Energy and Exergy Efficiency Analysis of Sealing Steam Condenser in Propulsion System of LNG Carrier

Analiza energijske i eksergijske efikasnosti kondenzatora brtvene pare u propulzijskom sustavu LNG tankera

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Summary

In ship propulsion systems today diesel engines are dominant, but steam propulsion systems prevail in one type of ships and that are LNG carriers. Such steam propulsion systems consist of many different components. One interesting component of these systems is sealing steam condenser analysed in this paper. Measurements of all necessary operating parameters for analysed sealing steam condenser were performed during the ship exploitation and they were used for calculating the energy and exergy efficiency of this device. Except the displayed movement of both efficiencies the reasons for those changes and proposals for possible improvements were presented. Also, it was displayed all operating parameters of sealing steam condenser that has an impact on its performance and efficiency. During the ship exploitation, improvements related to the sealing steam condenser efficiency are hard to expect because improvements would cause an increase in the steam propulsion system operating costs.

KEY WORDS

sealing steam condenser
steam propulsion system
energy efficiency
exergy efficiency

Sažetak

U današnjoj brodskoj propulziji dominiraju dizelski motori, no parni propulzijski sustavi prevladavaju na jednom tipu brodova, a to su LNG tankeri. Takvi parni propulzijski sustavi sastoje se od različitih komponenti. Jedna zanimljiva komponenta takvih sustava je kondenzator brtvene pare analiziran u ovom radu. Mjerenja svih potrebnih radnih parametara analiziranog kondenzatora brtvene pare provedena su tijekom brodske eksploatacije, a korištena su za izračun energijske i eksergijske efikasnosti ovog uređaja. Osim prikazanih kretanja za obje efikasnosti, predstavljeni su i razlozi izračunatih kretanja te su dani prijedlozi za moguća poboljšanja. Jednako tako, prikazani su svi radni parametri kondenzatora brtvene pare koji imaju utjecaj na njegove performanse i efikasnost. Tijekom brodske eksploatacije, poboljšanja vezana za efikasnost kondenzatora brtvene pare je teško za očekivati jer bi poboljšanja uzrokovala povećanje operativnih troškova parnog sustava.

KLJUČNE RIJEČI

kondenzator brtvene pare
parni propulzijski sustav
energijska efikasnost
eksergijska efikasnost

1. INTRODUCTION/*Uvod*

Although today's propulsion systems are based mostly on diesel engines, steam turbine propulsion is not a rare occurrence in the LNG carriers. Moreover, most modern LNG tankers are powered with steam turbine systems [1]. These propulsion systems consist of a number of constituent components [2]. In this paper, it was performed the energy and exergy efficiency analysis of a sealing steam condenser, which is an important component of every marine steam propulsion system.

During the exploitation were conducted measurements of flow, pressure and temperature of all the operating substances which passes through the analysed condenser. The measurements were made during the dynamic operating conditions of the steam propulsion system at the propeller accelerating mode.

The main characteristics of the LNG carrier on which is mounted analysed sealing steam condenser are given in the Table 1.

Table 1 Main characteristics of the analysed LNG carrier
Tablica 1 Osnovne karakteristike analiziranog LNG tankera

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)

2. SEALING STEAM CONDENSER CHARACTERISTICS / *Karakteristike kondenzatora brtvene pare*

Sealing steam condenser in the steam propulsion system has a dual function: first is the liquefaction of sealing steam and the second is feed water heating. The primary function is the condensation of vapour which passes through the labyrinth seals of the main steam turbine, turbo-generator turbines and main feed water pump turbine. Vapour thermal power has been used in this condenser for feed water heating.

Stationary steam power plants have no sealing steam condenser. In these power plants the vapour which passes the labyrinth seals returns with specifically designed channels in the main vapour steam flow. That "leakage vapour" in stationary plants was used in the following steam turbine housing for electrical generator driving or was supplied directly into the main condenser from the last turbine housing [3].

