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<th><strong>Chairman:</strong> Prof. DHC Georgi Popov</th>
<th><strong>Vice Chair:</strong> Prof. Dr. Eng. Tsanka Dikova</th>
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<td>BG</td>
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<td>Prof. Movlazade Vagif Zahid</td>
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<td>USA</td>
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<td>Prof. Yasar Pancar</td>
<td>TR</td>
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</tbody>
</table>
CONTENTS

SECTION MACHINES

ROTATIONAL MOTION OF TOWER CRANE - DYNAMIC ANALYSIS AND REGULATION USING SCHEMATIC MODELING
Prof.dr. Đoči Ilir, Prof.ass. Lajqi Shpetim ................................................................. 5

EFFECT OF BORONIZING PARAMETERS AND MATRIX STRUCTURES ON THE WEAR PROPERTY OF DUCTILE IRON
Ass. Prof. Dr. Toktaš A., Ass. Prof. Dr. Toktaš G., MSc. Mech. Eng. Gulişin K. ................................................................. 10

ERGONOMIC ASPECTS WHEN DESIGNING LUMINAIRES BASED ON LED LAMPS
Ass Prof. Vinogradov V.V., Ass Prof. Mokretsova L.O. ................................................................. 14

MODEL FOR DETERMINING THE STATIC LOAD ON MOVABLE SPATIAL CONSOLE LATTICE GIRDER BOUNDED WITH CLAMPS
Prof. Dr. Sc. Hristovska E., mech. eng., Assis. Prof. Dr. Sc. Sevde Stavrev, Prof. Dr. Sc. Vangelica Jovanovska, Assoc. Prof. Dr. Sc. Ivo Kuzmanov, Assoc. Prof. Dr. Sc. Zlatko Sovreski ................................................................. 20

CHANGE IN OPERATING PARAMETERS OF TURBOCHARGED DIRECT INJECTION DIESEL ENGINE DURING THE INJECTED FUEL MASS FLOW VARIATION
PhD. Mrzljak Vedran, PhD Student Eng. Poljak Igor, Student Žarković Božica ................................................................. 23

ENERGY EFFICIENCY AND ENERGY POWER LOSSES OF THE TURBOGENERATOR STEAM TURBINE FROM LNG CARRIER PROPULSION SYSTEM
PhD. Mrzljak Vedran, PhD. Senčić Tomislav, Prof. Prpić-Orsić Jasna ................................................................. 27

THE IMPACT OF THE CONSTRUCTIVE PARAMETERS OF THE BUMPER OVER THE CONSEQUENCES DERIVING FROM THE PROCESS OF COLLISION

EMBEDDED RESEARCHES ON ADAPTIVE PARAMETRIC MODELING OF HYDRAULIC GEAR PUMPS
Lecturer PhD. Eng. Ghionea Gabriel Ionuţ, Prof. PhD Eng. Opran Constantin Gheorghe, Lecturer PhD Eng. TARBA Cristian Ioan, PhD. Eng. Čuković Saša ................................................................. 35

THE TIMELESS DESIGN OR THE WELL DONE OLD
гл. ас. д-р Кремена Маркова ................................................................. 39

NUMERICAL SIMULATION ON THE VIBRATION OF A VEHICLE DRIVETRAIN WITH DUAL MASS FLYWHEEL
Assist. Prof. Eng. Pavlov N. PhD ................................................................. 42

KINETIC AND POWER ANALYSIS OF MULTI-STAGE PLANETARY GEARBOXES THROUGH THE TORQUE METHOD
Assoc. Prof. Dr. Karaivanov D., Velyanova M., Bakov V. ................................................................. 46

SECTION TECHNOLOGIES

ON THE APPLICATION OF FUNCTIONAL APPROACH TO CREATING AND PROVIDING OPERATIONAL CHARACTERISTICS OF ULTRALIGHT THERMAL PROTECTION OF REUSABLE LAUNCH SPACECRAFT

BUSINESS CLIMATE AND PRECONDITIONS FOR REVIVING THE BULGARIAN INDUSTRY
Mina Angelova, Valentina Nikolova-Alexieva ................................................................. 61

