УДК 621.6
DOI https://doi.org/10.15589/znp2023.2-3(491-492).10

POLAR SHIP PROPULSION SYSTEMS WITH THERMO-CHEMICAL RECUPERATION OF WASTE HEAT FOR LNG CARRIERS

ПРОПУЛЬСИВНІ УСТАНОВКИ СУДЕН ГАЗОВОЗІВ ЛЬОДОВОГО КЛАСУ З ТЕРМОХІМІЧНОЮ УТИЛІЗАЦІЄЮ ТЕПЛОТИ

Oleksandr K. Cherednichenko
oleksandr.cherednichenko@nuos.edu.ua
ORCID: 0000-0001-5745-8117

Natalya V. Korobyeynikova
natalya.korobeinikova@nuos.edu.ua

Oleg Yu. Basov
olegbasov39@gmail.com

О. К. Чередніченко,
докт. техн. наук, професор

Н. В. Коробєйнікова,
асистент

О. Ю. Басов,
аспірант

Admiral Makarov National University of Shipbuilding, Mykolaiv
Національний університет кораблебудування імені адмірала Макарова, м. Миколаїв

Abstract. The share of LNG carriers is growing every year, so the use of liquefied natural gas as a fuel for engines is steadily increasing. The article analyzes the current trends in the development of marine energy. Consideration was given to the specific features of the transportation of liquefied natural gas by gas tankers, which allow reducing the loss of natural gas during transportation and reducing the negative impact on the environment. One of the basic ways to reduce polluting emissions of ship power plants is application of innovative devices for on-board energy generation by means of secondary energy resources. The aim of the article is to determine the prospects for the use of secondary energy resources of marine dual-fuel engines running on liquid petroleum fuel and natural gas. The metal hydride units of a continuous action and the combined gas turbine and diesel engine plant with thermo-chemical recuperation of the heat of secondary energy resources has been considered. The potentials of waste heat from secondary energy sources of a gas turbine engine and a medium-speed four-stroke diesel engine are compared. It is proposed to study the analysis of changes in the specific consumption of liquefied natural gas in the installations of a combined gas turbine-electric and diesel-electric power plant with thermochemical utilization of exhaust gas heat by steam conversion of natural gas or cargo evaporation products when it operates on synthesis gas of different composition using mathematical modeling methods. The results of mathematical modeling of processes in a power plant with thermochemical utilization of exhaust gas heat by converting hydrocarbon fuel allow us to draw conclusions about the prospects and efficiency of using these plants to increase the energy efficiency index on gas carriers.
Key words: thermo-chemical recuperation; gas turbine engine; liquefied natural gas; LNG carrier; mathematical modeling.

Анотація. С кожним роком частка суден газовозів зростає, тому невпинно збільшується використання зрідженого природного газу в якості палива для двигунів. В статті проаналізовано сучасні тенденції розвитку суднової енергетики. Розглянуто особливості транспортування зрідженого природного газу танкерами-газовозами, які дозволяють зменшити втрати природного газу при транспортуванні та зменшити негативний вплив на навколишнє середовище. Одним з основних шляхів зниження шкідливих викидів суднових енергетичних установок є застосування інноваційних пристроїв для виробництва енергії на борту судна за рахунок вторинних енергоресурсів. Метою статті є визначення перспективи використання вторинних енергетичних ресурсів суднових двопаливних двигунів, які працюють на рідкому нафтовому паливі та природному газі. Розглянуто металогідридні установки безперервної дії та комбіновану газотурбінно-дизельну установку з термохімічною утилізацією теплоти вторинних енергоресурсів. Порівняно потенціали скидного тепла вторинних енергоресурсів газотурбінного двигуна та середньообортового чотиритактного дизельного двигуна. Дослідження аналізу зміни питомої витрати зрідженого природного газу в установках комбінованої газотурбінно-електричної та дизель-електричної електростанцій з термохімічною утилізацією теплоти відпрацьованих газів шляхом парової конверсії природного газу або продуктів випаровування вантажу при їх роботі на синтез-газі різного складу запропоновано проводити за допомогою методів математичного моделювання. Наведені результати математич-

ного моделювання процесів в енергетичній установці з термохімічною утилізацією теплоти відпрацьованих газів шляхом перетворення вуглеводневого палива, дозволяють зробити висновки щодо перспективності та ефективності використання даних установок для підвищення індексу енергетичної ефективності на суднах газовозах

Ключові слова: термохімічна рекуперація; газотурбінний двигун; скраплений природний газ; газовоз; математичне моделювання

OBJECTIVE

World primary energy production grows at 1.5 % per annum from 2012 to 2035. The annual analytical reports of the U.S. Energy Information Administration (EIA) provide comparative long-term forecasts for 2013 and 2019 (Fig. 1)[1, 2]. The EIA conducts its research using the World Energy Outlook System (WEPS+), an integrated economic model that captures the long-term relationships between energy supply, demand, and prices in regions under various assumptions. It should be noted that energy market forecasts are uncertain, as events shaping future changes in technology, demographic changes, economic trends, and resource availability are dynamic and multidirectional. Forecasts do not include the impact of certain possible future changes, such as changes in national borders and international agreements, disruptive geopolitical or economic events, the emergence of disruptive technologies, changes in existing policies, etc. A good illustration of this is the catastrophic collapse of oil prices in the first quarter of 2020 due to the impact of the coronavirus epidemic on the global economy and the "gas crisis" in Europe following Russia's full-scale military invasion of Ukraine.