Also, sealing steam condenser is not a classical condenser because in the classical condenser heat transferred from the steam to the feed water must be committed to the environment (usually by using cooling towers). In this case the heat from the steam is not lost, it warms the feed water so the sealing steam condenser can be observed and calculated as a regenerative feed water heater with a low thermal capacity of the heating steam [4]. The confirmation of this claim shows that the movement of condenser energy and exergy efficiency is exactly comparable with the movement of the first regenerative feed water heater in common stationary steam plants.

Analysed sealing steam condenser is a horizontal, shell and tube type heat exchanger with straight tubes, Figure 1. Cooling tubes are installed in the condenser by expanding into tube sheets at both ends. Differential expansion and contraction between the tubes and the condenser shell due to thermal effect are absorbed by a circumferential expansion joint provided in the shell plating so that the tubes and tube sheets are relieved of an excessive strain. Feed water passed through the condensate tubes. Non-condensable gas (air) is exhausted by the exhaust fan [5].

3. NUMERICAL MODEL / *Numerički model*

The best way for explaining the numerical model is to bring a brief explanation of energy efficiency, exergy flow rate and exergy efficiency.

The definition of energy efficiency is based on the first law of thermodynamics [6]. It may take different forms and different names depending on the type of the system. Usually energy efficiency can be written as:

$$\eta_{\mathrm{en}} = \frac{\text{Energy output}}{\text{Energy input}} \tag{1}$$

The exergy flow rate of a flowing substance is the maximum rate that work may be obtained from it as it passes reversibly to the environmental state exchanging heat and materials only with the surroundings [7]. In essence, exergy analysis states the theoretical limitations imposed upon a system, clearly pointing out that no real system can conserve exergy and that only a portion of the input exergy can be recovered. Also, exergy analysis quantitatively specifies practical limitations by providing losses in a form in which they are a direct measure of lost exergy. The exergy flow rate is defined by an equation [8]:

$$E_{\mathrm{i}} = \dot{m}_{\mathrm{i}} \cdot \varepsilon_{\mathrm{i}} \tag{2}$$

where E (kW) represents the exergy flow rate of flowing substance, $\dot{m}$ (kg/s) is mass flow and ε (kJ/kg) is specific exergy.

Specific exergy was defined according to [9] by an equation:

$$\varepsilon_{\mathrm{i}} = (h_{\mathrm{i}} - h_0) - T_0 \cdot (s_{\mathrm{i}} - s_0) \tag{3}$$

where h (kJ/kg) is specific enthalpy, T (K) is temperature and s (kJ/kg·K) is specific entropy. Index 0 represents an environment state (usually in literature known as "dead state"). In equations (2) and (3) index i represent any flowing substance.

The definition of exergy efficiency is based on the second law of thermodynamics [6]. It is also called second law efficiency or effectiveness. Exergy efficiency can be defined as:

$$\eta_{\mathrm{ex}} = \frac{\text{Exergy output}}{\text{Exergy input}} \tag{4}$$

For the analysed sealing steam condenser all the essential elements of numerical model were presented in Figure 2. The required enthalpies and entropies were calculated from the measured pressure and temperatures for every flow substance by using Nist REFPROP software [10].

