

ТЕРМОДИНАМІЧНИЙ АНАЛІЗ ТА МОДЕЛЮВАННЯ

УДК 629.56

Methods for managing the energy efficiency of a reliquefaction plant operating on the reverse brighton cycle of a LNG tanker

Victoriia Sokolovska-Yefymenko^{1✉}, Larisa Morosuk², Volodymyr Ierin³, Oleksandr Yefymenko⁴, Andrii Moshkatiuk⁵

^{1,2,4,5}Odesa National University of Technology, 112 Kanatnaya str., Odesa, 65039, Ukraine;

³NingboTech University, 1 Qianhu South Road, Ningbo, 315100, China

✉ e-mail: ¹kli24062006@gmail.com

ORCID: ¹<http://orcid.org/0000-0002-7275-5061>; ²<http://orcid.org/0000-0003-4133-1984>; ³<http://orcid.org/0000-0001-7941-9725>; ⁴<http://orcid.org/0000-0003-2571-9292>; ⁵<http://orcid.org/0000-0003-3354-0321>

LNG is transported over long sea and ocean distances only by tankers, called LNG carriers, in large on-board tanks at a temperature of -163°C . Although these tanks are well insulated, some of the LNG evaporates under the external factors influence, and boil-off-gas gas (BOG) is formed. The main method of dealing with BOG is the reliquefaction of LNG. Many LNG carriers use technology based on the reverse Brighton cycle (RBC) for reliquefaction. The study has been carried out by thermodynamic analysis methods of the actual parameters and characteristics of the BOG reliquefaction plant based on the data obtained during the operation of the LNG carrier "UMM AL AMAD". Energy and entropy-statistical methods of thermodynamic analysis have been used in the research. The reliquefaction plant operation has been evaluated based on the specific compression work consumption and the value of the effectiveness of a thermodynamic cycle. The analysis of the results showed that the investigated system operating according to the Brighton cycle has low energy efficiency values. The most energy-intensive loop is the nitrogen loop. It accounts for over 90% of the work overspending in the reliquefaction plant. The expander work partially compensates for the overexpenditure of compressor work. Irreversibility in the expander is 7.7%, and the N_2 compressor is approximately 48.7% of the total irreversibility of the liquefaction process. In the BOG/LNG loop, the main contribution to the processes' irreversibility is made by the BOG compressor ($\sim 3.7\%$) and the precooler ($\sim 1.55\%$) of the total irreversibility of the liquefaction process. The cryogenic heat exchanger is a component of both loops and its negative impact is estimated at 36.4% of the total irreversibility of the liquefaction process. The application of reliquefaction plants operating on the Brighton cycle is currently inefficient due to low energy efficiency and huge losses in the nitrogen loop, which does not meet IMO requirements for gas carriers.

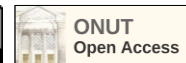
Keywords: LNG carrier; Reliquefaction plant; Energy efficiency; Entropy-statistical method

doi: <https://doi.org/10.15673/ret.v60i1.2821>

© The Author(s) 2024. This article is an open access publication

This work is licensed under the Creative Commons Attribution 4.0 International License (CC BY)

<http://creativecommons.org/licenses/by/4.0/>



Nomenclature:

g – relative mass flow rate, $\text{kg} \cdot \text{kg}^{-1}$

h – specific enthalpy, $\text{kJ} \cdot \text{kg}^{-1}$

$\dot{n}$ – molar flow rate, $\text{kmol} \cdot \text{h}^{-1}$

$\dot{m}$ – mass flow rate, $\text{kJ} \cdot \text{kg}^{-1}$

q – specific heat load, $\text{kJ} \cdot \text{kg}^{-1}$

P – pressure, bar, or MPa

s – specific entropy, $\text{kJ} \cdot \text{kg}^{-1} \cdot \text{K}^{-1}$

T – temperature, $^{\circ}\text{C}$ or K

w – specific work, kW

x – coefficient of BOG liquefaction, $\text{kg}_{\text{LNG}} \cdot \text{kg}_{\text{BOG}}^{-1}$

y – specific N_2 mass flow rate for cooling 1 kg BOG, $\text{kg}_{\text{N}_2} \cdot \text{kg}_{\text{BOG}}^{-1}$,

Δ – difference
 η – efficiency
 φ – coefficient of energy consumption

Acronyms:

BOG – boil-off gas
 LNH – liquefied petroleum gas
 RBC – reverse Brighton cycle

Subscripts:

amb – ambient
 CHE – cryogenic heat exchanger
 comp – compressor
 comp-exp – compander
 cool – cooling
 e – evaporator

exp – expander
 EV – expansion valve
 pc – precooler
 rej – reject
 sep – separator
 sup – supply
 1-18 – state of cycle

Superscripts:

act – actual
 ad – adiabatic
 is – isentropic
 min – minimal
 theo – theoretical
 tot – total

1. Introduction

Over the past two centuries, energy needs have increased dramatically. However, fossil fuels pollute the environment, and their reserves are limited. Replacing traditional energy with clean energy has become a common global practice. As the cleanest among fossil fuels, natural gas can be vital in transitioning to cleaner energy sources [1, 2].

Natural gas is converted into liquefied petroleum gas (LNG), with a much higher volumetric energy density for economical long-distance transportation. The energy crises of the last few years have made LNG trading a hotspot in the global energy market.

LNG is transported over long sea and ocean distances only by LNG tankers in large onboard (cryogenic) tanks at a temperature of -163°C . Although these tanks are well insulated, part of the LNG evaporates under external factor influence such as cargo movement inside the tank (splashing), during cargo unloading operations, etc. The result of this is the boil-off gas (BOG) formation. This phenomenon increases the pressure in the tanks, which increases the liquid cargo evaporation rate. In turn, it can lead to the tank balance destruction and the opening of safety valves. The International Maritime Organization (IMO) has established a provision on the limit of BOG boiling rate of 0.15% per day for LNG tanks [3]. Burning or releasing BOG into the atmosphere leads to economic losses and environmental problems [4]. To stabilize the pressure in tanks, BOG is either used as fuel (LNG is an ideal alternative ship fuel given its environmental friendliness and efficiency) or is restored by reliquefying. The modern LNG-powered engi-

ne application in the shipping industry also requires installing a BOG reliquefaction system. Therefore, for economic and environmental reasons, as well as the storage tanks safety, the BOG reliquefaction process is significant for LNG marine tankers.

The energy consumption of reliquefaction plants on LNG tankers is high; therefore, increasing their efficiency will help implement the “Ship Energy Efficiency Management Plan” [5].

Given the above, the study of the actual parameters and characteristics of the reliquefaction plant was carried out based on data obtained during the operation of the LNG carrier “UMM AL AMAD” by thermodynamic analysis methods [6]. The study will create an information base regarding the energy efficiency of the existing installation and processes requiring improvement.

2. Literature review and problem statement

The BOG reliquefaction system on LNG vessels is a study subject by many researchers. Various technological processes for reliquefying BOG are used on board LNG tankers, both direct and indirect since such technological schemes are a common method of liquefying NG in the industry [7]. However, the criteria by which the thermodynamic and economic efficiency of cycles in industry are evaluated do not meet the requirements for assessing the reliquefaction plant on board the ship. The selection of reliquefaction technology on board the vessel must meet certain criteria, the key points of which outweigh the energy efficiency [8]:

- Limited space on board requires minimal weight and size characteristics of the reliquefaction

plant.

- The conditions at sea should not affect the reliquefaction plant operation. The reliquefaction plant must work reliably under specific conditions (pitching, trim, roll, shocks, shocks, vibration of the body).

- Quick start of the reliquefaction plant with high availability and efficiency;

- Easy maintenance.

- The reliquefaction plant should be low-cost, simple in design, and have low power consumption.

Because of the above requirements, the largest number of LNG tankers for reliquefaction plants used indirect liquefaction technology based on the reverse Brighton cycle (RBC), which uses nitrogen (N_2) as the refrigerant.

The world's first BOG reliquefaction plant was built on the LNG carrier "LNG Jamal" from Mitsubishi Group in 2000 with a cargo capacity of 135,000 m³. The system worked according to RBC. Due to the lack of appropriate reliquefaction technology, the vessel's main engine was a steam turbine with a very low-efficiency value [9]. Pil et al. reviewed a high-performance reliquefaction system that worked according to RBC, assessed the system's reliability, and focused on optimization and maintenance strategies [10]. A dynamic simulation tool for a reliquefaction plant based on RBC has been developed by Shin and Lee [11]. This system can be used by design and management engineers to develop processes for reliquefaction plants of this type. Such a tool provides a flexible configuration of the reliquefaction plant on LNG vessels by modeling equipment using object orientation.

The research proposed by Sayyaadi and Babaei aims to develop a cost-effective solution for a BOG reliquefaction plant operating on RBC for LNG transportation [12]. Thermo-economic optimization of the BOG-LNG liquefaction system has been performed. A thermoeconomic model of the system has been developed. It has been found that an increase in the compression ratio of nitrogen compressors leads to a decrease in the total cost of the liquefaction effect. At the same time, an increase in the compression ratio of the BOG compressor leads to an enhancement in the total cost of the liquefaction effect. An exergetic analysis of the BOG reliquefaction system based on RBC has been carried out by Kochunni et al. [13]. The analysis showed that the process heat exchanger must be significantly larger than the BOG condenser to ensure acceptable system performance. Kwak et. al.

studied the small-scale process of BOG reliquefaction operating on RBC [14]. A method of systematic design and optimization of reliquefaction processes has been presented to increase the energy efficiency of the reliquefaction system. It has been established that the BOG compressor is one of the key design issues that should be carefully considered when determining the optimal solutions for the reliquefaction process.