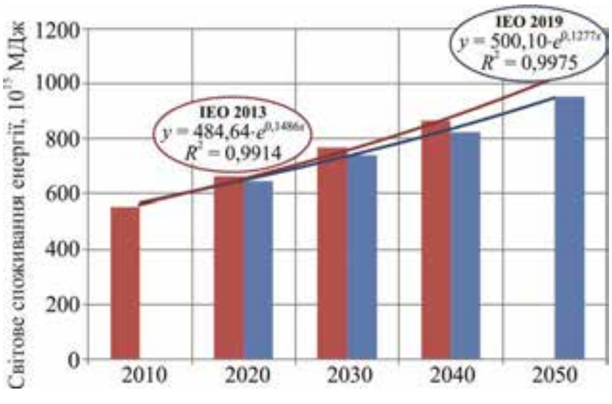


Fig. 1. Forecast of total global energy consumption

The share of total gas consumption grows from 31% in 2012 to 34% in 2035.

An assessment of the current situation on the natural gas market (volumes and traffic flows), taking into account the current geography of exporters and importers, and analyzing the technological level of transportation methods, reveals that the priority is given to pipeline and liquefied natural gas transportation technologies. This conclusion is confirmed by the forecasts of reputable energy market experts.

ANALYSIS OF RECENT RESEARCH AND PUBLICATIONS

Over the past 11 years (2012 – 2022), Australia and the United States have led the growth of global LNG capacity, adding 75% of the total increase in global capacity over this period [3].

Russia's energy projects in the Arctic face a bleak future after sanctions were imposed on the country following its invasion of Ukraine.[4] For example, Russia's LNG export project, Arctic LNG 2, which began in 2017, has been postponed and is now targeting 2023-2026 to launch three LNG lines [3].

At the same time, the production capacity of LNG plants on the Arctic coast of Canada is increasing. Thus, Shell's giant LNG Canada project is almost 85 percent complete and is scheduled to ship its first cargoes by mid-decade. The first phase of the LNG Canada project has been completed, which included the construction of two liquefaction units with a capacity of 14 million tons per year. In addition to Shell, other partners of Canada's first LNG export terminal include Malaysia's Petronas, PetroChina, Japan's Mitsubishi Corporation and South Korea's Kogas, and the main contractor for the project is JGC Fluor [5].

According to forecasts, by 2035, almost half of the volume of natural gas (Figure 2) will be transported in the form of liquefied natural gas (LNG) by ships – LNG carriers, sometimes called "floating pipelines".[6] LNG plants and LNG cargo terminals are located on all continents except Antarctica.

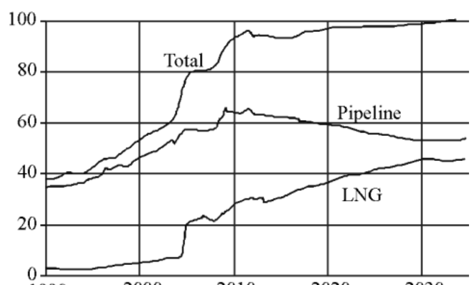


Fig. 2. Distribution of the methods of natural gas transportation

BASIC MATERIAL

The ice class LNG carriers will have independent icebreaking capabilities that enable them to sail in ice seas.

The ice class LNG carriers will be capable of transporting LNG from float LNG plants at gas fields to main

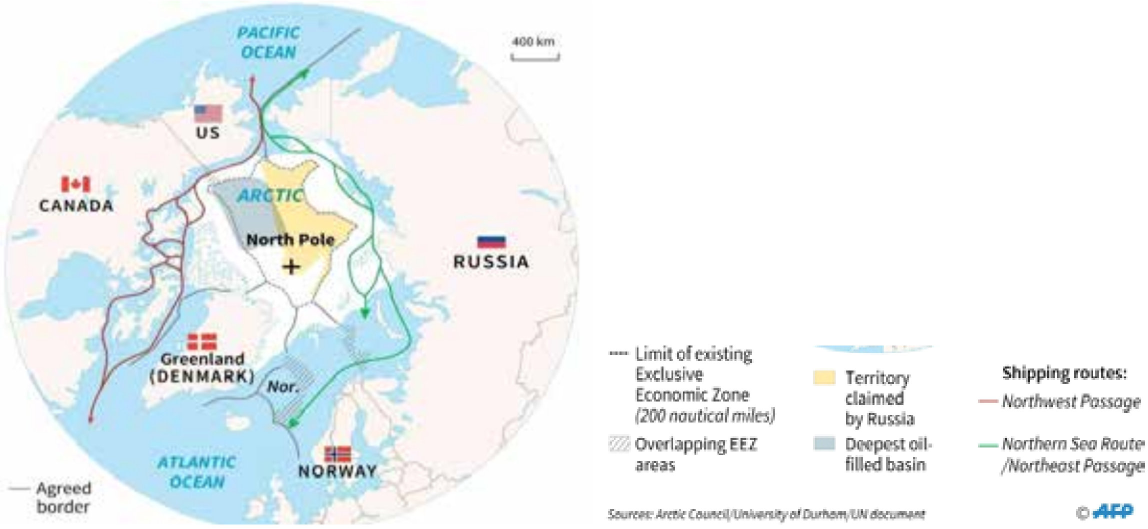


Fig. 3. Shipping routes in Arctic Ocean

Fig. 4. Siemens Energy's Ocean Green LNG carrier

LNG markets in the world. During summer period, the carriers will also be able to independently sail on Northern Sea Route and Northwest Passage to transport LNG.

Now more 705 LNG carriers were in service and order book includes 216 ships [7].