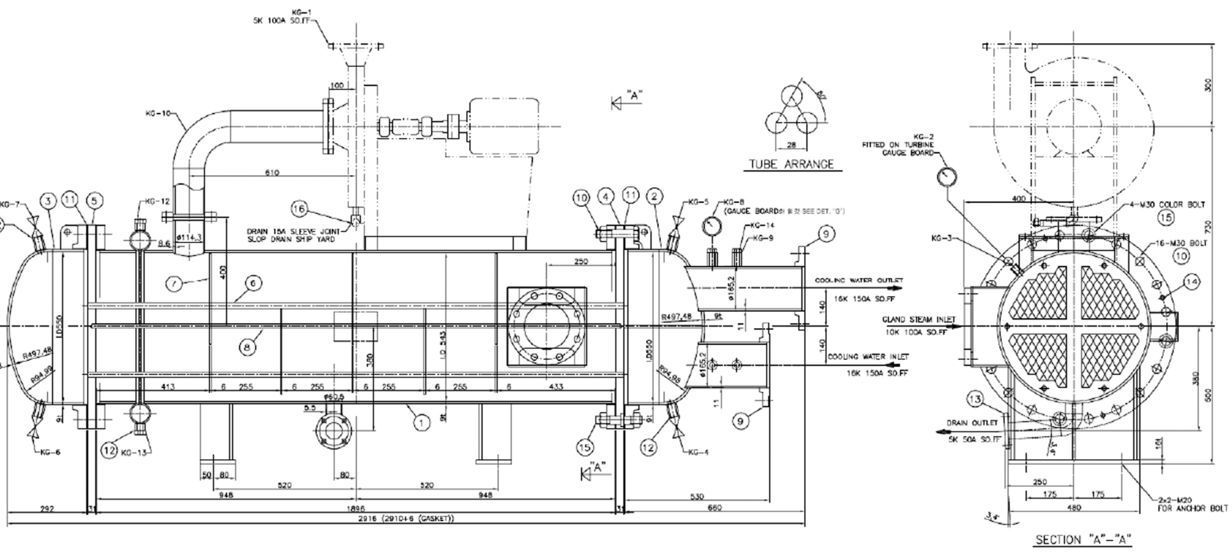

Figure 1 Draft and the cross section of the analysed sealing steam condenser [5]
Slika 1 Skica i presjek analiziranog kondenzatora brtvene pare [5]

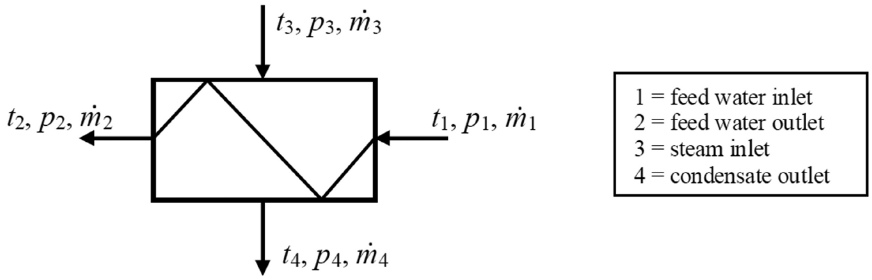

Figure 2 Sealing steam condenser symbol with main operating parameters used in the numerical model
Slika 2 Simbol kondenzatora brtvene pare sa glavnim radnim parametrima korištenim u numeričkom modelu

For sealing steam condenser, according to Figure 2 must be set three balances which are necessary for energy and exergy efficiency calculation. These balances are mass flow balance, energy balance and exergy balance.

- Sealing steam condenser mass flow balance:

$$\dot{m}_1 = \dot{m}_2 \tag{5}$$

$$\dot{m}_3 = \dot{m}_4 \tag{6}$$

- Sealing steam condenser energy balance and energy efficiency:

$$E_{\mathrm{L,en}} = \dot{m}_3 \cdot (h_3 - h_4) - \dot{m}_1 \cdot (h_2 - h_1) \tag{7}$$

where $E_{\mathrm{L,en}}$ (kW) is the rate of energy loss in the sealing steam condenser.

Energy efficiency of sealing steam condenser was obtained by using an equation (8), according to [11]:

$$\eta_{\mathrm{en}} = \frac{\dot{m}_1 \cdot (h_2 - h_1)}{\dot{m}_3 \cdot (h_3 - h_4)} \tag{8}$$

- Sealing steam condenser exergy balance and exergy efficiency:

$$E_{\mathrm{L,ex}} = \dot{m}_3 \cdot (\varepsilon_3 - \varepsilon_4) - \dot{m}_1 \cdot (\varepsilon_2 - \varepsilon_1) \tag{9}$$

where $E_{\mathrm{L,ex}}$ (kW) is the rate of exergy loss in the sealing steam condenser.