Yin and Ju considered two modified processes based on the BOG reliquefaction unit operating on RBC on small LNG tankers [15]. The first process involves the parallel expansion of nitrogen, and the second is sequential. The thermodynamic analysis of the two cases is performed from the point of view of energy and exergetic analyses, respectively. The analysis showed that the first process shows better performance. The first modified process is proposed to be implemented on small LNG vessels. The parametric assessment of the basic reliquefaction system operating according to RBC based on exergetic analysis has been performed by Kochunni and Chowdhury [16]. The main limitation preventing the performance improvement of the RBC-based reliquefaction system is the appearance of liquid at the turbine outlet. From a thermodynamic point of view, the ideal pressure at the turbine outlet should be 10 bar, while achieving a maximum rational exergetic efficiency of 22.9% and a liquefaction coefficient of 92.7. Based on the research [16], the authors further considered three modifications of the RBC-based system and presented the main results in his study [17]. One modification is based on the intermediate and precooling of the BOG before suctioning into the compressor. The rest modifications include compression of the BOG with ambient temperature. The influence of the main characteristics of each system configuration has been estimated using exergetic analysis. This analysis showed that BOG compression at ambient temperature has higher exergetic efficiency than compression with precooling. It was also determined that the system would deteriorate with a pressure drop in the heat exchanger.

Kochunni and Chowdhury proposed two modifications of the RBC-based reliquefaction technology that enabled zero methane losses without any reduction in pressure at the turbine outlet [18]. The first modification was without a phase separator, and the exhaust gas was recycled and reliquefied using BOG. Another modification proposed a distillation method with a nozzle instead of a phase separator for cleaning exhaust gases. The exhaust gases are thus purified to less than one part per million of methane, and almost

pure nitrogen is returned to the system. The results of the technology analysis showed that the exergetic efficiency of the exhaust gas recirculation system and the distillation column was 14.9% and 8.7% higher than that of the base system, respectively. Son and Kim proposed to increase the energy efficiency of a reliquefaction plant operating on RBC due to structural modifications of the cycle, such as a double expander cycle [19]. For systematic verification of a wide range of configuration options, the concept of structural optimization for a double expander cycle and a holistic assessment of their technical and economic impact have been proposed. The performance of the optimized process has increased by 23% compared to the classic RBC process. A multi-flow heat exchange process with a cryogenic heat exchange network (CHEN) and nitrogen regeneration has been proposed by Wang et al. for onboard BOG reliquefaction on LNG vessels [20]. Numerical modeling and experimental research have been carried out under design conditions. The study showed the feasibility of the proposed solution for new ships. Kim and Kim studied the method for improving the RBC reliquefaction system [21]. New design solutions for systems combined with a fuel gas supply system have been proposed. Modeling and optimization of the proposed systems have been carried out. The authors claimed that the concept proposed in the study is original in this area and will make a significant contribution to the improvement of BOG reliquefaction systems on LNG vessels.

A literature review on evaluating BOG reliquefaction plants operating according to RBC showed that energy optimizations are mainly discussed in the studies, using various mathematical optimization methods and corresponding algorithms. Many modified technological schemes based on the RBC for the BOG reliquefaction have been proposed. However, such schemes are improved in terms of energy efficiency, but they are huge and include a different amount of additional equipment that requires qualified maintenance, therefore they do not meet the criteria of marine equipment. The studies reviewed practically do not mention studies based on actual data on the operation of LNG carriers.

The main parameters of BOG change over time, and depend on many factors. Therefore, it is significant to conduct an experimental verification of the BOG reliquefaction process and compare it with a theoretical calculation to develop a reliable and safe process control structure in the installation. Thus, it

becomes relevant to continue scientific research based on available data from monitoring cargo operations of current LNG carriers with the involvement of scientific tools to improve the energy efficiency of the BOG liquefaction process and compliance with IMO rules related to environmental protection.

3. System description

According to the cargo transportation method, the gas carrier “UMM AL AMAD” belongs to LNG/C carriers. These are specialized types of gas carriers designed to transport large volumes of LNG at an evaporating temperature of about $-162\text{ }^{\circ}\text{C}$ and atmospheric pressure. The gas carrier belongs to the “Q-Flex” class with a tank capacity of 206958 m^3 . The vessel deadweight is 121730 t, gross tonnage is 136685 m^3 . The cargo retention system consists of five cargo tanks with double insulation. By design, the tanks are built-in, membrane type No. 96, with a BOG evaporation rate of less than 0.141% of the cargo volume per day [22].

The reliquefaction plant operates on the RBC using nitrogen as a working substance. The technological diagram of the reliquefaction system is shown in Fig.1.

The technological diagram comprises two circulation loops: BOG/LNG (cargo cycle) and nitrogen N_2 (refrigeration) loop.

3.1. Work processes in the BOG/LNG loop

The BOG/LNG loop includes the following components: a BOG precooler, a two-stage centrifugal cargo compressor (BOG compressor), a cryogenic heat exchanger (part of the Cool Box); an LNG separator (part of the Cool Box); an LNG cargo pump. To reduce external heat flows, the cryogenic heat exchanger and separator are technologically combined into a single cold insulated box (Cool Box).

BOG from cargo tanks is collected in a collector, where it is mixed with ballast vapor (state 9) formed during the boiling of LNG (state 8) in a precooler coil and sent to the same heat exchanger (state 2). In the precooler, the temperature for the flow supplied from the BOG collector (state 3) is stabilized by cooling with boiling LNG. The stable BOG flow temperature (state 3) ensures a constant discharge temperature of the cargo compressor to protect the Cool Box from temperature fluctuations that cause additional thermal stresses. In addition, the precooler performs the functions of a liquid separator. The precooler consists of a

tubular finned heat exchanger installed inside a vertical separator. The cooled BOG is compressed in a

cargo compressor (state 4), cooled, and condensed in a cryogenic multiflow LNG heat exchanger (state 5).

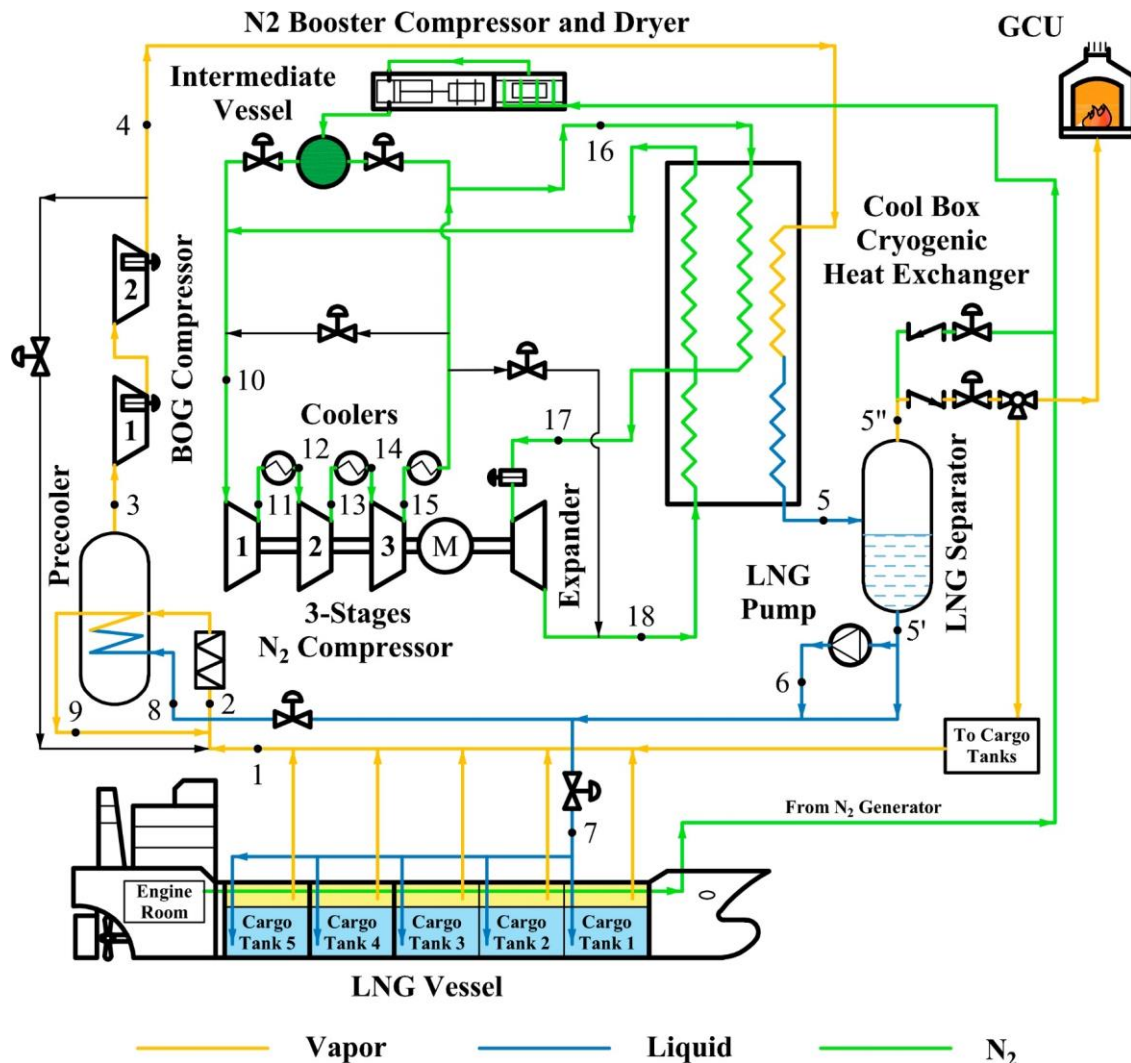


Figure 1 – Technological diagram of the reliquefaction system of the LNG carrier [6]

