ENERGY AND EXERGY ANALYSIS OF SEA WATER PUMP FOR THE MAIN CONDENSER COOLING IN THE LNG CARRIER STEAM PROPULSION SYSTEM

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Abstract: *Energy and exergy analysis of sea water pump which is used for the main condenser cooling at lower steam propulsion system loads on conventional LNG carrier is presented in this paper. By using the measured variables from the exploitation, it is presented different influences of pump used power on cumulative energy and exergy power inputs. Energy and exergy pump power losses are reverse proportional, while pump energy and exergy efficiencies are directly proportional to increase in pump load. The highest obtained pump energy efficiency amounts 59.61 %, while the highest obtained pump exergy efficiency amounts 60.25 %. From the viewpoint of efficiencies and power losses, it will be optimal that analyzed pump operates at the highest possible loads.*

Keywords: *ENERGY EFFICIENCY, ENERGY POWER LOSSES, EXERGY EFFICIENCY, EXERGY DESTRUCTION, SEA WATER PUMP*

1. Introduction

Steam propulsion systems are dominant propulsion systems of LNG carriers [1]. Such steam propulsion systems have many components, not only for ship propulsion, but also for electricity and heat production [2]. One of the constituent components of such marine steam propulsion system is main condenser. Main condenser is cooled with sea water, while the condenser cooling system can be performed in two different ways. First one is cooling with the sea water pump (or more of them) only. Second is combination of cooling with sea water pump at the low steam system loads [3], while on the high steam system loads (at high ship speed) sea water pump is switched off and condenser cooling is performed with the scoop. The scoop is a tube mounted under the ship and it leads sea water directly to main condenser cooling tubes. Condenser cooling with a scoop is very dependable on ship current speed so it cannot be performed under optimal ship speed, defined with scoop producer specifications.

In this paper is analyzed sea water pump from a conventional LNG carrier, which uses main condenser cooling with sea water pump at low and with scoop at high steam system loads. Main characteristics of the LNG carrier in which steam propulsion system is mounted analyzed sea water pump are presented in Table 1.

Table 1. *Main characteristics of the LNG carrier*

Dead weight tonnage	84,812 DWT
Overall length	288 m
Max breadth	44 m
Design draft	9.3 m
Propulsion turbine	Mitsubishi MS40-2 (max. power 29.420 kW)
Turbo-generators	2 x Shinko RGA 92-2 (max. power 3.850 kW each)

The main goal of this paper is to perform analysis of sea water pump during its operation from the aspect of energy and exergy. It was investigated the influences of pump driving power on energy and exergy pump inputs and it was performed analysis of pump energy and exergy power losses, for the entire pump operation range. Based on a measured data from ship exploitation, it was observed the change in pump energy and exergy efficiencies from the lowest to the highest pump load.

2. Sea water pump energy and exergy analysis

2.1. General equations for energy and exergy analysis

The first law of thermodynamics defined energy analysis of any steam system component [4]. Mass and energy balance equations for a standard volume in steady state disregarding potential and kinetic energy can be expressed according to [5]:

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

$$\dot{Q} - P = \sum \dot{m}_{\mathrm{OUT}} \cdot h_{\mathrm{OUT}} - \sum \dot{m}_{\mathrm{IN}} \cdot h_{\mathrm{IN}} \tag{2}$$

Energy power of a flow for any fluid stream can be calculated according to the [6] by using the equation:

$$\dot{E}_{\mathrm{en}} = \dot{m} \cdot h \tag{3}$$

Energy efficiency may take different forms and types. Usually, energy efficiency can be written as [7]:

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

Second law of thermodynamics defines exergy analysis [8]. The main exergy balance equation for a standard volume in steady state is [9]:

$$\dot{X}_{\mathrm{heat}} - P = \sum \dot{m}_{\mathrm{OUT}} \cdot \varepsilon_{\mathrm{OUT}} - \sum \dot{m}_{\mathrm{IN}} \cdot \varepsilon_{\mathrm{IN}} + \dot{E}_{\mathrm{ex,D}} \tag{5}$$

where the net exergy transfer by heat ($\dot{X}_{\mathrm{heat}}$) at the temperature T is equal to [10]:

$$\dot{X}_{\mathrm{heat}} = \sum (1 - \frac{T_0}{T}) \cdot \dot{Q} \tag{6}$$

Specific exergy was defined according to [11] by an equation:

$$\varepsilon = (h - h_0) - T_0 \cdot (s - s_0) \tag{7}$$

The total exergy of a flow for every fluid stream can be calculated according to [6]:

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

Exergy efficiency is also called second law efficiency or effectiveness [12]. It can be defined as:

$$\eta_{\mathrm{ex}} = \frac{\text{Exergy output}}{\text{Exergy input}} \tag{9}$$

2.2. Sea water pump efficiencies and losses (energy and exergy)

Analyzed sea water pump is used in LNG carrier steam propulsion system for the main condenser cooling at low propulsion system loads. Main condenser cooling on this LNG carrier is performed in two ways: at low propulsion system loads (at low ship speed) main condenser is cooled with pump, while at high propulsion system loads (at high ship speed) main condenser is cooled with the scoop. According to producer specifications [13], main pump characteristics are:

- Pump maximum capacity: 6000 m^3/h
- Pump maximum delivery height: 13 m
- Standard pump operation revolutions: 390 rpm

Power for sea water pump operation, in each operating point, is calculated according to producer specifications [13] by using sea water volume flow at the pump inlet. Sea water volume flow can be calculated by using measured sea parameters at the pump inlet: temperature, pressure and mass flow. Pump used power (P) is approximated by using sixth degree polynomial:

$$\begin{aligned} P = & 1.3216361 \cdot 10^{-20} \cdot \dot{V}^6 - 2.4675409 \cdot 10^{-16} \cdot \dot{V}^5 + \\ & + 1.7487692 \cdot 10^{-12} \cdot \dot{V}^4 - 6.0343228 \cdot 10^{-9} \cdot \dot{V}^3 + \\ & + 1.0365022 \cdot 10^{-5} \cdot \dot{V}^2 - 4.2656487 \cdot 10^{-3} \cdot \dot{V} + \\ & + 120.657 \end{aligned} \quad (10)$$

where pump used power P is obtained in (kW) when in equation (10) is placed sea water volume flow at the pump inlet $\dot{V}$ in (m^3/h).

For the analyzed sea water pump, all necessary operating points were presented in Fig. 1. The required specific enthalpies and specific entropies as well as other thermodynamic properties were calculated from measured pressures and temperatures for each fluid stream by using NIST REFPROP software [14].

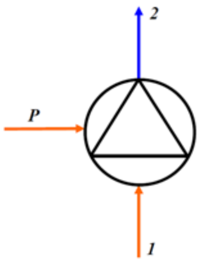

Fig. 1. *Sea water pump symbol with marked inlets (inputs) and outlet (output)*

Mass, energy and exergy balances for the analyzed pump, according to Fig. 1, are:

<u>Mass balance:</u>

$$\dot{m}_1 = \dot{m}_2 \quad (11)$$

<u>Energy balance:</u>

- Energy power input (only sea water flow):

$$\dot{E}_{\text{en,IN,sw}} = \dot{m}_1 \cdot h_1 \quad (12)$$

- Energy power input (cumulative):

$$\dot{E}_{\text{en,IN,c}} = \dot{m}_1 \cdot h_1 + P \quad (13)$$

- Energy power output:

$$\dot{E}_{\text{en,OUT}} = \dot{m}_2 \cdot h_2 \quad (14)$$

- Energy power loss:

$$\dot{E}_{\text{en,PL}} = \dot{E}_{\text{en,IN,c}} - \dot{E}_{\text{en,OUT}} = \dot{m}_1 \cdot h_1 + P - \dot{m}_2 \cdot h_2 \quad (15)$$

- Energy efficiency [15]:

$$\eta_{\text{en}} = \frac{\dot{E}_{\text{en,OUT}} - \dot{E}_{\text{en,IN,sw}}}{P} = \frac{\dot{m}_2 \cdot h_2 - \dot{m}_1 \cdot h_1}{P} \quad (16)$$