The size an LNG carrier is based on its obtainable volumetric capacity of liquid natural gas in m^3. The standard size for an LNG carrier has traditionally been 155,000 m^3, but the 31 Q-flex and 14 Q-max ships that were built over the 2007-2010 period, have capacity at 216,000 m^3 and 266,000 m^3, respectively.

Traditionally, first LNG carriers have been propelled by steam turbine. As of mid-2014 year 274 steam-powered LNG carriers were in service, however of the ships on order as of mid-2007 only 40% have steam turbine propulsion, in order on 1 July 2014 there were 8 % of such ships (Fig. 5).

Today there are very various proposals of the propulsion systems for LNG. The most widely used are DFDE propulsion systems (more 80%).

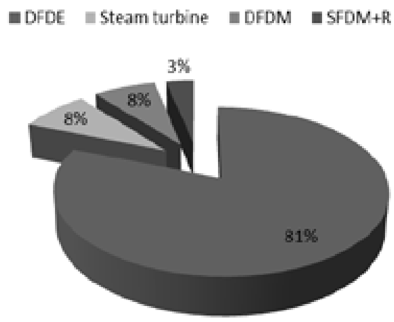


Fig. 5. Propulsion systems for LNG carriers

The gas evaporating during the LNG transportation is commonly referred to as Boil-off Gas (BOG). According to the data presented by Głomski [8], about 0.1-0.2% of the volume of the transported cargo evaporates daily. The BOG can be used as a fuel for the power plant [9, 10, 11, 12, 13] (Fig. 6, 7).

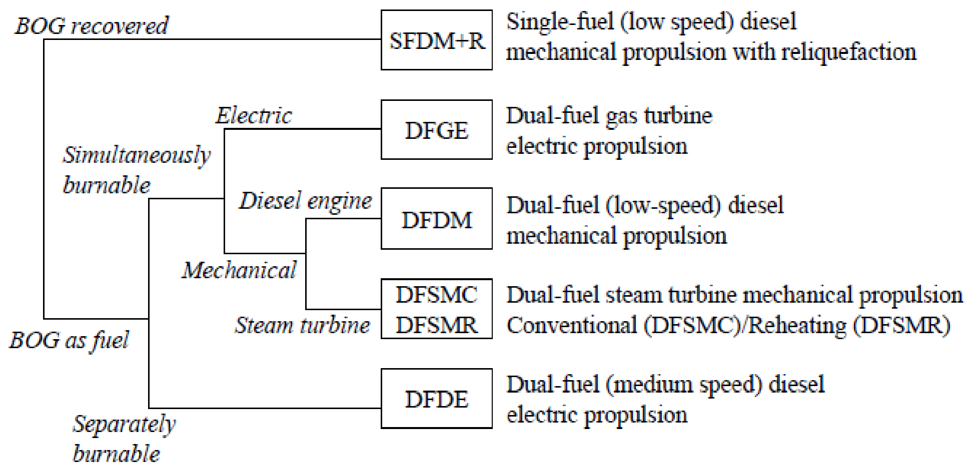


Fig. 6. Propulsion systems for LNG

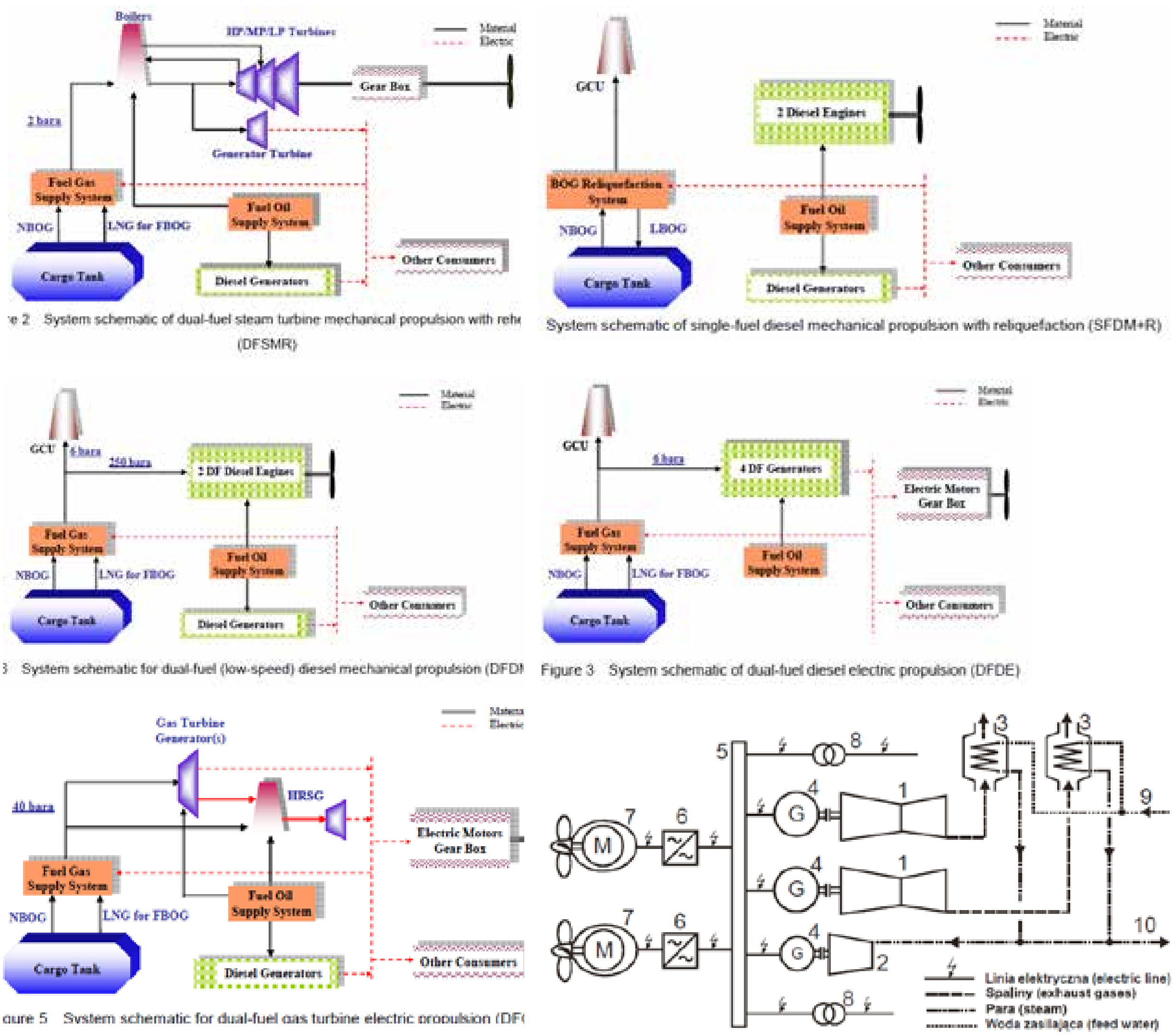
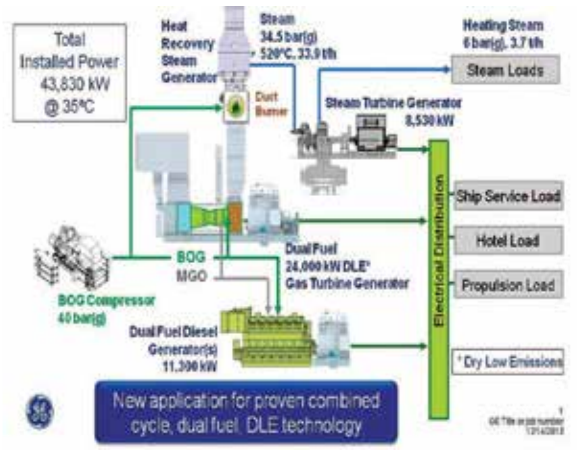