Non-condensable gases are separated in an LNG separator. The liquid phase of LNG (state 5') is returned to the cargo tanks under the pressure difference between the separator and the cargo tank, and the gas phase (state 5'') is sent to the gas combustion unit (GCU). Reliquefaction is carried out by free flow. The liquid column height in the LNG separator provides the pressure difference. If the height of the column is not enough, an LNG pump is used (state 6).

3.2. Work processes in the nitrogen N₂ loop

The nitrogen N₂ loop includes the following components: a three-stage centrifugal compressor, an expander, three water heat exchangers, a cryogenic heat exchanger (part of the Cool Box); a nitrogen circulation control system (a nitrogen dryer, a booster compressor, a nitrogen tank, an oil filter system). The sys-

tem provides for nitrogen leak replenishment from the seals of a three-stage compressor. The booster compressors are designed to regulate the cooling capacity of the nitrogen N₂ loop.

Nitrogen (state 10) is successively compressed in a three-stage compressor (states 11, 13, and 15) with intermediate cooling between stages in heat exchangers with seawater of constant temperature. This allows the process in the compressor to be attributed to isothermal. Further nitrogen cooling is carried out in a cryogenic heat exchanger. Nitrogen with high pressure and temperature (state 16) in the topping part of the heat exchanger is cooled (state 17) by a nitrogen flow with low pressure and temperature formed after the expander (state 18). A low-pressure nitrogen flow provides BOG vapor condensation in the bottoming part of the cryogenic heat exchanger. The expander returns part of the power spent in the compressor.

4. Modeling of the reliquefaction plant processes

In the study, the reliquefaction plant processes have been modeled using energy and entropy-statistical analysis methods. The main parameter values of the simulation reliquefaction plant operation have been obtained in actual operating conditions during the considered vessel. The data are presented in Tables 1 and 2. The following assumptions to simplify the theoretical model of the considered system are used:

- hydraulic losses in pipelines are not considered;
- heat transfer during separation and mixing of flows are not considered;

- the mechanical efficiency of the N₂ compressor $\eta_{\text{comp},\text{N}_2}$ is assumed to be 0.80;
- the mechanical efficiency of the N₂ expander $\eta_{\text{exp},\text{N}_2}$ is assumed to be 0.75;
- the mechanical efficiency of the BOG compressor $\eta_{\text{comp},\text{BOG}}$ is assumed to be 0.71.

The cooling medium is seawater with a temperature at the heat exchanger inlets: $T_{\text{amb}} = 41^\circ\text{C}$ (314 K).

Table 1 – Molar concentration of BOG/LNG

BOG composition	Chemical formula	Molar concentration, %
Nitrogen	N ₂	0.128
Methane	CH ₄	0.872
Ethane	C ₂ H ₆	-

Table 2 – Reliquefaction plant parameters based on real-time cargo operation monitoring records and the technological diagram in Fig.1.

State	Temperature $T, ^\circ\text{C}$	Pressure P, bar	Total mass flow rate $\dot{m}^{\text{tot}}$ $\text{kg}\cdot\text{h}^{-1}$	Total molar flow rate, $\dot{n}^{\text{tot}}$ $\text{kmol}\cdot\text{h}^{-1}$	Molar concentration, %		
					N ₂ , mole %	CH ₄ , mole %	C ₂ H ₆ , mole %
1	-100.0	1.06	6027	342.8	0.129	0.871	$1.1\cdot 10^{-4}$
2	-104.3	1.06	6473	368.2	0.129	0.871	$1.1\cdot 10^{-4}$
3	-120.0	1.06	6473	368.2	0.129	0.871	$1.1\cdot 10^{-4}$
4	-23.5	4.50	6473	368.2	0.129	0.871	$1.1\cdot 10^{-4}$
5	-159.5	4.50	6473	368.2	0.129	0.871	$1.1\cdot 10^{-4}$
5''		4.50	66	2.7	0.723	0.277	$1.1\cdot 10^{-4}$
5'		4.50	6407	365.5	0.124	0.878	$1.1\cdot 10^{-4}$
6		6.50	6407	365.5	0.124	0.878	$1.1\cdot 10^{-4}$
8		1.06	446	25.4	0.124	0.878	$1.1\cdot 10^{-4}$
9		1.06	446	25.4	0.124	0.878	$1.1\cdot 10^{-4}$
10	39.90	13.18	112500	4016	1.00	0	0
11	98.1	20.91	112500	4016	1.00	0	0
12	41.0	20.91	112500	4016	1.00	0	0
13	96.2	33.57	112500	4016	1.00	0	0
14	41.0	33.57	112500	4016	1.00	0	0
15	96.5	53.73	112500	4016	1.00	0	0
16	41.0	53.73	112500	4016	1.00	0	0
17	-110.1	53.73	112500	4016	1.00	0	0
18	-162.5	13.18	112500	4016	1.00	0	0

4.1. Energy analysis of the reliquefaction plant cycles

Based on the data in Tables 1 and 2, thermodynamic cycles for the BOG/LNG and N₂ loops have been formed (figs. 2 and 3) and an energy analysis of the cycles has been performed. The REFPROP software has been used to define the parameters of the system processes [23].

The state parameters of the cycles are presented in Table 3. The mass flow rates in the plant components are determined relative to 1 kg·s⁻¹ of the BOG total mass flow rate (g, kg·kg⁻¹).

BOG/LNG loop

The adiabatic specific work of compression in the BOG compressor is:

$$w_{\text{comp,BOG}}^{\text{ad}} = h_{4s} - h_3, \text{kJ}\cdot\text{kg}^{-1}_{\text{BOG}} \quad (1)$$

The actual specific work of compression in the BOG compressor is:

$$w_{\text{comp,BOG}}^{\text{act}} = h_4 - h_3, \text{ kJ} \cdot \text{kg}^{-1}_{\text{BOG}} \quad (2)$$

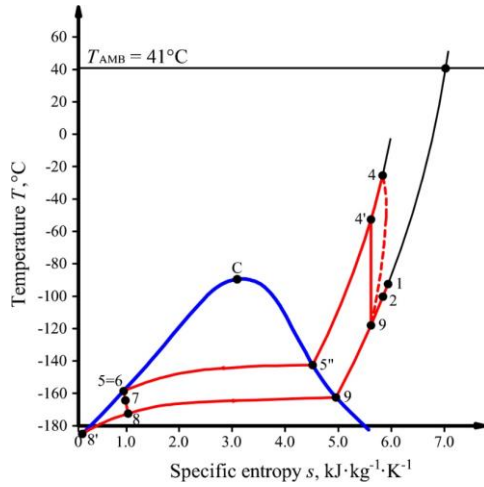


Figure 2 – The BOG/LNG cycle in the T-s diagram

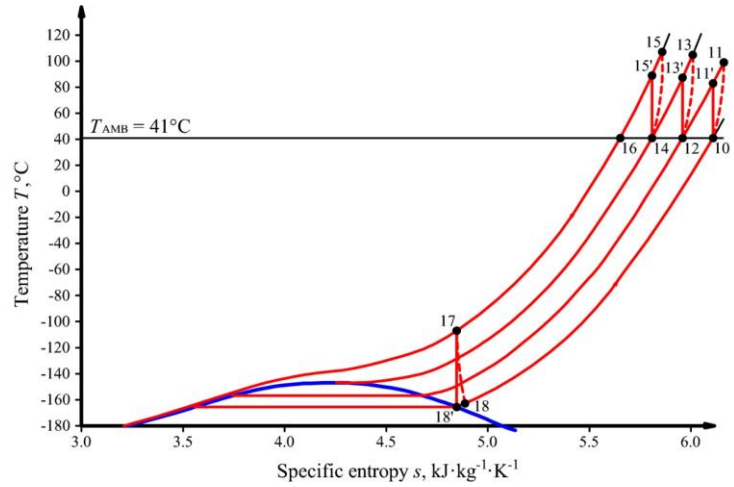


Figure 3 – The N₂ cycle in the T-s diagram

Table 3 – State parameters of the cycles r

State	Enthalpy h, kJ·kg ⁻¹	Entropy s, kJ·kg ⁻¹ ·K ⁻¹	Relative mass flow rate g, kg·kg ⁻¹
BOG/LNG loop			
1	582.80	5.72	0.93
2	574.30	5.67	1.00
3	543.20	5.48	1.00
4	730.00	5.73	1.00
4s	672.10	5.48	1.00
5	25.99	0.84	1.00
5'	5.30	0.98	0.99
5''	487.40	5.28	0.01
6	5.50	0.99	0.99
7	5.30	1.038	0.07
8	430.60	4.96	0.07
9	582.80	5.72	0.93
N ₂ loop			
10	322.40	6.12	1.00
11s	368.30	6.12	1.00
11	382.90	6.16	1.00
12	322.10	5.98	1.00
13	369.50	6.06	1.00
13s	379.30	6.06	1.00
14	319.70	5.83	1.00
15	377.30	5.86	1.00
15s	366.90	5.83	1.00
16	316.10	5.68	1.00
17	124.60	4.83	1.00
18	91.10	4.89	1.00
18s	84.20	4.83	1.00

The minimum liquefaction work (shaded area in Fig. 4) is equivalent to the liquefaction work provided the processes are reversible. According to the cycle, BOG is successively compressed by the compressor from the initial state (state 2) to high pressure (state 2'), then isothermally compressed (process 2'-y), and expands in the expander (process y-8') to obtain the liquid state 8' at the outlet (Fig.4).

