INFLUENCE OF THE AMBIENT TEMPERATURE CHANGE ON STEAM PRESSURE REDUCTION VALVE EXERGY DESTRUCTION AND EXERGY EFFICIENCY

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Abstract: *The paper presents an exergy analysis of pressure reduction valve mounted in the steam propulsion system on conventional LNG carrier. From exploitation are obtained that the valve pressure and temperature decrease become as higher as steam system load increases. Valve exergy power input and output decreases during the increase in steam system load, mostly because of the steam mass flow decrease. Steam system load increase in exploitation also causes a decrease in valve exergy destruction with a simultaneous decrease in valve exergy efficiency (from 68.42 % to 68.09 %). The ambient temperature variation showed that the valve exergy destruction is the lowest for the lowest observed ambient temperature, in any steam system load. The exergy efficiency of the pressure reduction valve is reverse proportional to valve exergy destruction. An increase in the ambient temperature for 10 °C causes a decrease in analyzed valve exergy efficiency for between 2.5 % and 3 %.*

KEYWORDS: AMBIENT TEMPERATURE, STEAM PRESSURE REDUCTION VALVE, EXERGY DESTRUCTION, EXERGY EFFICIENCY

1. Introduction

The main function of pressure reduction valves is reducing pressure of operating medium (in steam plants that operating medium is usually superheated steam). If the operating medium is superheated steam, along with the pressure reduction through the pressure reduction valve was also reduced steam temperature while steam specific entropy increases [1]. In such way the steam system maintained desired operating parameters [2] in all of its parts.

The basic rule for pressure reduction valve operation is that before and after valve specific enthalpy of operating medium remains constant [3]. It is irrelevant to investigate steam pressure reduction valves from the viewpoint of energy, because without any mass flow leakage, steam pressure reduction valves have energy efficiency of 100 % and energy power losses equal to zero, in any observed operating point.

In the land-based steam power plants pressure reduction valves are very rare [4], because in that kind of steam power plants is not necessary to reduce the masses of plant components. In order to remain the walls of every component from the marine steam plant as thick as possible and thus reduce their mass, pressure reduction valves are necessary on ship steam systems [5].

A detailed analysis of any valve type can be rarely found in the scientific literature. If some were found, mostly it is investigations of control valves for steam turbines [6], in some cases along with its actuation systems [7]. Investigations of steam pressure reduction valves are rare, especially for several steam system loads [8].

In this paper was analyzed steam pressure reduction valve, mounted on the main condenser "dump" line, through a several steam system loads. For each load is presented a decrease in steam temperature and pressure on the analyzed valve from the ship exploitation. Based on the measurements of valve operation parameters are presented valve exergy power inputs and outputs, as well as exergy destruction and exergy efficiency in each observed system load. Exergy power inputs and outputs, as well as exergy efficiency and exergy destruction of any steam system component are changeable when the ambient temperature increases or decreases. Engine room temperature variation is performed from 10 °C to 50 °C in steps of 10 °C what is usually expected change of engine room temperature. For observed ambient temperature variation is calculated and presented pressure reduction valve exergy destruction and exergy efficiency in each observed steam system load.

2. Analyzed pressure reduction valve elements and operation characteristics

Analyzed pressure reduction valve is mounted in LNG carrier steam propulsion plant near steam generators. Main characteristics of the LNG carrier which steam propulsion system includes the analyzed pressure reduction valve are presented in Table 1:

Table 1. *LNG carrier characteristics*

Dead weight tonnage	84.812 DWT
Overall length	288 m
Max breadth	44 m
Design draft	9.3 m
Propulsion turbine	Mitsubishi MS40-2 (29420 kW)
Steam generators	2 x Mitsubishi MB-4E-KS

The position of the analyzed pressure reduction valve in the LNG carrier steam system is near the steam generators. The pressure reduction valve is mounted on steam generators "dump" pipeline. This pressure reduction valve is involved in steam system operation during the system startup. During system startup, steam generators produce much more superheated steam than is necessary for system operation. These facts occur because from the ecological point of view, it is more appropriate to burn LNG surplus in steam generators, than release it into the atmosphere. The superheated steam amount which is not used in steam system was directed to the main condenser. Before entering the main condenser, it is necessary to reduce superheated steam pressure after which follows steam cooling by water spray injection. For pressure reduction of superheated steam before its entrance into the main condenser is responsible analyzed valve. So, the measurements of necessary steam operating parameters before and after pressure reduction valve are and can be performed only during the steam system startup period. General pressure reduction operating range of the analyzed valve is reduction from 6.13 MPa to 0.4 MPa.