Exergy efficiency of sealing steam condenser was obtained by using an equation (10), according to [12]:

$$\eta_{\mathrm{ex}} = \frac{\dot{m}_1 \cdot (\varepsilon_2 - \varepsilon_1)}{\dot{m}_3 \cdot (\varepsilon_3 - \varepsilon_4)} \tag{10}$$

The environment state (dead state) in the engine room of analysed LNG carrier during a measurement period was:

- Pressure: $p_0 = 0.1$ MPa
- Temperature: $T_0 = 25$ °C = 298.15 K

4. MEASUREMENT EQUIPMENT AND MEASURED RESULTS / *Mjerna oprema i izmjereni rezultati*

All the measurement results were obtained by using existing measuring equipment calibrated and already mounted on all the components of the analysed steam propulsion system. Control and maintenance are very important on such propulsion systems because it allows control and adjustment of all important operating parameters for each constituent component.

The sealing steam condenser measured data as well as a list of used measurement equipment are presented in two parts: the first part refers to feed water (inlet and outlet), and the second part refers to steam (inlet) and condensate (outlet).

Measuring equipment for feed water mass flow, temperature and pressure is presented in the Table 2 while measuring equipment for steam and condensate mass flow, temperature and pressure is presented in the Table 3.

Table 2 Measuring equipment for feed water at the condenser inlet and outlet
Tablica 2. Mjerna oprema za napojnu vodu na ulazu i izlazu iz kondenzatora

MEASURED PARAMETER	MEASURING EQUIPMENT
Feed water temperature at the inlet and outlet	2 x Greisinger GTF 401-Pt100 - Immersion probe [13]
Feed water pressure at the inlet and outlet	2 x Yamatake JTG940A - Pressure Transmitter [14]
Feed water mass flow (inlet)	Promass 80F - Coriolis Mass Flow Measuring System [15]

Table 3 Measuring equipment for sealing steam and condensate at the condenser inlet and outlet
Tablica 3. Mjerna oprema za brtvenu paru i kondenzat na ulazu i izlazu iz kondenzatora

MEASURED PARAMETER	MEASURING EQUIPMENT
Steam temperature (inlet)	Greisinger GTF 401-Pt100 - Immersion probe [13]
Steam pressure (inlet)	Yamatake JTD910A - Differential Pressure Transmitter [16]
Steam mass flow (inlet)	Yamatake JTD920A - Differential Pressure Transmitter [16]
Condensate temperature (outlet)	Greisinger GTF 401-Pt100 - Immersion probe [13]
Condensate pressure (outlet)	Yamatake JTD910A - Differential Pressure Transmitter [16]
Condensate mass flow (outlet)	Promass 80F - Coriolis Mass Flow Measuring System [15]

Finally, measured results for feed water at the condenser inlet and outlet were presented in the Table 4 while measured results for steam and condensate at the condenser inlet and outlet were presented in the Table 5. All measurements were presented as a function of propeller revolutions during LNG carrier acceleration.

Table 4 Measurement results for feed water at the condenser inlet and outlet
Tablica 4. Mjerni podaci za napojnu vodu na ulazu i izlazu iz kondenzatora