The minimum work required for BOG liquefaction can be determined with the system energy balance equation:

$$w_{\text{BOG,l}}^{\text{min}} = q_{\text{rej}} - q_{\text{sup}}, \text{ kJ} \cdot \text{kg}^{-1}_{\text{BOG}} \quad (3)$$

where q_{rej} is the specific heat rejected, kJ·kg_{BOG}⁻¹; q_{sup} is the specific heat supplied, kJ·kg_{BOG}⁻¹.

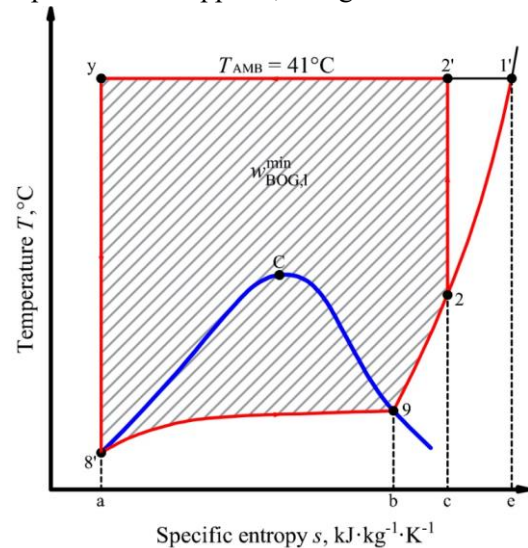


Figure 4 – The ideal BOG liquefaction cycle

According to Fig.3:

$$q_{rej} = \text{area } e1'ya \Leftrightarrow T_{amb} \cdot (s_{1'} - s_y), \text{ kJ} \cdot \text{kg}_{\text{BOG}}^{-1} \quad (4)$$

$$q_{sup} = \text{area } e1'ya - (\text{area } e1'2'c - \text{area } e1'2c) \Leftrightarrow \\ \Leftrightarrow T_{amb} \cdot (s_{1'} - s_{8'}) - T_{amb} \cdot (s_{1'} - s_{2'}) - h_{1'} - h_2, \text{ kJ} \cdot \text{kg}_{\text{BOG}}^{-1} \quad (5)$$

The minimum work required to liquefy 1 kg of BOG at inlet and outlet pressures of 1.06 bar:

$$w_{\text{BOG},l}^{\min} = T_{amb} \cdot (s_{2'} - s_{8'}) - (h_2 - h_{8'}), \text{ kJ} \cdot \text{kg}_{\text{LNG}}^{-1} \quad (6)$$

where $s_{8'}$ and $h_{8'}$ are the entropy and enthalpy of BOG at the temperature of the liquid corresponding to the saturation pressure $p = 1.06$ bar (point 8 in Fig.2).

The coefficient of BOG liquefaction is

$$x = \frac{\dot{m}_f^*}{\dot{m}_{\text{BOG}}^*}, \text{ kg}_{\text{LNG}} \cdot \text{kg}_{\text{BOG}}^{-1}, \quad (7)$$

where $\dot{m}_f^*$ is the mass flow rate of the returned LNG to cargo tanks, $\text{kg} \cdot \text{s}^{-1}$; $\dot{m}_{\text{BOG}}^*$ is the mass flow rate of BOG in the reliquefaction plant during operation, $\text{kg} \cdot \text{s}^{-1}$.

The specific cooling capacity of the BOG loop is:

$$q_{e,\text{BOG}} = h_5 - h_4, \text{ kJ} \cdot \text{kg}_{\text{BOG}}^{-1} \quad (8)$$

N₂ loop

The specific N₂ mass flow rate for cooling 1 kg BOG is:

$$y = \frac{\dot{m}_{\text{N}_2}}{\dot{m}_{\text{BOG}}^*}, \text{ kg}_{\text{N}_2} \cdot \text{kg}_{\text{BOG}}^{-1}, \quad (9)$$

where $\dot{m}_{\text{N}_2}$ is the N₂ mass flow rate during operation, $\text{kg} \cdot \text{s}^{-1}$.

The specific heat supplied to the N₂ flow during heating is:

$$q_{\text{sup},\text{N}_2} = h_{10} - h_{18}, \text{ kJ} \cdot \text{kg}_{\text{N}_2}^{-1} \quad (10)$$

The specific heat rejected from the N₂ flow during cooling is:

$$q_{\text{rej},\text{N}_2} = h_{16} - h_{17}, \text{ kJ} \cdot \text{kg}_{\text{N}_2}^{-1} \quad (11)$$

The isothermal specific work of compression in the first, second, and third stages of the N₂ compressor, respectively, is:

$$w_{\text{comp},\text{N}_2}^{\text{I, is}} = T_{amb} \cdot (s_{10} - s_{12}) - (h_{10} - h_{12}), \text{ kJ} \cdot \text{kg}_{\text{N}_2}^{-1} \quad (12)$$

$$w_{\text{comp},\text{N}_2}^{\text{II, is}} = T_{amb} \cdot (s_{12} - s_{14}) - (h_{12} - h_{14}), \text{ kJ} \cdot \text{kg}_{\text{N}_2}^{-1} \quad (13)$$

$$w_{\text{comp},\text{N}_2}^{\text{III, is}} = T_{amb} \cdot (s_{14} - s_{16}) - (h_{14} - h_{16}), \text{ kJ} \cdot \text{kg}_{\text{N}_2}^{-1} \quad (14)$$

The total isothermal specific work of compression in the N₂ compressor is:

$$w_{\text{comp},\text{N}_2}^{\text{tot, is}} = w_{\text{comp},\text{N}_2}^{\text{I, is}} + w_{\text{comp},\text{N}_2}^{\text{II, is}} + w_{\text{comp},\text{N}_2}^{\text{III, is}}, \text{ kJ} \cdot \text{kg}_{\text{N}_2}^{-1} \quad (15)$$

The actual specific work of compression in the N₂ compressor is:

$$w_{\text{comp},\text{N}_2}^{\text{act}} = (h_{11} - h_{10}) + (h_{13} - h_{12}) + (h_{15} - h_{14}), \text{ kJ} \cdot \text{kg}_{\text{N}_2}^{-1} \quad (16)$$

The adiabatic specific work of expansion in the N₂ expander is:

$$w_{\text{exp},\text{N}_2}^{\text{ad}} = h_{17} - h_{18}, \text{ kJ} \cdot \text{kg}_{\text{N}_2}^{-1} \quad (17)$$

The theoretical specific work in the compander (N₂ expander-compressor unit) is:

$$w_{\text{comp-exp},\text{N}_2}^{\text{theo}} = w_{\text{comp},\text{N}_2}^{\text{tot, is}} - w_{\text{exp},\text{N}_2}^{\text{ad}}, \text{ kJ} \cdot \text{kg}_{\text{N}_2}^{-1} \quad (18)$$

The actual specific work of expansion in the N₂ expander is:

$$w_{\text{exp},\text{N}_2}^{\text{act}} = h_{17} - h_{18}, \text{ kJ} \cdot \text{kg}_{\text{N}_2}^{-1} \quad (19)$$

The actual specific work in the compander is:

$$w_{\text{comp-exp},\text{N}_2}^{\text{act}} = w_{\text{comp},\text{N}_2}^{\text{act}} - w_{\text{exp},\text{N}_2}^{\text{act}}, \text{ kJ} \cdot \text{kg}_{\text{N}_2}^{-1} \quad (20)$$

The theoretical specific cooling capacity of the N₂ loop is:

$$q_{e,\text{N}_2}^{\text{theo}} = q_{\text{rej},\text{N}_2} - q_{\text{sup},\text{N}_2}, \text{ kJ} \cdot \text{kg}_{\text{N}_2}^{-1} \quad (21)$$

The theoretical coefficient of energy consumption for liquefaction in the cycle is:

$$\phi^{\text{theo}} = \frac{w_{\text{comp,BOG}}^{\text{ad}} \cdot y^{-1} + w_{\text{comp-exp,N2}}^{\text{theo}}}{q_{\text{e,N2}}^{\text{theo}}} \quad (22)$$

The effectiveness of a thermodynamic cycle is:

The actual specific work for BOG and N₂ compressing is:

$$\eta = \frac{w_{\text{BOG,l}}^{\text{min}}}{w_{\text{BOG,N2}}^{\text{tot, act}}} \quad (24)$$

$$w_{\text{BOG,N2}}^{\text{tot, act}} = \frac{w_{\text{comp,BOG}}^{\text{act}}}{x} + \frac{w_{\text{comp-exp,N2}}^{\text{act}} \cdot y}{x}, \text{ kJ} \cdot \text{kg}_{\text{N2}}^{-1} \quad (23)$$

The energy analysis results are shown in Table 4.