USING THE PLANNING PROCESS TO CONSTRUCTION MANAGEMENT OF THE IRRIGATION INFRASTRUCTURE
Assos. Prof. Eng. Banishka N. PhD., Eng. Vasilieva M. PhD St. ................................................................. 64

RESEARCH OF INTELLIGENT TRANSPORT SYSTEMS MANAGEMENT OF CONVOY OF UNMANNED VEHICLES WITH THE LEAD PILOT VEHICLE FOR WORK IN THE NORTH OF THE RUSSIAN FEDERATION IN THE ARCTIC AND ANTARCTIC
Dr.Sci.Tech, Saykin A., Ph.D., Endachev D., Ph.D., associate professor, Karpukhin K., Ph.D Kolbasov A. ................................................................. 67

DEPENDENCE OF THE ACTIVE POWER OF THE SERIAL RESONANT BRIDGE CONVERTER FROM THE PHASE DIFFERENCE AND THE DUTY CYCLE

PRECISE 3D CARTOGRAPHIC DESIGN USING BING-MAPS RESOURCES, 3D BLENDER AND THE SPECIALIZED BLENDERGIS-ADDON APPLICATION
Tihomir Dovramadjiev PhD ................................................................. 75

THE DEVELOPMENT OF CALIBRATION FOR THE ROLLING BALLS OF DIAMETER 40 MM IN CONDITIONS OF JSC "SSGPO"
D.t.s., professor Naizabekov A., c.t.s., associate professor Lezhnev S., Stepanov E., PhD Panin E. ................................................................. 77
MICROBIAL CLEANING OF MINE WATERS FOLLOWED BY ELECTRICITY GENERATION
Irena Spasova, Marina Nicolova, Plamen Georgiev, Stoyan Groudev, Veneta Groudeva ................................................................. 80

EXTRACTION OF PRECIOUS METALS FROM A PYRITIC CONCENTRATE PRETREATED BY MICROBIAL OXIDATION
Irena Spasova, Marina Nicolova, Plamen Georgiev, Stoyan Groudev ............................................................................................. 82

INFLUENCE OF GRID LAYOUT AND WHITE SPACE ON THE COMPOSITION OF WEB TYPOGRAPHY
gл. ас. д-р Илиев И. .................................................................................. 84

ADVANCED HYDROGEN STORAGE TECHNOLOGIES
Gjorgji Dosev, Nikola Sokolov, Assoc. Prof. Aleksandar Kostikj, PhD ......................................................................................... 87

THE INVESTIGATION OF THE NANORELIEFS OF OPTICAL ELEMENTS OF MEASURING INSTRUMENTS, WHICH
MODIFIED BY ELECTRON-BEAM MICROPROCESSING
Skoryna E., Medyanyk V., PhD. Bondarenko M., PhD Bondarenko I, PhD Bilokhin S., Prof. dr. eng. Antoniuk V. ................................. 90

THEORETICAL AND NUMERICAL ASPECTS REGARDING THE THERMOELASTIC BEHAVIOUR OF RUBBERLIKE
POLYMERS
M.Sc. Szüle V. .................................................................................................. 94

OPTIONS OF REAL TIME MONITORING METALWORKING FLUIDS
Ing. Jurina F., Prof. Dr. Ing. Peterka J. .................................................................... 98

CONTEMPORARY METHODS FOR OBTAINING NON-FERROUS AND RARE METALS FROM PRIMARY AND
TECHNOCENE RAW MATERIALS
Evgeni Petrov .................................................................................................. 102

MODELLING CONCEPTS FOR EFFICIENT PORT LOGISTICS MANAGEMENT
Senior Assistant Prof. PhD Varbanova A. ....................................................................... 107

EVALUATING THE IMPACT OF SECURITY MEASURES ON CONTAINER SUPPLY CHAINS
Senior Assistant Prof. PhD Varbanova A. ..................................................................... 110

ADMINISTRATIVE PROCESS MODELING: BASIC STRUCTURES AND MODELING
M.Sc. Trashlieva V., M.Sc. Radeva T. PhD ............................................................. 114

SECTION MATERIALS

NEW STEELS FOR METAL CONSTRUCTIONS IN THE DESIGN STANDARDS AND REGULATIONS
Vedyakov I.I. the Doctor of Technical Sciences, Professor, Odessky P.D. the Doctor of Technical Sciences, Professor, Gurov S.V. engineer,
Konina S.M. engineer ........................................................................................... 118