Fig. 7. Configurations of the propulsion plants for LNG carriers

The publication of Dzida [14] considers the GOGES power plants with the power of 40-50 MW for a LNG carrier with the cargo capacity of 266,000 m^3. The GOGES plant based on 4 GTEs Cyclone SGT 400 and a steam turbine waste-heat loop with two-pressure boilers has the efficiency of 50.7%.

The generated power of the steam turbine waste-heat loop is 49% of the total plant power, which raises some doubts about feasibility of such a configuration in the ship's conditions.



GE Marine, Dalian Shipbuilding Industry Company (DSIC) and Lloyd's Register have collaborated on the project of the COGES (combined gas turbine and steam with Electric propulsion) plant for 174,000 m^3 of the LNG carrier.

The plant includes one 30 MW gas turbine engine, one heat utilization turbine generator, and two dual-fuel diesel generators for operation on the low power consumption modes, and as a power reserve (Fig. 8). The main advantage of the plant is reduction of polluting emissions, improvement of the mass-dimensional parameters, and reliability. Fuel consumption for the DFDE and COGES plants is approximately the same [15, 16].

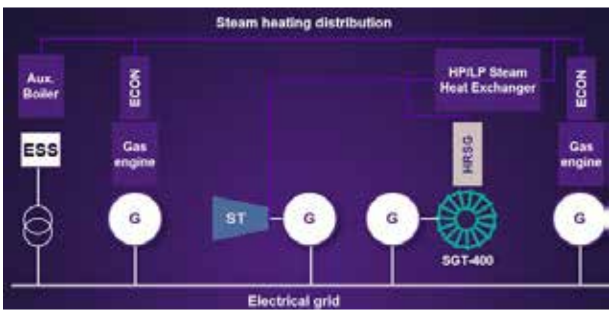


Fig. 8. The thermo-chemical recuperation (TCR) is the promising way of waste heat recovery of heat engine

Siemens Energy has developed the Ocean Green concept, a new low-emission power and propulsion system for deepwater shipping, particularly for LNG tankers. Ocean Green is a new and innovative hybrid combined cycle power plant that uses a gas turbine as the main engine in combination with a steam turbine and energy storage for electric propulsion and distribution system.

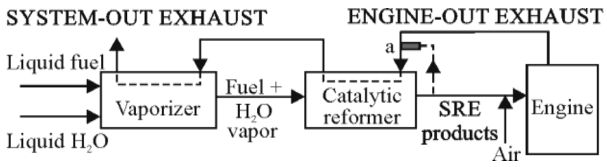


Fig. 9. Heat engine with thermo-chemical recuperation [17]

A substantial part of fuel energy introduced to heat engine is recovered with the engine exhaust gases. The energy of the exhaust gases can be used to provide endothermic reactions of hydrocarbon fuel transformation. The exhaust gases are directed into the chemical reformer and then into the vaporizer. The reformed fuel gas is used in the heat engine. Comparing the synthesis gas to the base hydrocarbon fuel, the fuel calorific value is increased.