Table 4 – Energy analysis results

Parameter	Value
The adiabatic specific work of compression in the BOG compressor $w_{\text{comp,BOG}}^{\text{ad}}, \text{kJ} \cdot \text{kg}_{\text{BOG}}^{-1}$	128.87
The actual specific work of compression in the BOG compressor $w_{\text{comp,BOG}}^{\text{act}}, \text{kJ} \cdot \text{kg}_{\text{BOG}}^{-1}$	186.81
The coefficient of BOG liquefaction $x, \text{kg}_{\text{LNG}} \cdot \text{kg}_{\text{BOG}}^{-1}$	0.92
The specific cooling capacity of the BOG loop $q_{\text{e,BOG}}, \text{kJ} \cdot \text{kg}_{\text{BOG}}^{-1}$	704.08
The minimum work required to liquefy 1 kg of BOG at inlet and outlet pressures of 1.06 bar $w_{\text{BOG,l}}^{\text{min}}, \text{kJ} \cdot \text{kg}_{\text{LNG}}^{-1}$	1052.10
The specific N ₂ mass flow rate for cooling 1 kg BOG $y, \text{kg}_{\text{N2}} \cdot \text{kg}_{\text{BOG}}^{-1}$	17.37
The specific heat supplied to the N ₂ flow during heating $q_{\text{sup,N2}}, \text{kJ} \cdot \text{kg}_{\text{N2}}^{-1}$	231.23
The specific heat rejected from the N ₂ flow during cooling $q_{\text{rej,N2}}, \text{kJ} \cdot \text{kg}_{\text{N2}}^{-1}$	191.43
The total isothermal specific work of compression in the N ₂ compressor $w_{\text{comp,N2}}^{\text{act}}, \text{kJ} \cdot \text{kg}_{\text{N2}}^{-1}$	131.90
The actual specific work of compression in the N ₂ compressor $w_{\text{comp,N2}}^{\text{act}}, \text{kJ} \cdot \text{kg}_{\text{N2}}^{-1}$	175.20
The adiabatic specific work of expansion in the N ₂ expander $w_{\text{exp,N2}}^{\text{ad}}, \text{kJ} \cdot \text{kg}_{\text{N2}}^{-1}$	40.47
The actual specific work of expansion in the N ₂ expander $w_{\text{exp,N2}}^{\text{act}}, \text{kJ} \cdot \text{kg}_{\text{N2}}^{-1}$	33.52
The theoretical specific work in the compander $w_{\text{comp-exp,N2}}^{\text{theo}}, \text{kJ} \cdot \text{kg}_{\text{N2}}^{-1}$	91.43
The actual specific work in the compander $w_{\text{comp-exp,N2}}^{\text{act}}, \text{kJ} \cdot \text{kg}_{\text{N2}}^{-1}$	141.68
The theoretical specific cooling capacity of the N ₂ loop $q_{\text{e,N2}}^{\text{theo}}, \text{kJ} \cdot \text{kg}_{\text{N2}}^{-1}$	39.80
The theoretical coefficient of energy consumption for liquefaction in the cycle ϕ^{theo}	2.47
The actual specific work for BOG and N ₂ compressing $w_{\text{BOG,N2}}^{\text{tot, act}}, \text{kJ} \cdot \text{kg}_{\text{LNG}}^{-1}$	2878.03
The effectiveness of a thermodynamic cycle η	0.37

4.2. Thermodynamic analysis of the LNG reliquefaction plant efficiency

The thermodynamic parameter of a system's performance for low-temperature cooling and liquefaction is the reversibility of its processes. All actual processes are accompanied by an increase in entropy, which, in turn, leads to an increase in energy expended.

For a visual representation of the role of entropy growth, entropy generation defines additional work to

compensate for the irreversibility of processes. Thus, the total entropy generation of all system components increases due to irreversibility. This principle is the base of entropy-statistical analysis as an LNG reliquefaction plant controlling method [24, 25].

The paper presents an approach for determining irreversibilities in actual cycle processes by the entropy-statistical method. The data from the vessel's operation and the energy analysis results have been used

for the analysis (Tables 1, 2, and 3). The reliquefaction plant efficiency is estimated based on the relative specific work consumption of the compressors and the value of the effectiveness of a thermodynamic cycle. The sequence of the main components analysis of the reliquefaction plant is presented below.

Allocation of work consumption to compensate for the entropy generation in the BOG/LNG loop

The minimum specific work required to cool 1 kg of BOG to LNG temperature is:

$$w_{\text{BOG,cool}}^{\min} = T_{\text{amb}} \cdot (s_2 - s_{5'}) - (h_2 - h_{5'}), \text{kJ} \cdot \text{kg}_{\text{BOG}}^{-1} \quad (25)$$

The minimum specific work required to cool 1 kg of BOG by N_2 is:

$$w_{\text{BOG,N2cool}}^{\min} = T_{\text{amb}} \cdot (s_4 - s_5) - (h_4 - h_5), \text{kJ} \cdot \text{kg}_{\text{BOG}}^{-1} \quad (26)$$

Since the BOG mass flow rate in the reliquefaction plant is $1 \text{ kg} \cdot \text{s}^{-1}$, the LNG relative mass flow rate going to cargo tanks through expansion valve EV1 equals the liquefaction coefficient $x = 0.92$. The LNG relative mass flow rate going to the pre-cooler through expansion valve EV2 is $z = 0.0689$. The vapor relative mass flow rate in the separator is $m = 0.0196$. These values are considered when determining the parameters according to equations (27)-(39).

The minimum required specific compression work to compensate for entropy generation during LNG throttling in expansion valves EV1 and EV2 are:

$$\Delta w_{\text{EV1}}^{\min} = T_{\text{amb}} \cdot (s_8 - s_{5'}) \cdot x, \text{kJ} \cdot \text{kg}_{\text{BOG}}^{-1} \quad (27)$$

$$\Delta w_{\text{EV2}}^{\min} = T_{\text{amb}} \cdot (s_8 - s_{5'}) \cdot x, \text{kJ} \cdot \text{kg}_{\text{BOG}}^{-1} \quad (28)$$

The minimum required specific compression work to compensate for entropy generation in the pre-cooler is:

$$\begin{aligned} \Delta w_{\text{pc}}^{\min} &= T_{\text{amb}} \cdot \Delta s_{\text{pc}} = \\ &= T_{\text{amb}} \cdot [(s_9 - s_8) \cdot z - (s_2 - s_3)], \text{kJ} \cdot \text{kg}_{\text{BOG}}^{-1} \end{aligned} \quad (29)$$

The total adiabatic specific compression work in the BOG loop necessary to compensate for part of the minimum specific work and entropy generation:

$$\begin{aligned} w_{\text{comp,BOG}}^{\text{ad}*} &= \Delta w_{\text{EV1}}^{\min} + \Delta w_{\text{EV2}}^{\min} + \Delta w_{\text{pc}}^{\min} + w_{\text{BOG,l}}^{\min} \cdot x + \\ &+ w_{\text{BOG,cool}}^{\min} \cdot m - w_{\text{BOG,N2cool}}^{\min}, \text{kJ} \cdot \text{kg}_{\text{BOG}}^{-1} \end{aligned} \quad (30)$$

Allocation of work consumption to compensate for the entropy generation in the N_2 loop

The minimum required specific compression work to compensate for entropy generation in the cryogenic heat exchanger is:

$$\Delta w_{\text{CHE}}^{\min} = T_{\text{amb}} \cdot \left[(s_{10} - s_{18}) - (s_{16} - s_{17}) - \frac{(s_4 - s_5)}{y} \right], \text{kJ} \cdot \text{kg}_{\text{N2}}^{-1} \quad (31)$$

The minimum required specific compression work to compensate for entropy generation in the expander is:

$$\Delta w_{\text{exp}}^{\min} = T_{\text{amb}} \cdot (s_{18} - s_{17}), \text{kJ} \cdot \text{kg}_{\text{N2}}^{-1} \quad (32)$$

The minimum required specific compression work to compensate the heat flows from the environment is:

$$\Delta w_{\text{amb}}^{\min} = \frac{\varphi^{\text{theo}} \cdot \Delta q}{y}, \text{kJ} \cdot \text{kg}_{\text{N2}}^{-1} \quad (33)$$

where Δq is the specific heat flows from the environment to the heat exchangers, $\text{kJ} \cdot \text{kg}_{\text{N2}}^{-1}$; $\Delta q = 0.81 \text{ kJ} \cdot \text{kg}_{\text{N2}}^{-1}$.