ION PLAZMA NITRIDING OF MECHANICAL PARTS
Ass. Jashari N. MSc, Prof. Dr Cvetkovski. S. PhD, Nacevski G. PhD. ................................................................. 124

SOFTWARE DEVELOPMENT FOR NUMERICAL SIMULATION OF FORMATTING THE PERIODIC NANOCONSTRUCTIONS
AFTER LASER IRRADIATION

STUDY OF STRUCTURE FORMATION AND HARDENING IN CARBON STEELS DURING HPT AT TEMPERATURES
BELOW RECRYSTALLIZATION
Dr.Sci. Raab G., Dr.Sci. Aleshin G., Kodirov I., Raab A. .................................................. 132

THE LABORATORY TESTING OF STEEL 20MnCr5
Opalčak I., mag.ing.mech., Marić A., dipl.ing., Hon.D.Sc. Dašić P., Prof. dr. sc. Marušić V. .......................................................... 136

EFFECTS OF MECHANOHERMAL TREATMENT OF ThO2 WITH UO2 AND CeO2
Assoc. Prof. P. Kovacheva PhD, Prof. D. Todorovsky DSc, M. Sc. N. Mirchev ............................................................................. 140

APPLICATION OF NONLINEAR CONTROLLED COOLING REGIMES FOR STRUCTURE FORMATION MANAGEMENT
IN EUTECTOID STEEL
Ph.D. Kaverinsky V., Prof., Dr.Sc. Trotsan A., eng. Sukhento Z., Prof., Dr.Sc. Bagliuk G. .................................................................. 144

A INVERSE PROBLEM IN ULTRASONIC TESTING AND MECHANICAL PROPERTIES OF POLYCRYSTALLINE
MATERIALS
Assoc. Prof, PhD. Alexander Popov, MSc Eng. Georgy Dobrev ......................................................................................... 146

MICROSTRUCTURAL EVOLUTION AND MECHANICAL PROPERTIES OF ALUMINUM IN THE PROCESS "PRESSING-
DRAWING"
Prof. dr. Nayzabekov A., Ass.prof. Lezhnev S., Ph.D. Volokitina I., Volokitin A. ................................................................. 148
ROBUST BI-CRITERIA APPROACH TO OPTIMIZE THE COMPOSITION AND PROPERTIES OF MAGNESIUM ALLOY
Yordan Kalev, Hai Hao, Nikolay Tontchev  .................................................................................................................. 151

THE IMPACT OF ELECTRIC FIELD DISTRIBUTION DURING Ti – AI – C SYSTEM BLEND PREPARATION ON PHYSICAL-
MECHANICAL PROPERTIES OF CONSOLIDATED MATERIALS
Prof., Dr. of Science Sizonenko O., PhD Zaichenko A., Lypian Ye., PhD Prystash M., Torpakov A., PhD Trehub V. ............................. 156

SOLIDIFICATION ON SURFACE.

МЕТОДИ И СРЕДСТВА ЗА ОПТИМИЗАЦИЯ НА ТЕХНОЛОГИЧНИ РЕЖИМИ ПРИ ЛЕЕНЕ ВЪЗ ОСНОВА НА
ЧИСЛЕНА СИМУЛАЦИЯ
Asst. Prof. Emil Yankov. PhD. ................................................................................................................................. 164

ТЕОРЕТИЧЕН АНАЛИЗ НА ПРОЦЕСА ХИДРАВЛИЧНО ИЗДУВАНЕ
Asst. Prof. Emil Yankov. Ph.D. ................................................................................................................................. 165
ENERGY EFFICIENCY AND ENERGY POWER LOSSES OF THE TURBO-GENERATOR STEAM TURBINE FROM LNG CARRIER PROPULSION SYSTEM

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Abstract: Turbo-generator (TG) steam turbine energy efficiency and energy power losses in a wide range of turbine loads were presented in this analysis. For TG steam turbine was investigated influence of steam specific entropy increment from the real (polytropic) steam expansion on energy power losses and energy efficiency. TG turbine energy power losses, during the all observed loads, were in the range from 646.1 kW to 685.5 kW. The most influenced parameter which defines change in TG turbine energy power losses is steam mass flow change, while for small steam mass flow changes, influence of steam specific entropy increment on steam turbine energy power losses is the most influential. Steam specific entropy incremental change can be used to estimate the change of TG steam turbine energy efficiency. Increase in steam specific entropy increment resulted with a decrease in TG turbine energy efficiency and vice versa. Analyzed steam turbine energy efficiency ranges from 53.84 % to 60.12 %, what is an expected range for low power steam turbines.