Hydrocarbon fuel can be converted into hydrogen-containing gas through steam reforming. If using methane, after absorbing heat in the reformer, the methane reacts with the steam according to the following reactions:

$$CH_4 + H_2O \rightarrow CO + 3H_2$$

$$(\Delta h = 206.2 \text{ kJ/ mol } CH_4);$$

$$CO + H_2O \rightarrow CO_2 + H_2 \ (\Delta h = -41.17 \text{ kJ/ mol CO}).$$

The main factors that affect the efficiency of a power plant with TCR are as follows:

– temperature potential of the flows of the waste heat energy sources in engines;

– dependence of change in the rate of increase of the base fuel calorific value on the reaction temperature;

– heat input of the exhaust gas necessary for fuel conversion.

Of special interest is the analysis of the temperature potentials of waste heat in such basic energy-converting machinery as a medium speed four-stroke diesel engine (4SDE) and a gas turbine engine (GT).

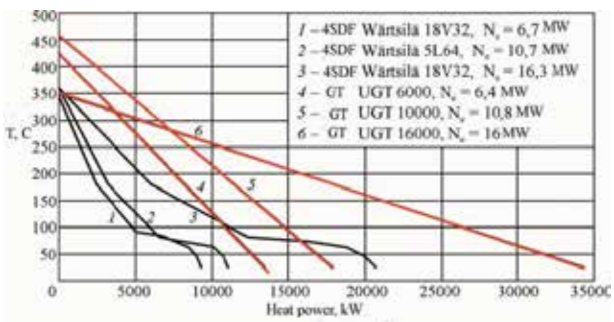


Fig. 10. Comparison of waste heat potentials of secondary energy sources of the GT and 4SDF

For the available temperature range of exhaust gases of the modern series-production gas turbine engine (up to 450°C) conversion is efficient.

Analysis of the results of calculation of the GT and 4SDE waste heat potentials shows the prospects of using a combined gas turbine-electric and diesel-electric power plant with thermo-chemical recuperation of the exhaust gases heat by means of steam conversion of natural gas or the cargo evaporation products (COGED+TCR).

The COGED+TCR 45 MW propulsion plant for a ice class LNG carrier was considered to comprise the gas turbine engine Siemens SGT 400 and three medium speed engines Wärtsilä 5L64.

The aim of the study is the high-level analysis of interrelations between thermodynamic parameters of the gas turbine plant with thermo chemical heat recuperation and characteristics of the Diesel engine that runs on the products of the gas conversion. A gas turbine engine with thermo-chemical recuperation (CRGT) is based on steam conversion of a hydrocarbon fuel by means of recuperation of the exhaust gases heat. The developed ASPEN Plus turbine blade-cooling model was incorporated into the simulation model (Fig.12).

The thermo-chemical reactor is modeled as an equilibrium reactor defined by the condition of minimization of the Gibbs free energy and taking into account the chemical and phase equilibrium.

Table 1. Parameters of the gas turbine Siemens SGT 400 used in the COGED+TCR propulsion plant

Parameters	**Value**
Number of compressors	1
Number of turbines	2
Turbine inlet temperature, T_3	1251°C
Compressor pressure ratio, $\pi_к$	16.8
Exhaust gas flow, G_{gas}	39.4 kg/s
Exhaust temperature, T_4	555°C
Power generation, N_e	12.9 MW
Efficiency	34.8%

The presented internal combustion engine model in the ASPEN Plus includes: substance flows of fuel, air and gas, flow mixers, turbochargers, intermediate charge air coolers, expansion unit, compression unit and reactor. A turbine (or expansion block) is used to simulate expansion processes in cylinders; a compressor is used for compression processes modeling, and combustion processes are modeled in the reactor.

The LNG composition varies substantially, which affects the conversion efficiency.

The method of mathematical modeling was applied to analyze the change in the specific consumption of LNG in the COGED+TCR during its operation on the convertible synthesis gas of various compositions.

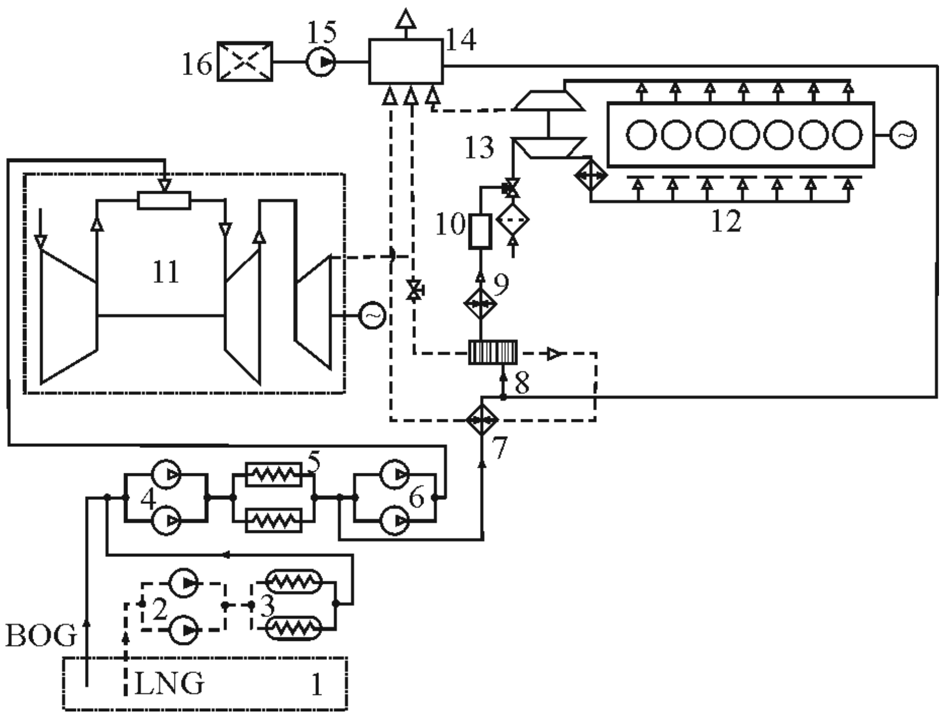


Fig. 11. Combined diesel-gas turbine power plant with the thermo-chemical heat recovery