The total adiabatic specific compression work in the N_2 loop necessary to compensate for irreversibilities in components and entropy generation is defined by the equation:

$$\begin{aligned} w_{\text{comp,N2}}^{\text{ad}*} &= (\Delta w_{\text{CHE}}^{\min} + \Delta w_{\text{exp}}^{\min} + \Delta w_{\text{amb}}^{\min}) \cdot y + \\ &+ w_{\text{BOG,N2cool}}^{\min}, \text{kJ} \cdot \text{kg}_{\text{BOG}}^{-1} \end{aligned} \quad (34)$$

The specific compression work for all reliquefaction plant loops is:

$$w^{\text{ad}*} = w_{\text{comp,BOG}}^{\text{ad}*} + w_{\text{comp,N2}}^{\text{ad}*}, \text{kJ} \cdot \text{kg}_{\text{BOG}}^{-1} \quad (35)$$

The specific compression work consumption to compensate for entropy generation due to the irreversibility of working processes in the BOG and N_2 compressors, respectively:

$$\Delta w_{\text{comp,BOG}} = \frac{w_{\text{comp,BOG}}^{\text{act}} - w_{\text{comp,BOG}}^{\text{ad}}}{x}, \text{kJ} \cdot \text{kg}_{\text{LNG}}^{-1} \quad (36)$$

$$\Delta w_{\text{comp,N2}} = \frac{(w_{\text{comp,N2}}^{\text{act}} - w_{\text{comp,N2}}^{\text{tot,is}}) \cdot y}{x}, \text{kJ} \cdot \text{kg}_{\text{LNG}}^{-1} \quad (37)$$

The specific compression work consumption to compensate for entropy generation in the expander is:

$$\Delta w_{\text{exp},N_2} = \frac{(w_{\text{exp},N_2}^{\text{act}} - w_{\text{exp},N_2}^{\text{ad}}) \cdot y}{x}, \text{ kJ} \cdot \text{kg}_{\text{LNG}}^{-1} \quad (38)$$

The specific compression work consumption to

compensate for entropy generation in the compander is:

$$\Delta w_{\text{comp-exp},N_2} = \frac{(w_{\text{comp-exp},N_2}^{\text{act}} - w_{\text{comp-exp},N_2}^{\text{theo}}) \cdot y}{x}, \text{ kJ} \cdot \text{kg}_{\text{LNG}}^{-1} \quad (39)$$

The results of the entropy-statistical method of thermodynamic analysis are shown in Table 5.

Table 5 – The results of the entropy-statistical method of thermodynamic analysis

Parameter	Value
The minimum specific work required to cool 1 kg of BOG to LNG temperature $w_{\text{BOG,cool}}^{\text{min}}, \text{ kJ} \cdot \text{kg}_{\text{BOG}}^{-1}$	317.23
The minimum specific work required to cool 1 kg of BOG by N_2 $w_{\text{BOG},N_2\text{cool}}^{\text{min}}, \text{ kJ} \cdot \text{kg}_{\text{BOG}}^{-1}$	809.87
The minimum required specific compression work to compensate for entropy generation during LNG throttling in the expansion valve EV1 $\Delta w_{\text{EV1}}^{\text{min}}, \text{ kJ} \cdot \text{kg}_{\text{BOG}}^{-1}$	16.07
The minimum required specific compression work to compensate for entropy generation during LNG throttling in the expansion valve EV2 $\Delta w_{\text{EV2}}^{\text{min}}, \text{ kJ} \cdot \text{kg}_{\text{BOG}}^{-1}$	1.10
The minimum required specific compression work to compensate for entropy generation $\Delta w_{\text{pc}}^{\text{min}}, \text{ kJ} \cdot \text{kg}_{\text{BOG}}^{-1}$	24.50
The total adiabatic specific compression work in the BOG loop $w_{\text{comp,BOG}}^{\text{ad*}}, \text{ kJ} \cdot \text{kg}_{\text{BOG}}^{-1}$	170.00
The minimum required specific compression work to compensate for entropy generation in the cryogenic heat exchanger $\Delta w_{\text{CHE}}^{\text{min}}, \text{ kJ} \cdot \text{kg}_{N_2}^{-1}$	32.66
The minimum required specific compression work to compensate for entropy generation in the expander $\Delta w_{\text{exp}}^{\text{min}}, \text{ kJ} \cdot \text{kg}_{N_2}^{-1}$	20.06
The minimum required specific compression work to compensate for the heat flows from the environment $\Delta w_{\text{amb}}^{\text{min}}, \text{ kJ} \cdot \text{kg}_{N_2}^{-1}$	0.96
The total adiabatic specific compression work in the N_2 $w_{\text{comp},N_2}^{\text{ad*}}, \text{ kJ} \cdot \text{kg}_{\text{BOG}}^{-1}$	1742.22
The specific compression work for all reliquefaction plant loops $w^{\text{ad*}}, \text{ kJ} \cdot \text{kg}_{\text{BOG}}^{-1}$	1942.22
The specific compression work consumption to compensate for entropy generation in the BOG compressor $\Delta w_{\text{comp,BOG}}, \text{ kJ} \cdot \text{kg}_{\text{LNG}}^{-1}$	62.98
The specific compression work consumption to compensate for entropy generation in the N_2 compressor $\Delta w_{\text{comp},N_2}, \text{ kJ} \cdot \text{kg}_{\text{LNG}}^{-1}$	817.52
The specific compression work consumption to compensate for entropy generation in the expander $\Delta w_{\text{exp},N_2}, \text{ kJ} \cdot \text{kg}_{\text{LNG}}^{-1}$	131.21
The specific compression work consumption to compensate for entropy generation in the compander $\Delta w_{\text{comp-exp},N_2}, \text{ kJ} \cdot \text{kg}_{\text{LNG}}^{-1}$	948.73

The discrepancy between the calculated values of the adiabatic compression work in the BOG/LNG loop (Eqs. (15) and (35)) does not exceed 10%, and in the N_2 loop (Eqs. (18) and (34)) does not exceed 9%. The result indicates an actual overspending of work relative to each reliquefaction plant component. The distribution of the specific work overspending by reli-

quefaction plant components related to 1 kg of LNG is shown in figs. 5 and 6.

5. Discussion of the results and conclusions

The paper analyzes the actual processes in the LNG reliquefaction plant operating on the reverse

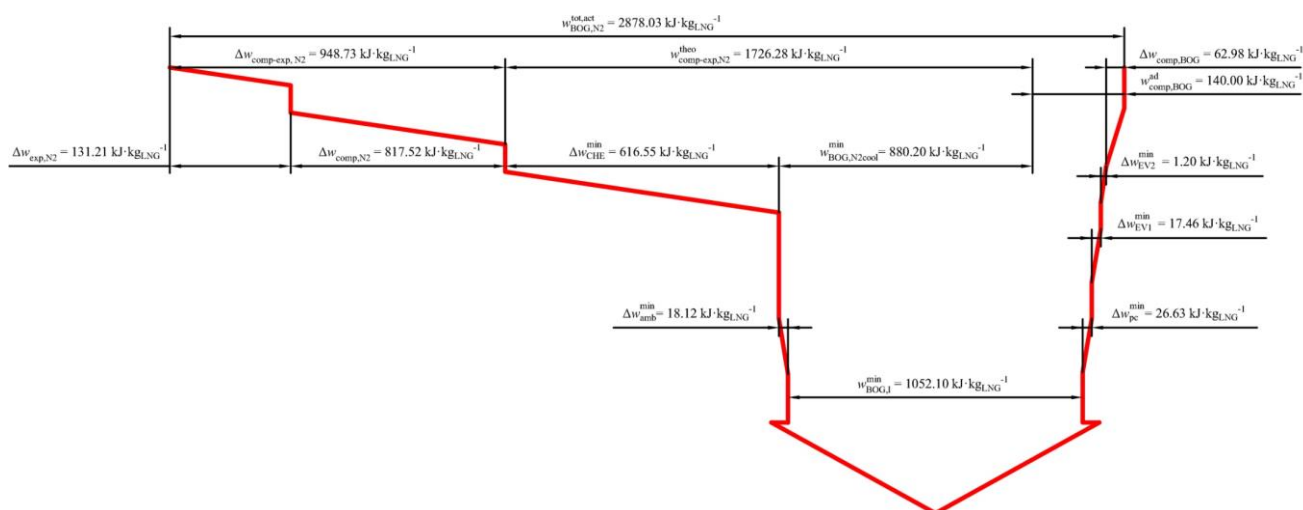


Figure 5 – Diagram of the work consumption distribution by components of the LNG reliquefaction plant operating on the Brighton cycle

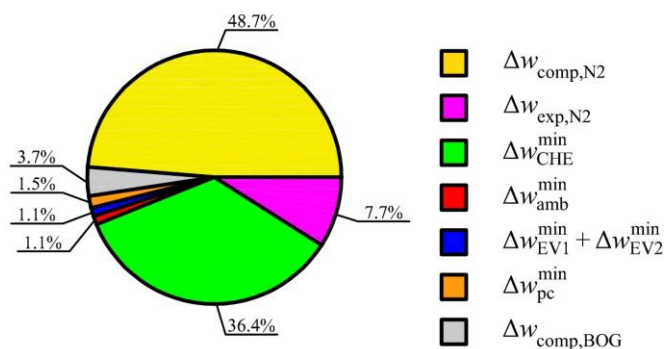


Figure 6 – Graphical interpretation of the results of estimating the work consumption by components of the LNG reliquefaction plant operating on the Brighton cycle

Brighton cycle of the LNG carrier “UMM AL AMAD”. The analysis has been carried out using the energy and entropy-statistical methods.

