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CALCULATION AND ANALYSIS OF THE REDUCTION OF BOIL-OFF GAS GENERATION ON FLOATING STORAGE AND REGASIFICATION UNITS

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The problem of the formation of boil-off gas (BOG) during the storage of liquefied natural gas on floating storage and regasification units is considered in this paper. The relevance of the study is due to the growing role of LNG infrastructure in the global energy sector, the need to increase the energy efficiency of cryogenic systems and reduce the load on auxiliary equipment. The purpose of the paper is calculation and analysis of the impact of reducing the heat input on the intensity of boil-off gas formation and the related operational and environmental indicators. Thermodynamic analysis, parametric comparison of calculation modes and assessment of the methane equivalent indicator are applied in this paper. The dependence between the thermal load on the reservoir, the amount of boil-off gas formed and the load on its processing systems has been established. The obtained results can be used for further modeling of thermal processes, improving liquefied natural gas storage systems and substantiating technical solutions for floating regasification complexes.

Keywords: *liquefied natural gas; boil-off gas (BOG); floating storage and regasification unit; heat input; thermal insulation; energy efficiency.*

Introduction

Liquefied natural gas occupies an important place in the modern system of international energy trade, since it is possible to transport it by sea regardless of the presence of direct pipeline connections between the supplier and the consumer. The development of liquefied natural gas infrastructure contributes to the diversification of sources and routes of supply, increasing the flexibility of gas markets and expanding the possibilities of rapid response to changes in demand [1].

With the changing geopolitical situation in the world and the reorientation of energy flows, technologies that allow to create or increase capacities for receiving, storing and regasifying liquefied natural gas in a relatively short time are gaining special importance. One of such technological solutions is floating storage and regasification units, which combine the functions of receiving cargo, its cryogenic storage, regasification and further transmission of natural gas to the coastal infrastructure.

Compared to land-based terminals, floating storage and regasification units are characterized by greater flexibility in placement, the possibility of phased infrastructure development and a reduction in the volume of onshore construction work. At the same time, the efficiency of their operation largely depends on the perfection of cryogenic storage systems, thermal insulation parameters, the intensity of heat input to the tanks and the modes of boil-off gas (BOG) handling [2]. As is known, liquefied natural gas is stored at a temperature of about minus 162 °C, as a result of which a significant temperature difference arises between the ambient and cryogenic environment. Even with the use of modern thermal insulation materials, it is impossible to completely eliminate the heat flow to the tank. Part of this heat is spent on the phase transition, which is accompanied by the BOG formation. The intensity of this process depends on the tank design, the characteristics of the thermal insulation system, the ambient temperature, the level of the tanks filling and the operating mode of the unit.

The generated BOG can be used as fuel, compressed, recondensed or reliquefied. However, increasing its quantity leads to an increase in the load on the compressor, heat exchange and auxiliary equipment, complicates the pressure control in the tanks and affects the overall energy balance of the unit. Therefore, reducing the heat input to the liquefied natural gas should be considered not only as a task of improving thermal insulation, but as a component of increasing the efficiency of the entire energy system of the floating unit.

In addition, the BOG contains a high content of methane, which creates problems from the point of view of environmentalists. Methane is characterized by a significant global warming potential, so the volume of its formation, the method of further use and possible losses should be taken into account when assessing the environmental performance of the liquefied natural gas infrastructure [3, 4]. Reducing the BOG amount at the storage stage can simultaneously contribute to reducing energy losses, reducing the load on its processing systems and reducing the potential methane-equivalent impact.

In this regard, it is relevant to develop a computational and analytical approach that allows establishing the dependence between heat input, operating cycle duration, BOG formation intensity, and related operational indicators. The obtained dependences can be used as a basis for further detailing the heat balance of tanks, assessing the effectiveness of thermal insulation systems, and modeling BOG formation processes using specialized software.

The potential role of FSRU in the development of Ukraine's LNG infrastructure

For Ukraine, the development of liquefied natural gas infrastructure can be of great importance in the context of diversifying natural gas supply sources, increasing the flexibility of the gas transportation system and expanding the possibilities of integration with the European energy market. The presence of a developed gas transportation infrastructure and large underground storage facilities creates the prerequisites for using additional routes for natural gas supply, in particular, through regasification facilities in European countries and potentially – through its own offshore facilities.

Floating storage and regasification units can be considered as one of the options for the phased development of the national liquefied natural gas direction. Their use allows combining the functions of reception, storage and regasification within one floating unit, as well as reducing the volume of initial shore construction compared to a classic land terminal. For Ukraine, this can be especially important in the case of implementing projects aimed at phased capacity expansion and further integration with the gas transportation system.

The location of such unit should not be limited to one predetermined site. The choice of a specific coastal location should be based on a set of technical and economic criteria, including sufficient sea depth, the possibility of mooring large-tonnage gas carriers, proximity to gas transportation infrastructure, the availability of port communications, the availability of electricity supply and the possibility of further expansion of the complex. It is also important to coordinate the operating modes of the floating unit with the capacity of onshore networks and the projected volumes of natural gas consumption.