Analyzed steam pressure reduction valve intersection, along with all main components can be seen in Fig. 1. This type of pressure reduction valve has two valves (main and auxiliary) for pressure pulsation compensation and for ensuring accurate outlet pressure.

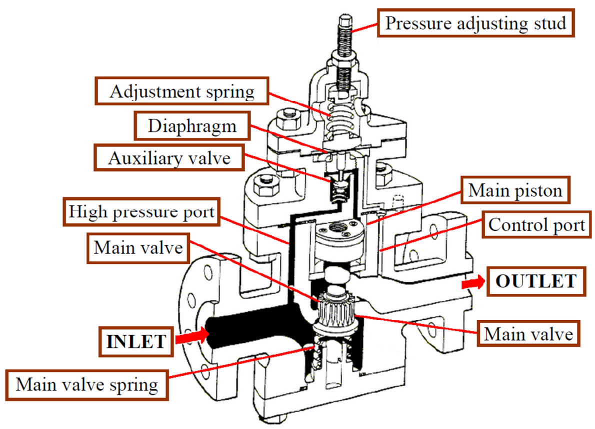

Fig. 1. *Analyzed steam pressure reduction valve intersection [9]*

3. Exergy analysis equations

3.1. Governing exergy analysis equations

Mass balance equation for a volume in steady state disregarding potential and kinetic energy can be expressed as [10]:

$$\sum \dot{m}_{\mathrm{IN}} = \sum \dot{m}_{\mathrm{OUT}} \tag{1}$$

Exergy analysis is based on the second law of thermodynamics [11]. The main exergy balance equation for a volume in steady state is [12]:

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

where the net exergy transfer by heat ($\dot{X}_{\mathrm{heat}}$) at the temperature T is equal to [13]:

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

Specific exergy can be defined according to [14] by an equation:

$$\varepsilon = (h - h_0) - T_0 \cdot (s - s_0) \tag{4}$$

The exergy power of a flow can be calculated according to [15]:

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

Exergy efficiency [16] is usually defined as:

$$\eta_{\mathrm{ex}} = \frac{\text{Exergy output}}{\text{Exergy input}} \tag{6}$$

3.2. Steam pressure reduction valve exergy analysis

For the analyzed pressure reduction valve, all necessary operating points were presented in Fig. 2. The required specific enthalpies and specific entropies were calculated from measured steam pressures and temperatures by using NIST REFPROP software [17].

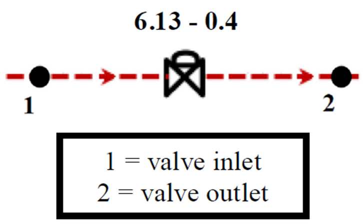

Fig. 2. *Steam pressure reduction valve scheme with a general operating range*

Mass and exergy balances for the analyzed steam pressure reduction valve are:

<u>Mass balance:</u>

$$\dot{m}_1 = \dot{m}_2 \tag{7}$$

<u>Exergy balance:</u>

- Exergy power input:

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

- Exergy power output:

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

- Exergy destruction:

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

- Exergy efficiency:

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

The ambient state in the LNG carrier engine room during the provided measurements was:

- pressure: $p_0 = 0.1$ MPa = 1 bar,
- temperature: $T_0 = 25$ °C = 298.15 K.

4. Measuring equipment and measurement results of pressure reduction valve

Measurements were performed in three different LNG carrier steam system operation points during the system startup. After system startup, all produced superheated steam is used in steam system and “dump” line is not in operation from that moment on. Required operating parameters (pressures, temperatures and mass flows) for each steam pressure reduction valve operating point are presented in Table 2 in relation to the main propulsion propeller speed. Main propulsion propeller speed is directly proportional to steam system load.

In Table 2 can be seen that as propulsion propeller speed increases, the steam mass flow, which is sent directly to the main condenser decreases. This fact presents that steam system uses more and more produced superheated steam as propulsion propeller speed (steam system load) increases. After 41.78 rpm, steam system uses all of produced superheated steam and steam “dump” line is closed.