The results showed that the N₂ loop accounts for over 90% of the work overspending in the reliquefaction plant. As shown in Fig.5, irreversibility in the compander unit makes the greatest contribution to the entropy generation of the N₂ loop (56%). The expander work partially compensates for the overexpenditure of compressor work. Irreversibility in the expander is 7.7%, the N₂ compressor is approximately 48.7%, and the cryogenic heat exchanger is 36.4% of the total irreversibility of the liquefaction process. In the BOG/LNG loop, the main contribution to the processes' irreversibility is made by the BOG compressor (~3.7%) and the precooler (~1.55%) of the total irreversibility of the liquefaction process (Fig.6).

The thermodynamic efficiency of the reliquefaction plant operating on the RBC is 0.36, which is a fairly low value for such processes. Irreversibility in a

cryogenic heat exchanger is explained by the large temperature difference between the refrigerant (N₂) and BOG. The level of perfection of the compander unit is insufficient. The operation results of such equipment have shown that the turbine and compressor have low-efficiency values.

According to the study results, it can be stated that the processes in the N₂ loop do not meet the IMO requirements for modern gas carriers today. Despite such reliquefaction plants are easy to operate and do not require mandatory shore maintenance and special training of maintenance personnel. The energy efficiency management of the reliquefaction plant should improve the processes of the N₂ loop.

CRediT author statement

Victoriia Sokolovska-Yefymenko: Methodology, Writing – Original Draft, Project administration, Supervision. **Larisa Morosuk:** Conceptualization, Formal analysis, Writing – Review & Editing. **Volodymyr Ierin:** Investigation, Data Curation, Writing – Review & Editing. **Oleksandr Yefymenko:** Funding acquisition, Resources, Software. **Andrii Moshkatiuk:** Visualization, Validation.

References

1. U.S. Energy Information Administration. Effects of fossil fuels on climate change study, US Energy Information Administration. 1998. Retrived 13 February 2024 from <https://www.eia.gov>.
2. Energy Transitions Commission. The future of fossil fuels: how to steer fossil fuel use in a transition to a low-carbon energy system. 2017. Retrived 13

- February 2024 from <https://www.energy-transitions.org/publications/the-future-of-fossil-fuels/>.
3. **Romera, B.M.** (2016). The Paris Agreement and the Regulation of International Bunker Fuels. *Review of European, Comparative & International Environmental Law* 25(2), 215-227. <https://doi.org/10.1111/reel.12170>
 4. **Jin, C., Lim, Y., Xu, X.** (2023) Performance analysis of a boil-off gas re-liquefaction process for LNG carriers. *Energy* 278, 127823. <https://doi.org/10.1016/j.energy.2023.127823>
 5. Annex VI of MARPOL 73/78-Regulations for the Prevention of Air Pollution from Ships. Retrived 13 February 2024 <https://www.maritimenz.govt.nz/rules/MARPOL-Annex-VI/default.asp>.
 6. Vessel Finder. UMM AL AMAD, LNG Tanker, IMO 9360829, 2008. Retrived 13 February 2024 <https://www.vesselfinder.com/ru/vessels/UMM-AL-AMAD-IMO-9360829-MMSI-538003073>.
 7. **Yin, L., Ju, Y.** (2022) Review on the design and optimization of BOG re-liquefaction process in LNG ship. *Energy* 244, 123065. <https://doi.org/10.1016/j.energy.2021.123065>.
 8. **Gómez, J.R., Gómez, M.R., Garcia, R.F., Catoira, A.D.M.** (2014) On board LNG reliquefaction technology: a comparative study. *Polish Maritime Research* 21, 77-88. <https://doi.org/10.2478/pomr-2014-0011>
 9. **Yoneyama, H., Irie, T., Hatanaka, N.** (2003) The first BOG reliquefaction system on board ship in the world “LNG Jamal”. *Proceedings of the 22nd World Gas Conference, June 1-5, Tokyo, Japan*.
 10. **Pil, C.K., Rausand, M., Vatn, J.** (2008) Reliability assessment of reliquefaction systems on LNG carriers. *Reliability Engineering & System Safety* 93, 1345-1353. <https://doi.org/10.1016/j.ress.2006.11.005>.
 11. **Shin, Y., Lee, Y.P.** (2009) Design of a boil-off natural gas reliquefaction control system for LNG carriers. *Appl. Energy* 86, 37-44. <https://doi.org/10.1016/j.apenergy.2008.03.019>
 12. **Sayyaadi, H., Babaelahi, M.** (2010) Thermo-economic optimization of a cryogenic refrigeration cycle for re-liquefaction of the LNG boil-off gas. *Int. J. Refrigeration* 33, 1197-1207. <https://doi.org/10.1016/j.ijrefrig.2010.03.008>
 13. **Kochunni, S.K., Ghosh, P., Chowdhury, K.** (2015) Optimization of UA of heat exchangers and BOG compressor exit pressure of LNG boil-off gas reliquefaction system using exergy analysis. *IOP Conference Series: Materials Science and Engineering* 101, 012090. <http://dx.doi.org/10.1088/1757-899X/101/1/012090>
 14. **Kwak, D.-H., Heo, J.-H., Park, S.-H., Seo, S.-J., Kim, J.-K.** (2018) Energy-efficient design and optimization of boil-off gas (BOG) re-liquefaction process for liquefied natural gas (LNG)-fuelled ship. *Energy* 148, 915-929. <https://doi.org/10.1016/j.energy.2018.01.154>
 15. **Yin, L., Ju, Y.L.** (2019) Comparison and analysis of two nitrogen expansion cycles for BOG Re-liquefaction systems for small LNG ships. *Energy* 172, 769-776. <https://doi.org/10.1016/j.energy.2019.02.038>
 16. **Kochunni, S.K., Chowdhury, K.** (2019) LNG boil-off gas reliquefaction by Brayton refrigeration system – Part 1: Exergy analysis and design of the basic configuration. *Energy* 176, 753-764. <https://doi.org/10.1016/j.energy.2019.04.032>
 17. **Kochunni, S.K., Joy, J., Chowdhury, K.** (2019) LNG boil-off gas reliquefaction by Brayton refrigeration system – Part 2: Improvements over basic configuration. *Energy* 176, 861-873. <https://doi.org/10.1016/j.energy.2019.04.033>
 18. **Kochunni, S.K., Chowdhury, K.** (2020) Zero methane loss in reliquefaction of boil-off gas in liquefied natural gas carrier ships by using packed bed distillation in reverse Brayton system. *Journal of Cleaner Production* 260, 121037. <https://doi.org/10.1016/j.jclepro.2020.121037>
 19. **Son, H., Kim, J.-K.** (2020) Energy-efficient process design and optimization of dual-expansion systems for BOG (Boil-off gas) Re-liquefaction process in LNG-fueled ship. *Energy* 203, 117823. <https://doi.org/10.1016/j.energy.2020.117823>
 20. **Wang, Z., Han, F., Ji, Y., Li, W.** (2020) Analysis on feasibility of a novel cryogenic heat exchange network with liquid nitrogen regeneration process for onboard liquefied natural gas reliquefaction. *Case Studies in Thermal Engineering* 22, 100760. <https://doi.org/10.1016/j.csite.2020.100760>
 21. **Kim, J.-S., Kim, D.-Y.** (2023) Energy, Exergy, and Economic (3E) Analysis of Boil-Off Gas Re-Liquefaction Systems Using LNG Cold Energy for LNG-Fueled Ships. *Journal of Marine Science and Engineering* 11, 587. <https://www.mdpi.com/2077-1312/11/3/587>
 22. **Park, Y.I.L., Lee, J.H.** (2018) Buckling strength of GTT NO96 LNG Carrier cargo containment system. *Ocean Engineering* 154, 43-58. <https://doi.org/10.1016/j.oceaneng.2018.02.017>

23. Lemmon, E.W.; Bell, I.H.; Huber, M.L.; McLinden, M.O. (2018) Reference fluid thermodynamic and transport properties database (REFPROP), Version 10.0; NIST Standard Reference Database 23; National Institute of Standards and Technology: Gaithersburg, MD, USA. <http://dx.doi.org/10.18434/T4/1502528>
24. Morozyuk, L., Sokolovska-Yefymenko, V., Gayduk, S., Moshkatiuk, A. (2018) Entropy-based methods applied to the evaluation of a real refrigeration machine. *Eastern-European Journal of Enterprise Technologies* 6(8), 49-56. <https://doi.org/10.15587/1729-4061.2018.147710>
25. Morosuk, L., Sokolovska-Yefymenko, V., Ierin, V., Yefymenko, O., Moshkatiuk, A. (2022) Thermodynamic analysis of a real marine refrigeration system for cruise ship “Scarlet Lady”. *Refrigeration Engineering and Technology* 58, 80-91. <https://doi.org/10.15673/ret.v58i2.2384>