1. LNG tank; 2. LNG pumps; 3. LNG vaporizer; 4. LP compressor; 5. preheater; 6. HP compressor; 7. heat recovery preheater; 8. thermo-chemical reactor; 9. synthesis gas cooler; 10. neutralization tank; 11. gas turbine; 12. diesel engine; 13. turbocharger; 14. heat recovery steam generator; 15. water pump; 16. water tank

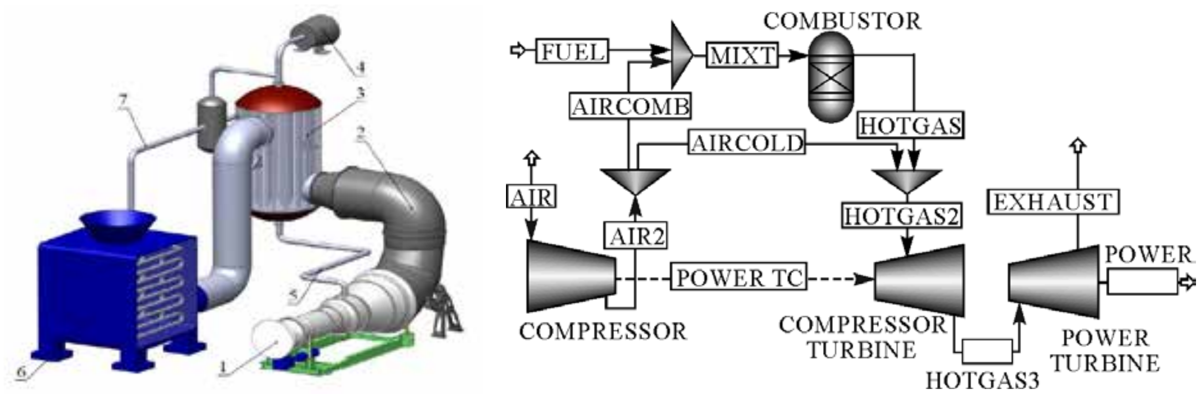


Fig. 12. ASPEN Plus turbine blade-cooling model

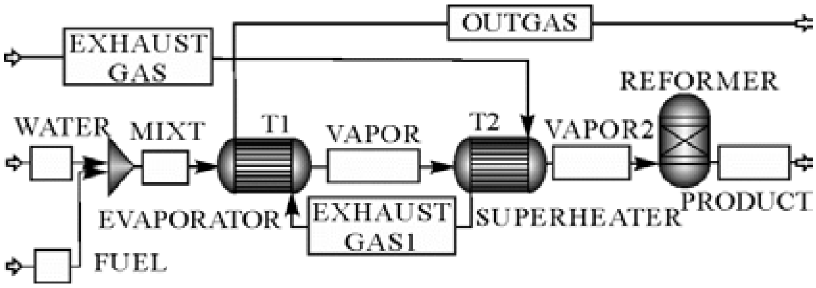


Fig. 13. ASPEN Plus three-section thermo-chemical reactor model

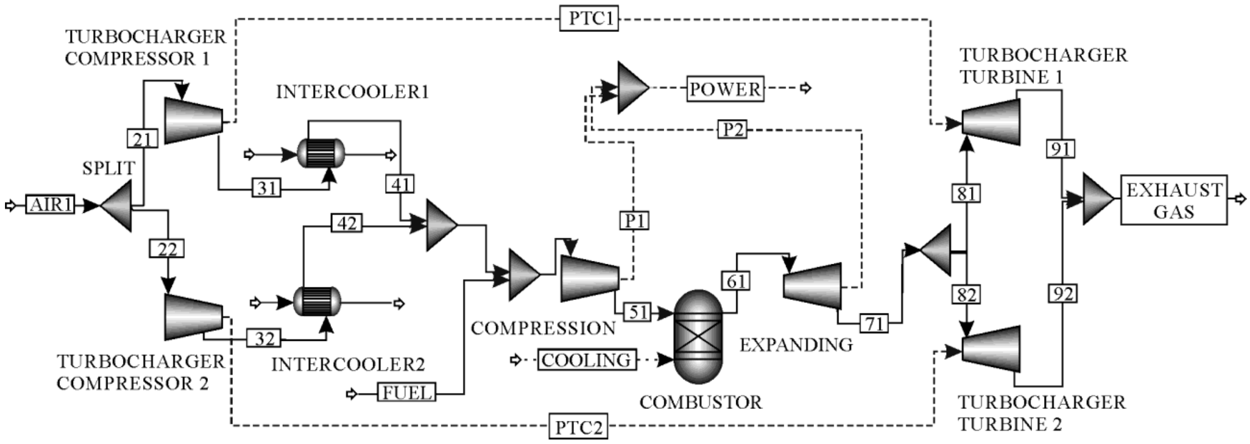


Fig. 14. ASPEN Plus internal combustion engine model

Table 2. LNG classification based on density

Parameter	LNG		
	Light	**Medium**	**Heavy**
Density, kg/m^3	427.7	445.7	464.8
Composition;% Methane (CH_4)	98.0	92.0	87.0
Ethane (C_2H_6)	1.4	6.0	9.5
Propane (C_3H_8)	0.4	1.0	2.5
Butane (C_4H_{10})	0.1	0.0	0.5
Nitrogen (N_2)	0.1	1.0	0.5

The following two variants were considered:

Variant 1. The GT operates on natural gas, while the 4SDE runs on the convertible synthesis gas.