Keywords: TURBO-GENERATOR, STEAM TURBINE, ENERGY EFFICIENCY, ENERGY POWER LOSSES

1. Introduction

Marine steam turbine propulsion plants nowadays can be found in a number of LNG carriers [1]. Such steam propulsion plant consists of many constituent components [2] and one of them is turbo-generator (TG) which steam turbine is analyzed in this paper from the aspect of energy.

The analyzed LNG carrier has at disposal two identical turbo-generators which are designed to cover all ship requirements for electrical power. Each TG turbine has identical operating parameters (inlet and outlet temperatures, pressures and mass flows) and for the analysis is selected one of them. Steam turbine for each electric generator comprises of nine Rateau stages. Steam turbines with Rateau stages and their complete analysis can be found in [3]. Many details of the classic and special designs of marine steam turbines and their auxiliary systems are presented in [4] and [5].

The goal of the TG steam turbine analysis was to determine the specific entropy increment increase during steam expansion from the real exploitation for different steam turbine loads. Increase in steam specific entropy increment, usually indicate an increase in system energy power losses (in this analysis system is a TG steam turbine). It was examined the influence of steam specific entropy increment change on TG turbine energy power losses and energy efficiency change, at each observed operating point.

Main characteristics of the LNG carrier in which steam propulsion system is mounted analyzed turbo-generator are presented in Table 1.

Table 1. Main specifications of the LNG carrier

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dead weight tonnage</td>
<td>84,812 DWT</td>
</tr>
<tr>
<td>Overall length</td>
<td>288 m</td>
</tr>
<tr>
<td>Max breadth</td>
<td>44 m</td>
</tr>
<tr>
<td>Design draft</td>
<td>9.3 m</td>
</tr>
<tr>
<td>Propulsion turbine</td>
<td>Mitsubishi MS40-2 (max. power 29420 kW)</td>
</tr>
<tr>
<td>Turbo-generators</td>
<td>2 x Shinko RGA 92-2 (max. power 3850 kW each)</td>
</tr>
</tbody>
</table>

2. Equations for steam turbine energy analysis

2.1. General equations for the energy analysis

Energy analysis is defined by the first law of thermodynamics, which is related to the conservation of energy [6]. Mass and energy balance equations for a standard volume in steady state disregarding potential and kinetic energy can be expressed according to [7] and [8] as:

\[ \dot{m}_{\text{in}} = \dot{m}_{\text{out}} \] (1)

\[ \dot{Q} = \dot{m}_{\text{out}} h_{\text{out}} - \dot{m}_{\text{in}} h_{\text{in}} \] (2)

Energy power of a flow for any fluid stream can be calculated according to the equation [9]:

\[ \dot{E}_{\text{in}} = \dot{m} \cdot h \] (3)

Energy efficiency may take different forms depending on the type of the system. Usually, energy efficiency can be written as [10]:

\[ \eta_{\text{en}} = \frac{\text{Energy output}}{\text{Energy input}} \] (4)

2.2. Turbo-generator turbine energy efficiency and energy power losses

Steam turbine for each turbo-generator drive is condensing type and consists of nine Rateau stages [11]. Schematic view of steam turbine directly connected to an electric generator (the whole set of steam turbine and electric generator is called turbo-generator) is presented in Fig. 1. In Fig. 1 is also presented steam mass flow along with specific enthalpy and specific entropy at the steam turbine inlet and outlet.
where $P_{\text{TG,RE}}$ was obtained in (kW) when $m_{\text{TG}}$ in (kg/h) was placed in the equation (5). Steam mass flow through the TG turbine ($m_{\text{TG}}$) was measured component, while the developed real TG turbine power was calculated according to equation (5).