Table 2. *Steam pressure reduction valve inlet and outlet - measurement results*

Propulsion propeller speed (rpm)	Pressure reduction valve - steam inlet (1*)			Pressure reduction valve - steam outlet (2*)		
	Temperature (°C)	Pressure (MPa)	Mass flow (kg/h)	Temperature (°C)	Pressure (MPa)	Mass flow (kg/h)
25.58	312.5	6.010	15767	232.6	0.4	15767
34.33	309.0	6.080	13175	225.6	0.4	13175
41.78	304.0	6.110	3695	216.5	0.4	3695

* Streams numeration refers to Fig. 2.

Measurement results presented in Table 2 were obtained by using the existing measuring equipment mounted before and after analyzed pressure reduction valve. List of used measuring equipment is presented in Table 3. From Table 3 only the Shaft Power Meter used for propulsion propeller speed measuring is not mounted at the analyzed pressure reduction valve inlet or outlet, it is mounted directly on propulsion propeller shaft.

Table 3*. List of used measurement equipment*

Steam temperature (valve inlet and outlet)	Greisinger GTF 401-Pt100 - Immersion probe [18]
Steam pressure (valve inlet)	Yamatake JTG960A - Pressure Transmitter [19]
Steam pressure (valve outlet)	Yamatake JTG940A - Pressure Transmitter [19]
Steam mass flow (valve inlet and outlet)	Yamatake JTD960A - Differential Pressure Transmitter [20]
Propulsion propeller speed	Kyma Shaft Power Meter (KPM-PFS) [21]

5. Pressure reduction valve exergy analysis results with the discussion

5.1. Pressure reduction valve exergy analysis - exploitation

Decrease in pressure and temperature on the analyzed pressure reduction valve is presented on Fig. 3. During the increase in steam system load, steam pressure at the analyzed pressure reduction valve inlet increases, Table 2, and this occurrence causes a simultaneous increase in pressure reduction. At the propulsion propeller speed of 25.58 rpm, analyzed valve reduces steam pressure for 5.61 MPa, at 34.33 rpm steam pressure reduction amounts 5.68 MPa, while at the highest observed propulsion propeller speed of 41.78 rpm, right before the closing of “dump” line, pressure reduction amounts 5.71 MPa.

Increase in steam pressure reduction resulted also with the increase in steam temperature reduction. During the increase in steam system load, the steam temperature reduction increases from 79.9 °C (at 25.58 rpm) to 87.5 °C (at 41.78 rpm).

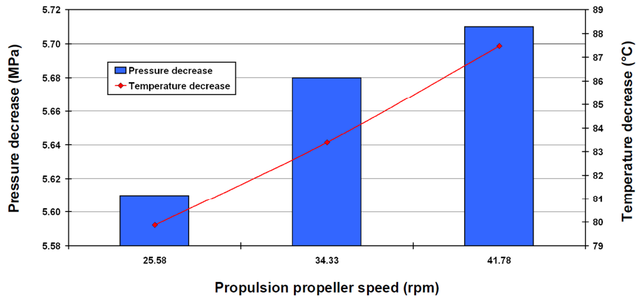

Fig. 3. *The steam pressure and temperature decrease on the pressure reduction valve - exploitation*

Exergy power input and output of the analyzed pressure reduction valve continuously decreases during the increase in steam system load, Fig. 4. According to the equations (8) and (9) the main reason for such decrease in the exergy power input and output can be found in the decrease in steam mass flow, Table 2. After 41.78 rpm, steam system uses all of the produced steam, so amount of steam, which passes directly from steam generators to main condenser is equal to zero.

Increase in steam system load causes decrease in valve exergy power input from 4823.8 kW (at 25.58 rpm) to 1115.7 kW (at 41.78 rpm) while exergy power output simultaneously decreases from 3300.3 kW to 759.7 kW between the same propulsion propeller speeds.