Measurement No.	Propeller revolutions (min-1)	Feed water mass flow (kg/h)	Feed water temperature at the condenser inlet (°C)	Feed water pressure at the condenser inlet (MPa)	Feed water temperature at the condenser outlet (°C)	Feed water pressure at the condenser outlet (MPa)
1	25.00	28179	36.95	0.75	44	0.75
2	34.33	31448	36.00	0.75	43	0.75
3	41.78	28692	35.05	0.75	43	0.75
4	56.65	35884	52.37	0.75	58	0.75
5	61.45	45127	51.48	0.75	56	0.75
6	62.52	44671	51.45	0.75	56	0.75
7	63.55	47731	50.75	0.75	55	0.75
8	65.10	50051	50.00	0.75	54	0.75
9	66.08	51664	50.10	0.75	54	0.75
10	67.68	54739	49.30	0.75	53	0.75
11	68.66	54751	49.30	0.75	53	0.75
12	69.49	56137	49.30	0.75	53	0.75
13	70.37	57725	49.30	0.75	53	0.75
14	71.03	58354	48.40	0.75	52	0.75
15	73.09	63486	48.00	0.75	51	0.75
16	74.59	65472	49.00	0.75	52	0.75
17	76.56	70211	48.00	0.75	51	0.75
18	78.41	76328	48.20	0.75	51	0.75
19	79.46	75216	48.15	0.75	51	0.75
20	80.44	79398	50.30	0.75	53	0.75
21	81.49	80114	51.35	0.75	54	0.75
22	82.88	83171	50.45	0.75	53	0.75
23	83.00	84500	50.50	0.75	53	0.75

Table 5 Measurement results for sealing steam and condensate at the condenser inlet and outlet
Tablica 5. Mjerni rezultati za brtvene paru i kondenzat na ulazu i izlazu iz kondenzatora

Measurement No.	Propeller revolutions (min-1)	Steam mass flow (kg/h)	Steam temperature at the condenser inlet (°C)	Steam pressure at the condenser inlet (MPa)	Condensate temperature at the condenser outlet (°C)	Condensate pressure at the condenser outlet (MPa)
1	25.00	398	99	0.09730	98.8	0.09730
2	34.33	443	99	0.09730	98.8	0.09730
3	41.78	458	99	0.09730	98.8	0.09730
4	56.65	410	99	0.09730	98.8	0.09730
5	61.45	410	99	0.09730	98.8	0.09730
6	62.52	410	99	0.09730	98.8	0.09730
7	63.55	410	99	0.09730	98.8	0.09730
8	65.10	410	99	0.09730	98.8	0.09730
9	66.08	410	99	0.09730	98.8	0.09730
10	67.68	410	99	0.09730	98.8	0.09730
11	68.66	410	99	0.09730	98.8	0.09730
12	69.49	410	99	0.09730	98.8	0.09730
13	70.37	410	99	0.09730	98.8	0.09730
14	71.03	410	99	0.09730	98.8	0.09730
15	73.09	410	99	0.09730	98.8	0.09730
16	74.59	410	99	0.09730	98.8	0.09730
17	76.56	410	99	0.09730	98.8	0.09730
18	78.41	410	99	0.09730	98.8	0.09730
19	79.46	410	99	0.09730	98.8	0.09730
20	80.44	410	99	0.09730	98.8	0.09730
21	81.49	410	99	0.09730	98.8	0.09730
22	82.88	410	99	0.09730	98.8	0.09730
23	83.00	410	99	0.09730	98.8	0.09730

5. RESULTS AND DISCUSSION / *Rezultati i diskusija*

Feed water flow change in relation to propeller revolutions change was presented in Figure 3. Feed water flow almost exponentially increased with the increase of propeller revolutions which is expected appearance. During the load increase of the steam propulsion system (increase in propeller revolutions) more and more water is added to the steam system. Feed water is supplied to the steam generators which produces increased amount of steam. With the increased amount of steam, the current needs of all steam consumers will be satisfied. Analysed LNG carrier has two identical, mirror-oriented steam generators and each of them can receive 70000 kg/h of water at maximum load.

Measurement results show that with feed water mass flow increase at the same time does not increase the amount of steam supplied to the sealing steam condenser. This fact leads to two conclusions. The first conclusion says that all labyrinth seals from the all steam turbines were very efficient because the amount of steam that passed through the seals is not increasing with system load increase but it remains constant. From the fact that the amount of steam supplied to the sealing steam condenser is almost identical in all operating modes directly follows the second conclusion which leads to the expected movement of exergy efficiency. As the mass flow of the heating medium (steam) was constant and operating steam parameters (pressure and temperature) are low, it is expected that exergy efficiency of the sealing steam condenser will not achieve high values.