<u>Exergy balance:</u>

- Exergy power input (only sea water flow):

$$\dot{E}_{\text{ex,IN,sw}} = \dot{m}_1 \cdot \varepsilon_1 \quad (17)$$

- Exergy power input (cumulative):

$$\dot{E}_{\text{ex,IN,c}} = \dot{m}_1 \cdot \varepsilon_1 + P \quad (18)$$

- Exergy power output:

$$\dot{E}_{\text{ex,OUT}} = \dot{m}_2 \cdot \varepsilon_2 \quad (19)$$

- Exergy power loss (exergy destruction):

$$\dot{E}_{\text{ex,D}} = \dot{E}_{\text{ex,IN,c}} - \dot{E}_{\text{ex,OUT}} = \dot{m}_1 \cdot \varepsilon_1 + P - \dot{m}_2 \cdot \varepsilon_2 \quad (20)$$

- Exergy efficiency [16]:

$$\eta_{\text{ex}} = \frac{\dot{E}_{\text{ex,OUT}} - \dot{E}_{\text{ex,IN,sw}}}{P} = \frac{\dot{m}_2 \cdot \varepsilon_2 - \dot{m}_1 \cdot \varepsilon_1}{P} \quad (21)$$

Ambient conditions during measurements were:

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

3. Measurement results and measuring equipment of the analyzed sea water pump

Measurement results for sea water pump during pump operation are presented in Table 2. Pump operating parameters were presented in relation to propulsion propeller speed. Propulsion propeller speed is directly proportional to steam system load - higher propulsion propeller speed denotes a higher steam system load and vice versa. It also should be noted that the sea water pump load is directly proportional to steam system load, during the entire pump operating time.

Table 2. *Measurement results for sea water pump during its operation*

Propulsion propeller speed (rpm)	**Sea water pump - inlet**			**Sea water pump - outlet**	
	Temperature (°C)	**Pressure (MPa)**	**Sea mass flow (kg/h)**	**Temperature (°C)**	**Pressure (MPa)**
0.00	30	0.1	1120106	30.003	0.223
25.58	22	0.1	1346990	22.002	0.221
34.33	22	0.1	1795986	22.002	0.217
41.78	22	0.1	1795986	22.002	0.218
53.50	22	0.1	2244983	22.002	0.214
56.65	18	0.1	2471535	18.001	0.212

The measurement results were obtained from the existing measuring equipment mounted on the pump inlet and outlet. All measuring equipment is tested and calibrated by producers. List of all used measuring equipment is presented in Table 3.

Table 3. *Used measuring equipment for the pump analysis*

Sea temperature (pump inlet and outlet)	Greisinger GTF 401-Pt100 - Immersion probe [17]
Sea pressure (pump inlet and outlet)	Yamatake JTG940A - pressure transmitter [18]
Sea mass flow (pump inlet)	Promass 80F - Coriolis Mass Flow Measuring System [19]
Propulsion propeller speed	Kyma Shaft Power Meter (KPM-PFS) [20]

4. Results of pump energy and exergy analysis

At each operating point of the analyzed sea water pump is calculated sea volume flow, an essential element for pump used power calculation. Sea water volume flow is calculated for the pump inlet by using measured sea temperature and pressure along with measured sea mass flow, Table 2.

Fig. 2 presents the change in sea water volume flow at the pump inlet for each pump (steam system) load during pump operation. Increase in pump load causes a continuous increase in sea water volume flow from the lowest value (1125 m^3/h at propulsion propeller speed of 0.00 rpm) to the highest value (2475 m^3/h at propulsion propeller speed of 56.65 rpm).

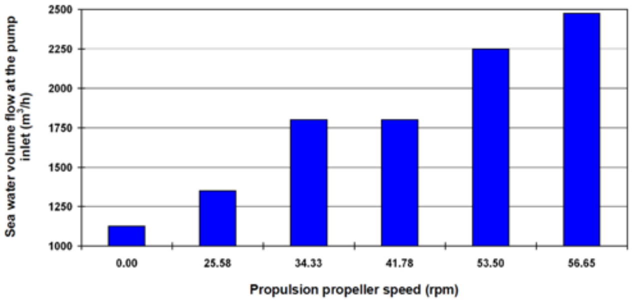

Fig. 2. *Change in sea water volume flow at the pump inlet for various pump loads*

Pump used power is calculated from the sea water volume flow at the pump inlet, according to equation (10). As presented in Fig. 3, pump used power change has the same trend as sea water volume flow. At the lowest load (0.00 rpm of the propulsion propeller) pump uses power of 122.77 kW, while at the highest load (56.65 rpm of the propulsion propeller) pump uses power of 127.85 kW. As expected, sea water pump used power increases during the increase in pump (steam system) load.