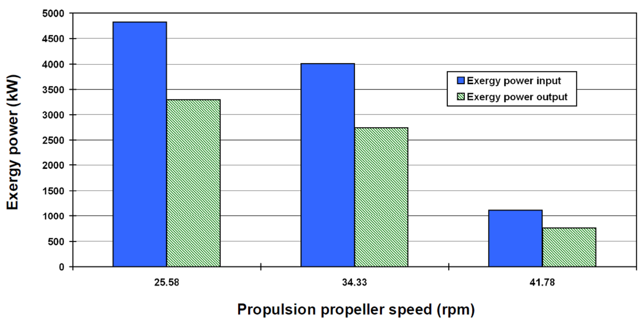

Fig. 4. *Change in exergy power input and output of analyzed valve - exploitation*

Increase in steam system load causes decrease in pressure reduction valve exergy destruction (exergy power losses), Fig. 5, which is caused mostly because of a decrease in steam mass flow. Pressure reduction valve exergy destruction decreases from 1523.5 kW at 25.58 rpm to 356 kW at 41.78 rpm.

The same decrease trend during the increase in propulsion propeller speed can also be seen in pressure reduction valve exergy efficiency, Fig. 5, which decreases from 68.42 % at 25.58 rpm to 68.09 % at 41.78 rpm.

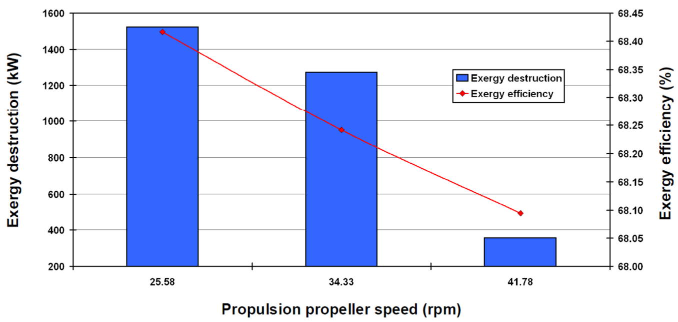

Fig. 5. *Exergy destruction and exergy efficiency of the pressure reduction valve - exploitation*

5.2. Pressure reduction valve exergy analysis during the ambient temperature variation

Exergy analysis of any steam plant component is dependable on the ambient pressure and temperature. In realistic conditions, ambient pressure can not be changed for a significant value, so the influence of the ambient pressure on exergy analysis is almost negligible. Change in the ambient temperature is significant for land-based steam plants during the season change (summer/winter). For the marine steam plants change in the ambient temperature significantly influenced exergy destruction and exergy efficiency of any plant component because it depends on the geographical area in which ship operates. It is realistic to expect that the ambient temperature in the analyzed LNG carrier engine room can be changed from 10 °C (when ship operates in Nordic areas) to 50 °C when ship operates in warm areas (for example Persian Gulf).

At any observed pressure reduction valve operating point, exergy destruction (exergy power loss) is the lowest for the lowest observed ambient temperature. An increase in the ambient temperature causes an increase in valve exergy destruction, Fig. 6.

Valve exergy destruction is also related to steam mass flow through the valve; higher steam mass flow resulted in the higher exergy destruction at any steam system load and at any temperature.

Increase in the ambient temperature causes an increase in valve exergy destruction. Between propulsion propeller speeds of 25.58 rpm and 41.78 rpm, valve exergy destruction amounts from 1446.62 kW to 338.05 kW for the ambient temperature of 10 °C, while for the ambient temperature of 50 °C valve exergy destruction amounts from 1651.16 kW to 385.86 kW in the same operation range.

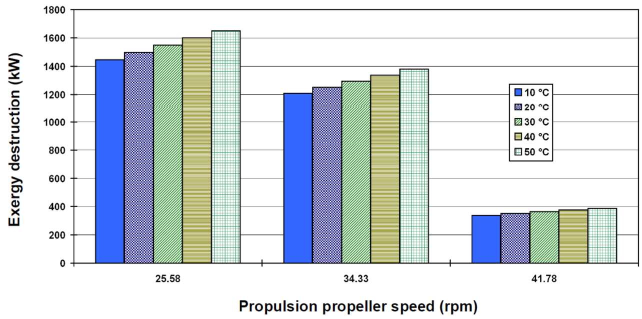

Fig. 6. *Change in the exergy destruction of analyzed valve during the ambient temperature change*

During the ambient temperature variation, exergy efficiency of the analyzed pressure reduction valve is reverse proportional to valve exergy destruction. The highest valve exergy efficiency is obtained for the lowest ambient temperature of 10 °C (and for the lowest exergy destruction), while the lowest valve exergy efficiency is obtained for the highest ambient temperature of 50 °C (and for the highest exergy destruction), Fig. 7.