Variant 2. Simultaneous operation of the GT and 4SDE on the convertible synthesis gas. More efficient plant operation on the Heavy LNG is caused by high content of ethane in gas of this type. In this conversion temperature range (500-550°C), the increase in calorific value of the ethane conversion products is three times higher than that of methane

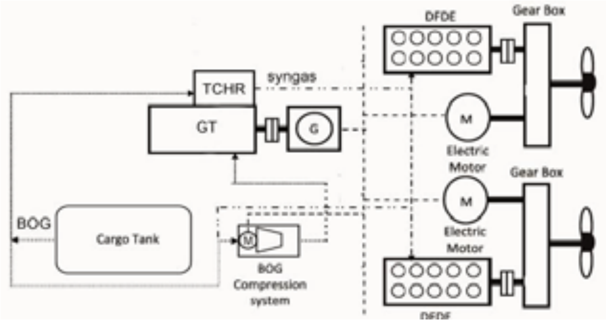


Fig. 15. COGED+TCR ship power plants

DISCUSSION OF THE RESULTS

According to the requirements of Chapter 4 of MARPOL Annex VI, the Energy Efficiency Design Index (EEDI) is a mandatory mechanism of the energy efficiency standard for ships. The attained EEDI is a measure of a ship's energy efficiency determined as follows [18, 19]:

$$EEDI = \frac{CO_2 \text{emission}}{\text{Transport\_work}}.$$

The values of the attained EEDI for the simulated variants and the base variant are compared. The basic version is the single fuel low speed Diesel engine with the system for re-liquefying the evaporated cargo.

Table 3. Analysis of the effectiveness of the COGED+TCR ship power system

Type of power plant	Type of LNG		
	Light	Medium	Heavy
	Plant efficiency, %		
COGED without TCR	44.0		
COGED + TCR, var. 1	46.5	46.7	46.7
COGED + TCR, var. 2	48.2	48.5	48.9

The calculations show a significant (by 35-38%) reduction in the Energy Efficiency Design Index.

The EEDI values obtained correspond to IMO requirements, which will take effect on January 1, 2025.

CONCLUSIONS

The results of mathematical modeling of the characteristics of diesel and gas turbine power plants with thermo-chemical heat recovery of the gas turbine exhaust gases heat by means of hydrocarbon fuel converting show possibilities for reducing fuel consumption in the diesel engine up to 20%.

The gas turbine waste heat can provide efficient conversion of hydrocarbon fuels at the ratio of the powers a diesel engine and a gas turbine engine being up to 6.

The obtained theoretical results concerning the working processes in the combined diesel and gas turbine plants with TCR show that simultaneous operation of the diesel and gas turbine engines on the LNG vapor conversion products increases the efficiency coefficient of the plant by 4–5%.

REFERENCES

[1] Alves LG, Nebra SA (2003). Thermoeconomic Evaluation of a Basic Optimized Chemically Recuperated Gas Turbine Cycle. *Int.J. Thermodynamics*, Vol.6 (No.1), pp.13-22

[2] Benito A (2009). Accurate determination of LNG quality unloaded in Receiving Terminals An Innovative Approach. *IGU*. Buenos Aires. 1–23.

[3] Hydrocarbon Engineering (2023) Growth in global LNG export capacity will be limited in 2023. Retrieved from: https://www.hydrocarbonengineering.com/gas-processing/03022023/growth-in-global-lng-export-capacity-will-be-limited-in-2023 [in England]

[4] The Diplomat (2023) What Does Russia's Invasion of Ukraine Mean for China in the Arctic? Retrieved from: https://thediplomat.com/2022/03/what-does-russias-invasion-of-ukraine-mean-for-china-in-the-arctic/ [in Asia]

[5] LNGPrime The World Premier LNG Platform.(2023) LNG Canada terminal almost 85 percent complete. Retrieved from: https://lngprime.com/lng-terminals/lng-canada-terminal-almost-85-percent-complete/85669/ [in Bosnia and Herzegovina]

[6] BP Energy Outlook 2035 (2016).

[7] International Gas Union (IGU) 44 Southampton Buildings WC2A 1AP London United Kingdom (2022) WORLD LNG REPORT.71

[8] Głomski P, Michalski R (2011). Problems with Determination of Evaporation Rate and Properties of Boil-off Gas on Board LNG Carriers. *Journal of Polish CIMAC*, *Energetic aspects*, Vol. 6, No. 1, Gdańsk, 133–140.

[9] Oka M, Hiraoka K, Tsumura K (2004). Advanced LNG Carrier with Energy Saving Propulsion Systems: Two Options. Mitsubishi Heavy Industries, Ltd. LNG 14. DOI:10.1016/j.energy.2013.05.002

[10] MAN Diesel A/S (2007). LNG Carriers ME-GI Engine with High Pressure Gas Supply System, Copenhagen, Denmark.

[11] Chang D, Rhee T, Nam K, Chang K, Lee D, Jeong S (2008). A study on availability and safety of new propulsion systems for LNG carriers. *Reliability Engineering System Safety*, 93 (12),1877–85. DOI:10.1016/j.ress.2008.03.013

[12] MAN Diesel & Turbo (2013). Propulsion Trends in LNG Carriers, Copenhagen, Denmark.

