9] Qian, J. Y., Wei, L., Zhang, M., Chen, F. Q., Chen, L. L., Jiang, W. K., Jin, Z. J.: *Flow rate analysis of compressible superheated steam through pressure reducing valves*, Energy 135, p. 650-658, 2017. (doi:10.1016/j.energy.2017.06.170)

[10] 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. 51-65, 2014. (doi:10.1016/j.applthermaleng.2014.07.030)

[11] Bloch, H. P., Singh, M. P.: *Steam Turbines - Design, Applications, and Re-rating*, The McGraw-Hill Companies, Inc., Second Edition, 2009.

[12] 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)

[13] Mrzljak, V., Poljak, I., Medica-Viola, V.: *Energy and Exergy Efficiency Analysis of Sealing Steam Condenser in Propulsion System of LNG Carrier*, International Journal of Maritime Science & Technology "Our Sea" 64 (1), p. 20-25, 2017. (doi:10.17818/NM/2017/1.4)

[14] Orović, J., Mrzljak, V., Poljak, I.: *Efficiency and Losses Analysis of Steam Air Heater from Marine Steam Propulsion Plant*, Energies 2018, 11 (11), 3019 (doi:10.3390/en11113019)

[15] Mrzljak, V., Poljak, I., Prpić-Oršić, J.: *Exergy analysis of the main propulsion steam turbine from marine propulsion plant*, Shipbuilding Vol. 70., No. 1, p. 59-77, 2019. (doi:10.21278/brod70105)

[16] Mrzljak, V., Poljak, I., Mrakovčić, T.: *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, p. 307–323, 2017. (doi:10.1016/j.enconman.2017.03.007)

[17] 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)

[18] 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)

[19] Mrzljak, V., Senčić, T., Žarković, B.: *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)

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

[21] 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.

[22] 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)

XXVII INTERNATIONAL SCIENTIFIC CONFERENCE

trans & MOTAUTO '19

PROCEEDINGS

ISSN 1313-5031 (Print), **ISSN** 2535-0307(Online)
YEAR III, USSUE 1 (6), SOFIA, BULGARIA 2019

SECTION
"TRANSPORT. SAFETY AND ECOLOGY. LOGISTICS AND MANAGEMENT. EDUCATION THEORY"

SESSION
"TRANSPORT TECHNIQUES. INVESTIGATION OF ELEMENTS. VEHICLE ENGINES"

17.06. – 20.06.2019
BURGAS, BULGARIA

Publisher: Scientific-technical union of mechanical engineering „Industry-4.0"

C O N T E N T S

SECTION
TRANSPORT. SAFETY AND ECOLOGY. LOGISTICS AND MANAGEMENT. EDUCATION THEORY

SECTION
TRANSPORT TECHNIQUES. INVESTIGATION OF ELEMENTS. VEHICLE ENGINES