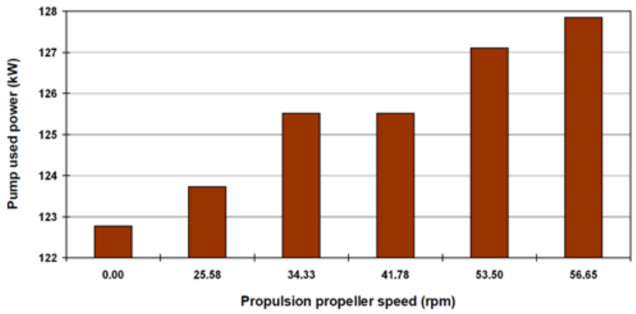

Fig. 3. *Change in a pump used power for various pump loads*

Energy power input and output of the analyzed pump in each observed operating point is presented in Fig. 4. According to equation (13), cumulative energy power input is a sum of only sea water flow power input and pump used power. At each pump operating point, pump used power influence on cumulative energy power input is very small, the dominant element of the cumulative energy power input is sea water flow energy power input. Only sea water flow energy power input amounts from 99.64 % to 99.78 % of cumulative pump energy power input.

In the entire pump operating range, cumulative energy power input amounts from 34686 kW up to 57732 kW, while energy power output amounts from 34608 kW up to 57676 kW. Energy power loss in each observed pump operating point is the difference between cumulative energy power input and energy power output. By taking into account the amount of cumulative energy power input and output, energy power loss for the observed pump will have small values in each operating point, which will not exceed 85 kW.

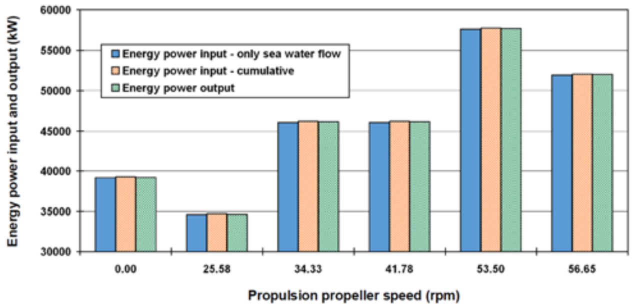

Fig. 4. *Change in pump energy power input and output for various pump loads*

Fig. 5 presents change in sea water pump energy power losses and energy efficiency. At the lowest pump load (0.00 rpm of the propulsion propeller) energy power loss is the highest and amounts 82.32 kW. Pump energy power losses continuously decrease during the increase in pump load and the lowest energy power loss was obtained at the highest pump load (56.65 rpm of the propulsion propeller) and amounts 51.64 kW.

The lowest pump energy efficiency was obtained at the lowest pump load and amounts 32.95 %, while the highest pump energy efficiency was obtained at the highest pump load and amounts 59.61 %. From Fig. 5 can be seen that pump energy efficiency continuously increases during the increase in pump load.

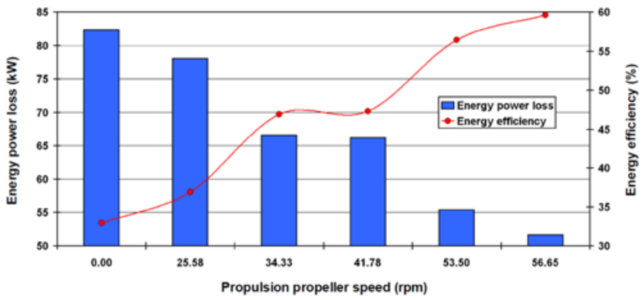

Fig. 5. *Change in pump energy power loss and energy efficiency for various pump loads*

Change in pump exergy power input and output is presented in Fig. 6. Pump used power has a strong influence on pump cumulative exergy power input. Only sea water flow exergy power input amounts from 16.12 % to 30.52 % of cumulative pump exergy power input for all pump operating points except for one at the highest pump load. It can be concluded that pump used power has a strong influence on pump cumulative exergy power input, while its influence on cumulative pump energy power input is low, Fig. 4.