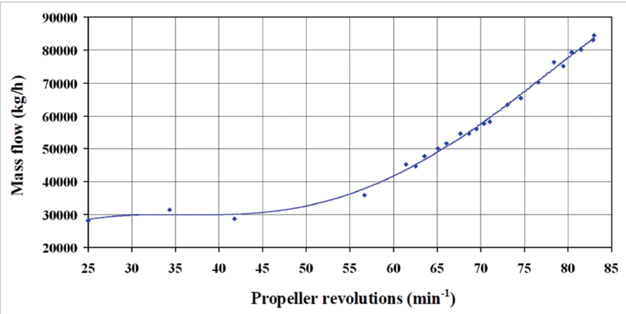

Figure 3 Feed water mass flow through the sealing steam condenser

Slika 3 Maseni protok napojne vode kroz kondenzator brtvene pare

At low propeller revolutions while the steam system does not operate at optimum load, feed water temperatures at the sealing steam condenser inlet and outlet are the lowest, Figure 4. The sharp rise in both temperatures is evident during propeller revolutions increase from 45 min^{-1} to 55 min^{-1}. During further increase in the steam system load both feed water temperatures at the condenser inlet and outlet decreases slightly and on the highest system load during the measurement period, both temperatures began to rise again.

From Figure 4 an essential conclusion is necessary to perform from the feed water temperature differences at the inlet and outlet of the sealing steam condenser. By observing the temperature difference it is evident that this difference is constantly decreasing with an increase in propeller revolutions. This phenomenon occurs because the amount of heating medium (steam) is almost constant in all operating modes and the amount of feed water is continuously increasing with system load increase.

When designing such condenser must be taken into account that during the whole operation time condenser must effectively fulfil a dual function - function of steam condenser and feed water heating function.

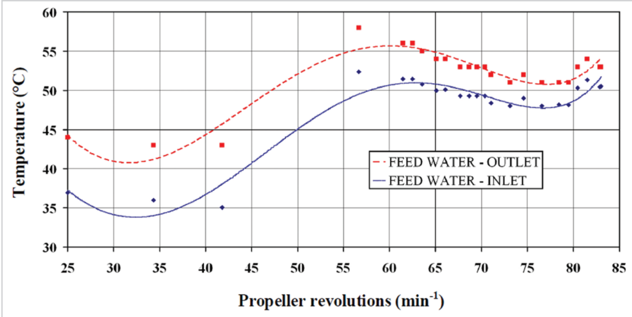

Figure 4 Feed water temperature changes at the sealing steam condenser inlet and outlet

Slika 4 Promjena temperature napojne vode na ulazu i izlazu iz kondenzatora brtvene pare

Figure 5 presents the movement of energy and exergy efficiency of the analysed sealing steam condenser during the overall observed propeller operating area.

The energy efficiency of the sealing steam condenser is very high and for any steam system load has values above 90%. The highest values of energy efficiency were achieved at the largest loads of the steam propulsion system. This trend of sealing steam condenser energy efficiency change is expected, it is moving in the same limits as for any conventional heat exchanger.

On the other side exergy efficiency of the sealing steam condenser is quite low. When the steam system was starting up exergy efficiency is just slightly above 20% and with load increase exergy efficiency has increased to approximately 40%. At the level of 40% exergy efficiency retained until the largest observed system load. The trend of change shows that at the greatest load of the steam system exergy efficiency will further increase. This conclusion can be justified by the fact that the temperature of the feed water at the sealing steam condenser inlet during the maximum system load will get the highest values.

It is important to notice that the trends of change for exergy efficiency have the same shape as the trends of change in feed water temperature at the sealing steam condenser inlet and outlet. Therefore, it is important to conclude that the temperature of the feed water has a decisive influence on the movement of exergy efficiency.