According to Fig. 1 and Fig. 3, $h_1$ is steam specific enthalpy at the turbine inlet, and $h_2$ is steam specific enthalpy at the turbine outlet after real (polytropic) expansion. Steam specific enthalpy at the turbine inlet was calculated from the measured pressure and temperature. Steam specific entropy at the turbine inlet $s_1$ was also calculated from measured steam pressure and temperature at the turbine inlet. Steam real specific enthalpy at the turbine outlet was calculated from the turbine power $P_{\text{TG,RE}}$ in (kW) and measured steam mass flow $m_{\text{TG}}$ in (kg/s) according to [12] by using an equation:

$$h_2 = h_1 - \frac{P_{\text{TG,RE}}}{m_{\text{TG}}} \quad (7)$$

The steam real specific entropy at the turbine outlet $s_2$ was calculated from steam real specific enthalpy at the turbine outlet $h_2$, calculated by using equation (7), and measured pressure at the turbine outlet.

Steam specific enthalpy after isentropic expansion $h_{2S}$ was calculated from the measured steam pressure at the turbine outlet $p_2$ and from known specific entropy at the turbine inlet $s_1$. Ideal isentropic expansion assumes no change in steam specific entropy ($s_1 = s_2S$), Fig. 3.

Steam specific enthalpy at the turbine inlet, steam specific enthalpy at the end of isentropic expansion and both steam specific entropies (at the turbine inlet and outlet) were calculated by using NIST REFPROP 8.0 software [13].

To proper described TG turbine energy power losses, in any steam turbine operating range, it must be known the real turbine developed power and isentropic power, which can be developed in the ideal situation (when the change in steam specific entropy does not occur). Isentropic steam turbine power, according to Fig. 3, should be calculated as:

$$P_{\text{TG,IS}} = m_{\text{TG}} \cdot (h_1 - h_{2S}) \quad (8)$$

Isentropic steam turbine power will always be higher than the real developed power, because of higher specific enthalpy difference (increment) during the isentropic expansion in comparison to the real polytrophic expansion.

Steam turbine (TG turbine) energy power losses can be calculated as:

$$E_{\text{TG,en,PL}} = P_{\text{TG,IS}} - P_{\text{TG,RE}} = m_{\text{TG}} \cdot (h_2 - h_{2S}) \quad (9)$$

Energy efficiency of TG steam turbine can be calculated according to [14] and [15] by using the following equation:

$$\eta_{\text{TG,fn}} = \frac{(h_1 - h_2)}{(h_1 - h_{2S})} = \frac{P_{\text{TG,RE}}}{P_{\text{TG,IS}}} \quad (10)$$

3. Measurement results and measuring equipment of the analyzed TG steam turbine

Measurement results of required operating parameters for TG turbine are presented in relation to the propulsion propeller speed. Table 2. Propulsion propeller speed is directly proportional to steam system loads and vice versa.

### Table 2. Measurement results for TG turbine

<table>
<thead>
<tr>
<th>Propulsion propeller speed (rpm)</th>
<th>Steam pressure at the TG turbine inlet (MPa)</th>
<th>Steam temperature at the TG turbine inlet (°C)</th>
<th>Steam pressure at the TG turbine outlet (MPa)</th>
<th>Steam temperature at the TG turbine outlet (°C)</th>
<th>Steam mass flow through the TG turbine (kg/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>25.00</td>
<td>6.21</td>
<td>491.0</td>
<td>0.00541</td>
<td>4648.83</td>
<td></td>
</tr>
<tr>
<td>41.78</td>
<td>6.22</td>
<td>491.0</td>
<td>0.00489</td>
<td>4556.16</td>
<td></td>
</tr>
<tr>
<td>56.65</td>
<td>5.97</td>
<td>490.5</td>
<td>0.00425</td>
<td>4000.58</td>
<td></td>
</tr>
<tr>
<td>65.10</td>
<td>6.07</td>
<td>491.0</td>
<td>0.00392</td>
<td>3838.78</td>
<td></td>
</tr>
<tr>
<td>70.37</td>
<td>6.07</td>
<td>502.5</td>
<td>0.00397</td>
<td>3778.91</td>
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</tr>
<tr>
<td>76.56</td>
<td>6.01</td>
<td>504.5</td>
<td>0.00420</td>
<td>4070.84</td>
<td></td>
</tr>
<tr>
<td>80.44</td>
<td>5.89</td>
<td>501.5</td>
<td>0.00554</td>
<td>4689.03</td>
<td></td>
</tr>
<tr>
<td>83.00</td>
<td>5.90</td>
<td>493.5</td>
<td>0.00561</td>
<td>4487.93</td>
<td></td>
</tr>
</tbody>
</table>