At each observed ambient temperature, pressure reduction valve exergy efficiency slowly decreases during the increase in steam system load. Increase in the ambient temperature for a 10 °C causes decrease in valve exergy efficiency for between 2.5 % and 3 %.

When compared analyzed pressure reduction valve exergy efficiency with steam turbines, it can be concluded that valve exergy efficiency are much more affected by the change in the ambient temperature than steam turbines in general, because an increase in the ambient temperature for 10 °C causes decrease in steam turbine exergy efficiency for 1 % or less [5].

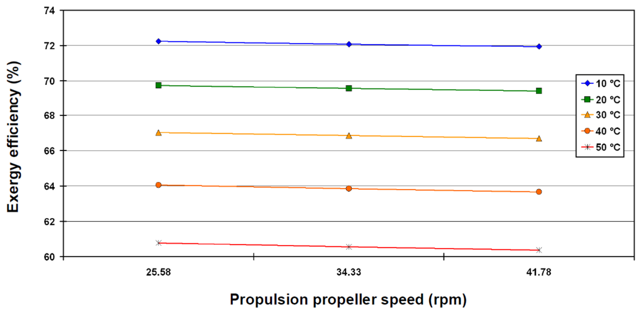

Fig. 7. *Change in exergy efficiency of analyzed valve during the ambient temperature change*

6. Conclusion

This paper presented an exergy analysis of pressure reduction valve mounted in the steam propulsion system on conventional LNG carrier. The pressure reduction valve is analyzed in two different ways: based on measurement data from exploitation and based on the ambient temperature variation. Analyzed valve is mounted on the steam generators "dump" line, which led superheated steam surplus direct to the main condenser.

From LNG carrier exploitation data are obtained that the valve pressure and temperature decrease become as higher as steam system load increases. Valve exergy power input and output decreases during the increase in steam system load, mostly because of the steam mass flow decrease (superheated steam surplus is as lower as the system load increases). Steam system load increase in exploitation also causes a decrease in valve exergy destruction (from 1523.5 kW at 25.58 rpm to 356 kW at 41.78 rpm) with a simultaneous decrease in valve exergy efficiency (from 68.42 % at 25.58 rpm to 68.09 % at 41.78 rpm).

Pressure reduction valve exergy destruction is the lowest for the lowest observed ambient temperature, in any steam system load. An increase in the ambient temperature causes an increase in valve exergy destruction. Valve exergy destruction is related to steam mass flow through the valve; higher steam mass flow resulted in the higher exergy destruction at any steam system load and at any temperature.

The exergy efficiency of the pressure reduction valve is reverse proportional to valve exergy destruction - the highest exergy efficiency is obtained for the lowest observed ambient temperature (and for the lowest exergy destruction), while the lowest valve exergy efficiency is obtained for the highest observed ambient temperature (and for the highest exergy destruction). An increase in the ambient temperature for 10 °C causes a decrease in analyzed valve exergy efficiency for between 2.5 % and 3 %.

7. Acknowledgment

The authors would like to extend their appreciations to the main ship-owner office for conceding measuring equipment and for all help during the exploitation measurements. This work has been fully supported by the Croatian Science Foundation under the project IP-2018-01-3739.

NOMENCLATURE

Abbreviations:		**Greek symbols:**	
LNG	Liquefied Natural Gas	ε	specific exergy, kJ/kg
		η	efficiency, -
Latin Symbols:		**Subscripts:**	
$\dot{E}$	stream flow power, kJ/s	0	ambient conditions
h	specific enthalpy, kJ/kg	D	destruction
$\dot{m}$	mass flow rate, kg/s or kg/h	ex	exergy
p	pressure, MPa	IN	inlet (input)
P	work done, kJ/s	OUT	outlet (output)
$\dot{Q}$	heat transfer, kJ/s		
s	specific entropy, kJ/kg·K		
T	temperature, °C or K		
$\dot{X}_{heat}$	heat exergy transfer, kJ/s		

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YEAR III, ISSUE 1 (12), BOROVETS, BULGARIA 2019

VOLUME I
MACHINES. TECHNOLOGIES. MATERIALS

ISSN 2535-0021 (PRINT)
ISSN 2535-003X (ONLINE)

PUBLISHER:

SCIENTIFIC TECHNICAL UNION OF MECHANICAL ENGINEERING INDUSTRY-4.0

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