Received 13 February 2024

Approved 28 March 2024

Available in Internet 10 April 2024

Методи управління енергоефективністю установки повторного зрідження, що працює за зворотним циклом брайттона танкера-газовоза LNG

В.В. Соколовська-Єфименко^{1✉}, Л.І. Морозюк², В.О. Єрін³, О.О. Єфименко⁴, А.В. Мошкатиук⁵

^{1,2,4,5}Одеський національний технологічний університет, вул. Канатна, 112, Одеса, 65039, Україна;

³Технологічний університет Нінбо, 1 Qian Hu South Road, Нінбо, 315100, Китай

✉ e-mail: ¹kli24062006@gmail.com

ORCID: ¹<http://orcid.org/0000-0002-7275-5061>; ²<http://orcid.org/0000-0003-4133-1984>; ³<http://orcid.org/0000-0001-7941-9725>; ⁴<http://orcid.org/0000-0003-2571-9292>; ⁵<http://orcid.org/0000-0003-3354-0321>

На далекі морські та океанські дистанції LNG транспортують лише танкерами, що називаються газовозами LNG, у великих бортових резервуарах при температурі -163°C . Хоча ці резервуари добре ізольовані, частина LNG випаровується під впливом зовнішніх факторів та утворюється відпарний газ (BOG). Основним методом боротьби з BOG є його повторне зрідження. Значна кількість газовозів LNG для повторного зрідження використовують технологію, що ґрунтується на зворотному циклі Брайтона (ЗЦБ). У роботі проведено дослідження методами термодинамічного аналізу дійсних параметрів та характеристик установки повторного зрідження BOG на підставі даних, отриманих під час експлуатації танкера-газовозу LNG «UMM AL AMAD». В аналізі використані: енергетичний та ентропійно-статистичний методи термодинамічного аналізу. Оцінка роботи установки проводилася за відносними витратами роботи в компресорах та значенням показника термодинамічної ефективності. Аналіз отриманих результатів показав, що досліджувана установка, яка працює за циклом Брайтона має низькі значення енергетичної ефективності. Найбільш енергоємним є азотний контур. На його частку припадає понад 90% перевитрати роботи в установці загалом. Найбільший внесок у виробництво ентропії азотного контуру вносить перевитрата роботи в агрегаті компандер – 56,4% (у детандері – 7,7%, у компресорі N2 – 48,7%). У контурі BOG/LNG основна перевитрата роботи спостерігається в компресорі BOG ~ 3,7% і попередньому охолоджувачі ~1,55% від загальної незворотності процесу зрідження. Кріогенний теплообмінник є елементом обох контурів, його негативний вплив оцінюється в 36,4% від загальної незворотності процесу зрідження. Застосування установок повторного зрідження, що працюють за циклом Брайтона, на сьогодні технологічно недосконале через низьку енергетичну ефективність і величезні втрати в азотному контурі – це не відповідає вимогам ІМО, які висуваються до танкерів-газовозів.

Ключові слова: Танкер-газовоз LNG; Установка повторного зрідження; Енергоефективність; Ентропійно-статистичний метод.

Література

1. U.S. Energy Information Administration. Effects of fossil fuels on climate change study, US Energy Information Administration. 1998. URL: <https://www.eia.gov> (дата звернення 13.02.2024)
2. Energy Transitions Commission. The future of fossil fuels: how to steer fossil fuel use in a transition

- to a low-carbon energy system. 2017. URL: <https://www.energy-transitions.org/publications/the-future-of-fossil-fuels/> (дата звернення 13.02.2024).
3. **Romera B.M.** The Paris Agreement and the Regulation of International Bunker Fuels // *Review of European, Comparative & International Environmental Law*. – 2016. – Vol. 25(2). – P. 215-227.
 4. **Jin C., Lim Y., Xu X.** Performance analysis of a boil-off gas re-liquefaction process for LNG carriers // *Energy*. – 2023. – Vol. 278. – P. 127823.
 5. Annex VI of MARPOL 73/78-Regulations for the Prevention of Air Pollution from Ships. URL: <https://www.maritimenz.govt.nz/rules/MARPOL-Annex-VI/default.asp> (дата звернення 13.02.2024)
 6. Vessel Finder. UMM AL AMAD, LNG Tanker, IMO 9360829, 2008. URL: <https://www.vesselfinder.com/ru/vessels/UMM-AL-AMAD-IMO-9360829-MMSI-538003073> (дата звернення 13.02.2024)
 7. **Yin L., Ju Y.** Review on the design and optimization of BOG re-liquefaction process in LNG ship // *Energy*. – 2022. – Vol. 244. – P. 123065.
 8. **Gómez J.R., Gómez M.R., Garcia R.F., Catoira A.D.M.** On board LNG reliquefaction technology: a comparative study // *Polish Maritime Research*. – 2014. – Vol. 21. – P. 77-88.
 9. **Yoneyama H., Irie T., Hatanaka N.** The first BOG reliquefaction system on board ship in the world “LNG Jamal” // *Proceedings of the 22nd World Gas Conference*, June 1-5, Tokyo, Japan. – 2003.
 10. **Pil C.K., Rausand M., Vatn J.** Reliability assessment of reliquefaction systems on LNG carriers // *Reliability Engineering & System Safety*. – 2008. – Vol. 93. – P. 1345-1353.
 11. **Shin Y., Lee Y.P.** Design of a boil-off natural gas reliquefaction control system for LNG carriers // *Applied Energy*. – 2009. – Vol. 86. – P. 37-44.
 12. **Sayyaadi H., Babaelahi M.** Thermoeconomic optimization of a cryogenic refrigeration cycle for reliquefaction of the LNG boil-off gas // *International Journal of Refrigeration*. – 2010. – Vol. 33. – P. 1197-1207.
 13. **Kochunni S.K., Ghosh P., Chowdhury K.** Optimization of UA of heat exchangers and BOG compressor exit pressure of LNG boil-off gas reliquefaction system using exergy analysis // *IOP Conference Series: Materials Science and Engineering*. – 2015. – Vol. 101. – P. 012090.
 14. **Kwak D.-H., Heo J.-H., Park S.-H., Seo S.-J., Kim J.-K.** Energy-efficient design and optimization of boil-off gas (BOG) re-liquefaction process for liquefied natural gas (LNG)-fuelled ship // *Energy*. – 2018. – Vol. 148. – P. 915-929.
 15. **Yin L., Ju Y.L.** Comparison and analysis of two nitrogen expansion cycles for BOG Reliquefaction systems for small LNG ships // *Energy*. – 2019. – Vol. 172. – P. 769-776.
 16. **Kochunni S.K., Chowdhury K.** LNG boil-off gas reliquefaction by Brayton refrigeration system – Part 1: Exergy analysis and design of the basic configuration // *Energy*. – 2019. – Vol. 176. – P. 753-764.
 17. **Kochunni S.K., Joy J., Chowdhury K.** LNG boil-off gas reliquefaction by Brayton refrigeration system – Part 2: Improvements over basic configuration // *Energy*. – 2019. – Vol. 176. – P. 861-873.
 18. **Kochunni S.K., Chowdhury K.** Zero methane loss in reliquefaction of boil-off gas in liquefied natural gas carrier ships by using packed bed distillation in reverse Brayton system // *Journal of Cleaner Production*. – 2020. – Vol. 260. – P. 121037.
 19. **Son H., Kim J.-K.** Energy-efficient process design and optimization of dual-expansion systems for BOG (Boil-off gas) Re-liquefaction process in LNG-fueled ship // *Energy*. – 2020. – Vol. 203. – P. 117823.
 20. **Wang Z., Han F., Ji Y., Li W.** Analysis on feasibility of a novel cryogenic heat exchange network with liquid nitrogen regeneration process for on-board liquefied natural gas reliquefaction // *Case Studies in Thermal Engineering*. – 2020. – Vol. 22. – P. 100760.
 21. **Kim J.-S., Kim D.-Y.** Energy, Exergy, and Economic (3E) Analysis of Boil-Off Gas Re-Liquefaction Systems Using LNG Cold Energy for LNG-Fueled Ships // *Journal of Marine Science and Engineering*. – 2023. – Vol. 11. – P. 587.
 22. **Park Y.I.L., Lee J.H.** Buckling strength of GTT NO96 LNG Carrier cargo containment system // *Ocean Engineering*. – 2018. – Vol. 154. – P. 43-58.
 23. **Lemmon E.W., Bell I.H., Huber M.L., McLinden M.O.** Reference fluid thermodynamic and transport properties database (REFPROP), Version 10.0; NIST Standard Reference Database 23; National Institute of Standards and Technology: Gaithersburg, MD, USA. – 2018.
 24. **Morozyuk L., Sokolovska-Yefymenko V., Gayduk S., Moshkatiuk A.** Entropy-based methods applied to the evaluation of a real refrigeration machine // *Eastern-European Journal of Enterprise Technologies*. – 2018. – Vol. 6(8). – P. 49-56.
 25. **Morozyuk L., Sokolovska-Yefymenko V., Ierin V., Yefymenko O., Moshkatiuk A.** Thermodynamic analysis of a real marine refrigeration system for cruise ship “Scarlet Lady” // *Refrigeration Engineering and Technology*. – 2022. – Vol. 58. – P. 80-91.