All the measurement results were obtained from the existing measuring equipment mounted on the TG turbine inlet and outlet. List of all used measuring equipment was presented in the Table 3.

### Table 3. Used measuring equipment for the TG turbine analysis

| Steam temperature (TG inlet) | Greisinger GT101-Pt100, Immersion probe [16] |
| Steam pressure (TG inlet)    | Yamatake JTD980A, Pressure Transmitter [17]  |
| Steam pressure (TG outlet)   | Yamatake JTD910A, Pressure Transmitter [18]  |
| Steam mass flow (TG inlet)   | Yamatake JTD960A, Pressure Transmitter [18]  |
| Propulsion propeller speed   | Kyma Shaft Power Meter, (KPM-PFS) [19]       |
Steam specific entropy difference (increment) between the inlet and outlet of the TG steam turbine is presented in Fig. 4 for all the observed steam system loads. As the steam specific entropy at a TG turbine inlet is almost constant during the all propulsion propeller speeds, specific entropy increment is the most influenced by steam specific entropy at the TG turbine outlet.

From the lowest to the highest observed propulsion propeller speeds, TG turbine steam specific entropy increment (difference) firstly increases from 1.69 kJ/kg·K at 25.00 rpm up to 2.02 kJ/kg·K at propulsion propeller speed of 70.37 rpm, after which decreases to the lowest value of 1.69 kJ/kg·K at 83.00 rpm.

Increase in steam specific entropy increment, usually indicates an increase in system energy power losses, for a large number of different systems [14]. It will be interesting to analyze does the same conclusion is valid for the TG steam turbine.

Steam specific entropy difference (increment) between the inlet and outlet along with specific entropy difference (increment) between inlet and outlet are influenced by steam specific entropy. TG real power is the power developed according to real measured operating parameters in the LNG carrier propulsion system during navigation.

In the whole range of observed steam system loads, isentropic TG turbine power varies from 1423 kW up to 1711 kW, while in the same load range real TG turbine power varies from 766 kW up to 1025.5 kW. The real TG turbine power depends on the current need for electricity and it changes depending on the inclusion or exclusion of the individual electrical consumers. The difference in isentropic and real TG turbine power represents energy power losses of the real TG steam turbine process in comparison with ideal one.

Steam specific entropy increment reduces available steam specific enthalpy difference which will be used in steam turbine. As a result, increase in steam specific entropy increment will cause a decrease in real developed steam turbine power. From Fig. 4 and Fig. 6 can be seen that the change in TG turbine specific entropy increment does not have the most significant influence on TG steam turbine energy power losses. For example, between propulsion propeller speed of 41.78 rpm and 56.65 rpm, steam specific entropy increment increases, Fig. 4, while for the same propulsion propeller speeds TG turbine energy power loss decreases, Fig. 6. The same occurrence is visible between propulsion propeller speeds of 76.56 rpm and 80.44 rpm when steam specific entropy increment decreases while for the same propulsion propeller speeds TG turbine energy power loss increases.

The most significant influence on TG steam turbine energy power losses has steam mass flow through the turbine. In general, increase in steam mass flow will increase TG turbine energy power losses, while a decrease in steam mass flow will decrease TG turbine energy power losses. TG steam turbine energy power losses, between some observed operating points, during a small change in steam mass flow are also influenced by steam specific entropy increment.

Between propulsion propeller speed of 41.78 rpm and 56.65 rpm, TG turbine energy power losses decrease, Fig. 6, because of a noticeable decrease in steam mass flow from 4556.16 kg/h to 4000.58 kg/h, Table 2. Increase in steam specific entropy increment between these two propulsion propeller speeds does not have significant influence on energy power losses change, Fig. 4.