[13] Fernández IA, Gómez MR, Gómez JR, Insua AB (2017). Review of propulsion systems on LNG carriers. *Renewable and Sustainable Energy Reviews,* 67, 1395–1411 DOI: 10.1016/j.rser.2016.09.095

[14] Dzida M, Olszewski W (2011). Comparing combined gas tubrine/steam turbine and marine low speed piston engine/steam turbine systems in naval applications. *POLISH MARITIME RESEARCH*, 4(71), Vol 18, 43–48. DOI: 10.2478/v10012-011-0025-8

[15] GE Marine (2013). Gas Turbine-Based Power & Propulsion systems for LNG Carriers. LNG 17

[16] GE Marine (2014). Compact GE Marine Gas Turbines for Next Generation LNG Carrier…More Cargo, Same Size Hull. (10-15) AE 71856

[17] Tartakovsky L., Baibikov V., Gutman M., Poran M., A., Veinblat, M., (2014). Thermo-Chemical Recuperation as an Efficient Way of Engine's Waste Heat Recovery. *Applied Mechanics and Materials,* Vol. 659 (2014), pp. 256-261 DOI:10.4028/www.scientific.net/AMM.659.256

[18] IMO (2014). Guidelines on the method of calculation of the Attained Energy Efficiency Design Index (EEDI) for new ships (2014). MEPC 66/21/Add.1 p:1

[19] IMO (2016). Train the Trainer (TTT) Course on Energy Efficient Ship Operation. Module 2 – Ship Energy Efficiency Regulations and Related Guidelines

BIBLIOGRAPHY

[1] Alves LG, Nebra SA (2003). Thermoeconomic Evaluation of a Basic Optimized Chemically Recuperated Gas Turbine Cycle. *Int.J. Thermodynamics*, Vol.6 (No.1), pp.13-22

[2] Benito A (2009). Accurate determination of LNG quality unloaded in Receiving Terminals An Innovative Approach. *IGU*. Buenos Aires. 1–23.

[3] Hydrocarbon Engineering (2023) Growth in global LNG export capacity will be limited in 2023. Retrieved from: https://www.hydrocarbonengineering.com/gas-processing/03022023/growth-in-global-lng-export-capacity-will-be-limited-in-2023 [in England]

[4] The Diplomat (2023) What Does Russia's Invasion of Ukraine Mean for China in the Arctic? Retrieved from: https://thediplomat.com/2022/03/what-does-russias-invasion-of-ukraine-mean-for-china-in-the-arctic/ [in Asia]

[5] LNGPrime The World Premier LNG Platform.(2023) LNG Canada terminal almost 85 percent complete. Retrieved from: https://lngprime.com/lng-terminals/lng-canada-terminal-almost-85-percent-complete/85669/ [in Bosnia and Herzegovina]

[6] BP Energy Outlook 2035 (2016).

[7] International Gas Union (IGU) 44 Southampton Buildings WC2A 1AP London United Kingdom (2022) WORLD LNG REPORT.71

[8] Głomski P, Michalski R (2011). Problems with Determination of Evaporation Rate and Properties of Boil-off Gas on Board LNG Carriers. *Journal of Polish CIMAC*, *Energetic aspects*, Vol. 6, No. 1, Gdańsk, 133–140.

[9] Oka M, Hiraoka K, Tsumura K (2004). Advanced LNG Carrier with Energy Saving Propulsion Systems: Two Options. Mitsubishi Heavy Industries, Ltd. LNG 14. DOI:10.1016/j.energy.2013.05.002

[10] MAN Diesel A/S (2007). LNG Carriers ME-GI Engine with High Pressure Gas Supply System, Copenhagen, Denmark.

[11] Chang D, Rhee T, Nam K, Chang K, Lee D, Jeong S (2008). A study on availability and safety of new propulsion systems for LNG carriers. *Reliability Engineering System Safety*, 93 (12),1877–85. DOI:10.1016/j.ress.2008.03.013

[12] MAN Diesel & Turbo (2013). Propulsion Trends in LNG Carriers, Copenhagen, Denmark.

[13] Fernández IA, Gómez MR, Gómez JR, Insua AB (2017). Review of propulsion systems on LNG carriers. *Renewable and Sustainable Energy Reviews,* 67, 1395–1411 DOI: 10.1016/j.rser.2016.09.095

[14] Dzida M, Olszewski W (2011). Comparing combined gas tubrine/steam turbine and marine low speed piston engine/steam turbine systems in naval applications. *POLISH MARITIME RESEARCH*, 4(71), Vol 18, 43–48. DOI: 10.2478/v10012-011-0025-8

[15] GE Marine (2013). Gas Turbine-Based Power & Propulsion systems for LNG Carriers. LNG 17

[16] GE Marine (2014). Compact GE Marine Gas Turbines for Next Generation LNG Carrier…More Cargo, Same Size Hull. (10-15) AE 71856

[17] Tartakovsky L., Baibikov V., Gutman M., Poran M., A., Veinblat, M., (2014). Thermo-Chemical Recuperation as an Efficient Way of Engine's Waste Heat Recovery. *Applied Mechanics and Materials,* Vol. 659 (2014), pp. 256-261 DOI:10.4028/www.scientific.net/AMM.659.256

[18] IMO (2014). Guidelines on the method of calculation of the Attained Energy Efficiency Design Index (EEDI) for new ships (2014). MEPC 66/21/Add.1 p:1

[19] IMO (2016). Train the Trainer (TTT) Course on Energy Efficient Ship Operation. Module 2 – Ship Energy Efficiency Regulations and Related Guidelines

Дата надходження статті до редакції: 01.06.2023
Дата затвердження статті до друку: 25.06.2023