For the whole sea water pump operating range, cumulative pump exergy power input amounts from 147.50 kW up to 367.64 kW, while pump exergy power output amounts from 69.15 kW up to 316.82 kW.

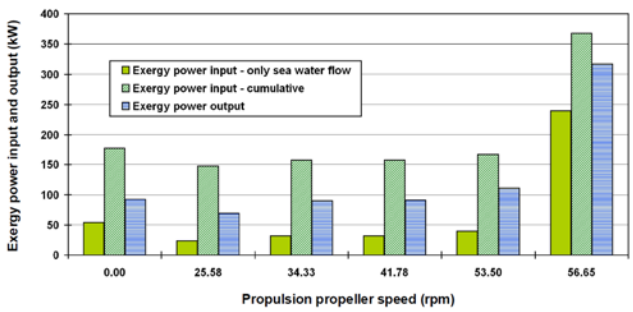

Fig. 6. *Change in pump exergy power input and output for various pump loads*

The change in sea water pump exergy power losses (exergy destruction) and exergy efficiency is presented in Fig. 7. The lowest pump exergy efficiency was obtained at the lowest pump load (0.00 rpm of the propulsion propeller) and amounts 31.31 %, while the highest pump exergy efficiency was obtained at the highest pump load (56.65 rpm of the propulsion propeller) and amounts 60.25 %.

At the lowest pump load exergy destruction has the highest value and amounts 84.33 kW. Pump exergy destruction continuously decreases during the increase in pump load and the lowest exergy destruction was obtained at the highest pump load and amounts 50.83 kW.

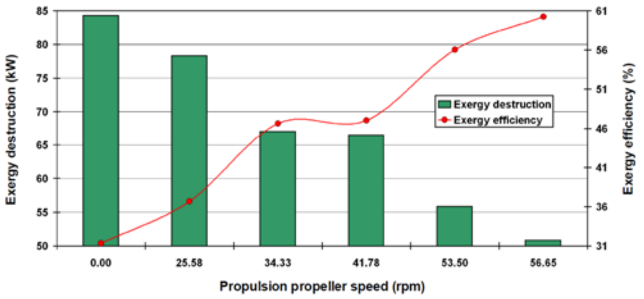

Fig. 7. *Change in pump exergy destruction and exergy efficiency for various pump loads*

5. Conclusions

The paper presents energy and exergy analysis of sea water pump which is used for the main condenser cooling at lower steam propulsion system loads on conventional LNG carrier.

By using the measured variables from the exploitation, it can be concluded that pump used power has a strong influence on pump cumulative exergy power input, while its influence on pump cumulative energy power input is minor, for the whole observed pump operation range.

Pump energy power losses and exergy destruction are reverse proportional to pump load. Increase in pump load also causes a continuous increase in both energy and exergy efficiencies. The highest pump energy efficiency amounts 59.61 %, while the highest pump exergy efficiency amounts 60.25 %. Increase in both efficiencies (and decrease in both power losses at the same time) will be possible if the pump operates at the highest possible loads, higher that presented ones from LNG carrier exploitation.

6. Acknowledgment

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NOMENCLATURE		**Greek symbols:**	
		ε	specific exergy, kJ/kg
Abbreviations:		η	efficiency, -
LNG	Liquefied Natural Gas		
		Subscripts:	
Latin Symbols:		0	ambient state
$\dot{E}$	stream flow power, kJ/s	c	cumulative
h	specific enthalpy, kJ/kg	D	destruction
$\dot{m}$	mass flow, kg/s or kg/h	en	energy
p	pressure, MPa	ex	exergy
P	power, kJ/s	IN	inlet
$\dot{Q}$	heat transfer, kJ/s	OUT	outlet
s	specific entropy, kJ/kg·K	PL	power loss
$\dot{X}_{heat}$	heat exergy transfer, kJ/s	sw	sea water
T	temperature, °C or K		
$\dot{V}$	volume flow, m^3/h		

7. References

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