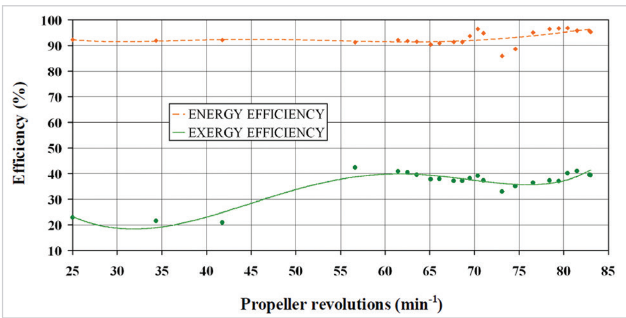

Figure 5 Sealing steam condenser energy and exergy efficiency change in relation to propeller revolutions

Slika 5 Promjena energijske i eksergijske efikasnosti kondenzatora brtvene pare u odnosu na brzinu vrtnje propelera

In Figure 6 can be directly seen how on the exergy efficiency affects the feed water temperature at the sealing steam condenser inlet. Dependence is almost linear, which shows that an increase in feed water temperature at the condenser inlet causes an increase in exergy efficiency. A similar conclusion applies to the feed water temperature at the condenser outlet. Another way for sealing steam condenser exergy efficiency increase could be with increasing the mass flow and with increasing the operating parameters of steam which enters in the condenser. For example, steam may be supplied from the main turbine or directly from the steam generator. However, that would effectively increase the steam system costs because the additional steam mass flow will cause the main turbine power decrease or will cause higher fuel consumption in the steam generator. For this reason shipowners sacrifice the exergy efficiency of this condenser in order to avoid the increase of the steam propulsion system costs.

The properties and characteristics of the energy and exergy efficiency for the analysed sealing steam condenser show almost identical trends of change as for the first low-pressure regenerative feed water heater in stationary steam power plants [12], because the operating conditions of this heater are very similar to those for the observed sealing steam condenser.

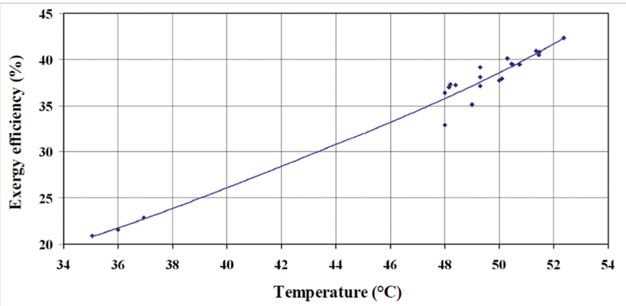

Figure 6 Sealing steam condenser exergy efficiency in relation to feed water temperature at the condenser inlet
Slika 6 Eksergijska efikasnost kondenzatora brtvene pare u odnosu na temperaturu napojne vode na ulazu u kondenzator

6. CONCLUSION/*Zaključak*

Although in today's ship propulsion prevail diesel engines, steam propulsion is still dominant in the LNG carriers. In this paper, it was analysed one component of such steam propulsion system and that is sealing steam condenser.

Based on the measured data of mass flow rates, pressures and temperatures for all the operating media through the sealing steam condenser it was performed the condenser energy and exergy analysis. All the measurements were conducted under the real exploitation conditions of the analysed LNG carrier.

The analysis results show that from the standpoint of energy efficiency sealing steam condenser is an almost perfect device because his energy losses are very small.

On the other side, exergy analysis shows very low efficiency of this device. Distinct effect on exergy efficiency has a feed water temperature at the sealing steam condenser inlet and outlet. By increasing the temperature of the feed water or by increasing the mass flow rate and operating parameters of steam will cause an increase in sealing steam condenser exergy efficiency. The low exergy efficiency of this condenser represents the sacrifice that shipowners consciously accept because with an increase in the exergy efficiency of the sealing steam condenser inevitably will grow steam propulsion system operating costs.

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