Also, between propulsion propeller speeds of 76.56 rpm and 80.44 rpm TG turbine energy power losses increases, Fig. 6, because of noticeable increase in steam mass flow from 4070.84 kg/h to 4689.03 kg/h, Table 2, regardless of steam specific entropy increment noticeable decrease, Fig. 4.

On the other side, for a small change in steam mass flow, steam specific entropy increment can have an important influence on TG turbine energy power losses change. When compared propulsion propeller speeds of 65.10 rpm and 70.37 rpm, steam mass flow decreases from 3838.78 kg/h to 3778.91 kg/h, Table 2, but this steam mass flow decrease does not cause a decrease in TG turbine energy power losses, Fig. 6. Between these two propulsion propeller speeds, increase in TG turbine energy power losses occurs because of a notable increase in steam specific entropy increment, Fig. 4.

Final conclusion which can be derived is that the most influenced parameter on TG turbine energy power losses is steam mass flow. For a small change in steam mass flow, steam specific entropy increment takes a leading role in affecting the change of TG turbine energy power losses.

Steam specific entropy increment can be used as an essential parameter for evaluation of TG steam turbine energy efficiency change. During the increase in steam specific entropy increment, TG turbine energy efficiency decreases and during the decrease in steam specific entropy increment, TG turbine energy efficiency increases. This conclusion is valid for every two observed propulsion propeller speeds, during the whole investigated TG turbine load range, Fig. 4 and Fig. 7.

The highest TG turbine energy efficiency of 60.12% was obtained for the lowest steam specific entropy increment of 1.69
kJ/kg·K at the propulsion propeller speed of 25.00 rpm (the lowest observed TG turbine load), Fig. 7. The lowest TG turbine energy efficiency of 53.84 % was obtained for the highest steam specific entropy increment of 2.02 kJ/kg·K at the propulsion propeller speed of 70.37 rpm.

The analyzed TG steam turbine is a low power steam turbine. Its energy efficiency, for the observed loads, ranges from 53.84 % to 60.12 %, which is an expected range of energy efficiency for low power steam turbine in general [9].

### 6. Acknowledgment

The authors would like to extend their appreciations to the main ship-owner office for concealing measuring equipment and for all help during the exploitation measurements. This work was supported by the University of Rijeka (contract no. 13.09.1.1.05) and Croatian Science Foundation-project 8722.

### 7. References


### NOMENCLATURE

<table>
<thead>
<tr>
<th>Abbreviations:</th>
<th>Greek symbols:</th>
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<tbody>
<tr>
<td>LNG</td>
<td>η</td>
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<td>Turbo generator</td>
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<table>
<thead>
<tr>
<th>Latin Symbols:</th>
<th>Subscripts:</th>
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<tr>
<td>δ</td>
<td>energy</td>
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<td>h</td>
<td>inlet</td>
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<td>m</td>
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<td>Q</td>
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<td>s</td>
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**Fig. 7.** TG turbine energy efficiency change in all observed propulsion propeller speeds

5. Conclusions

This paper presents an analysis of energy efficiency and energy power losses for low power steam turbine, in a wide range of turbine loads. For the analyzed TG steam turbine was investigated influence of steam specific entropy increment from the real (polytropic) expansion process on energy power losses and energy efficiency.

TG steam turbine energy power losses were calculated as a difference between steam turbine real developed power (polytropic steam expansion) and power which can be developed in an ideal situation without any specific entropy increment (isentropic steam expansion). It was found that TG turbine energy power losses, during the all observed loads, were in the range from 646.1 kW to 685.5 kW. Steam specific entropy increment does not have a major influence on TG turbine energy power losses change in general, but for small steam mass flow change, influence of steam specific entropy increment on steam turbine energy power losses is dominant. The most influenced parameter which defines change in TG turbine energy power losses is steam mass flow - increase in steam mass flow caused an increase in TG turbine energy power losses and vice versa.

Steam specific entropy increment change can be used to estimate the change of TG steam turbine energy efficiency. Increase in steam specific entropy increment resulted with a decrease in TG turbine energy efficiency and decrease in steam specific entropy increment resulted with an increase in TG turbine energy efficiency.