Previous initiatives to create a liquefied natural gas infrastructure in Ukraine confirm the interest in this direction. At the same time, the implementation of a full-scale floating or land-based terminal requires the participation of large companies with experience in the field of transportation, storage and regasification of liquefied natural gas. Such projects are associated with high capital intensity, the need to coordinate marine, port and gas transportation infrastructure, as well as the involvement of specialized technological equipment.

In the case of practical development of this direction, the efficiency of storage of liquefied natural gas on floating units will acquire independent technical significance. The magnitude of the heat input, the characteristics of thermal insulation systems, the intensity of the BOG formation and the load on auxiliary equipment will directly affect the operating costs and overall energy efficiency of the complex. Therefore, the assessment of thermal processes in tanks should be a component of the feasibility study of future projects.

Regarding our country, we note that in Ukrainian realities, seasonal changes in air and sea water temperature, the intensity of solar radiation, cargo acceptance modes and the regasification schedule should be taken into account. These factors will determine the actual heat balance of the floating unit and the intensity of the BOG formation. Accordingly, the results of the calculation and analytical assessment can be used when choosing the configuration of tanks, thermal insulation parameters, the performance of the systems for BOG handling and the operating modes of auxiliary equipment.

Thus, the potential use of floating storage and regasification units in Ukraine should be considered not only as a logistics or infrastructure project, but also as a complex task of power engineering. Its solution requires a deep analysis of thermal processes, cryogenic equipment, regasification systems, energy supply and integration with the onshore gas transmission network.

The problem of BOG formation during LNG storage

Liquefied natural gas is stored at cryogenic temperatures close to its saturation temperature. Under such conditions, even a small amount of heat input to the tank causes the evaporation of part of the liquid phase and the BOG formation. The intensity of this process is determined by the magnitude of the external heat input, the thermodynamic properties of liquefied natural gas, the tank design, the thermal insulation characteristics, and the operating mode of the unit.

The thermal load on the tank is formed due to thermal conductivity through the body and thermal insulation layers, convective heat exchange with the external environment, solar radiation, and thermal bridges in the places where pipelines, supports, fittings, and other structural elements pass. For floating units, as already mentioned, additional importance is given to the temperature of the sea water, daily and seasonal changes in air temperature, wind speed, the position of the vessel relative to solar radiation, and the variable level of the tanks filling.

In a simplified form, the heat input entering the tank can be determined by the relation

$$Q = \frac{\Delta T}{R_{\Sigma}},$$

where Q is the heat input, W; ΔT is the temperature difference between the environment and the liquefied natural gas, K; R_{Σ} is the total thermal resistance of the tank structure and the thermal insulation system, K/W

For a surface with a known area and a given heat transfer coefficient, the dependence can be written as

$$Q = k \cdot A \cdot \Delta T,$$

where k is the total heat transfer coefficient, W/(m²·K); A is the heat exchange surface area, m².

The abovementioned dependencies show that the intensity of heat input is determined not only by the temperature difference, but also by the structure of the thermal insulation circuit. An increase in the total thermal resistance or a decrease in local thermal bridges directly reduces the amount of heat entering the cryogenic medium.

Part of the received heat is spent on heating the liquid phase, and part of it – on the phase transition with the BOG formation. Under conditions close to the quasi-stationary mode, the mass of the formed BOG can be estimated by the ratio

$$m_{\text{BOG}} = \frac{Q \cdot \tau}{h_v},$$

where m_{BOG} is the BOG mass, kg; τ is the duration of the calculation period, s; h_v is the specific heat of the liquefied natural gas vaporization, J/kg.

This dependence implies that, with unchanged thermodynamic properties of the product, the amount of BOG is directly proportional to the heat input and storage duration. That is why, when comparing different modes, it is necessary to simultaneously take into account both the daily BOG formation coefficient and the actual duration of the operating cycle.

For practical assessments, the daily BOG formation coefficient, which characterizes the share of liquefied natural gas that passes into the gas phase during the day, is often used. Its value depends on the tank type, the technical condition of thermal insulation, temperature conditions, filling level and operating mode. For modern storage systems, lower values of this indicator are typical compared to units of previous generations, which is associated with the improvement of thermal insulation materials and tank design [5, 6].

The BOG formation affects the pressure in the gas space of the tank. With insufficient gas extraction, its accumulation leads to an increase in pressure, which requires the operation of compression systems, gas supply to the fuel system, recondensation or re-liquefaction. Accordingly, the amount of heat input indirectly determines the load on compressors, heat exchangers, pipelines, valves and automatic control systems.

On floating storage and regasification units, the mode of BOG formation is additionally related to the regasification performance. At high rates of LNG withdrawal, part of the heat and mass balance is compensated by a constant decrease in the amount of product in the tanks. During periods of reduced withdrawal or temporary reduction of gas supply to the onshore network, BOG can accumulate faster, which increases the requirements for its processing systems.

Thus, the BOG amount is an integral indicator of the thermal efficiency of the storage system. Its reduction can be achieved by improving thermal insulation, reducing local heat inputs, optimizing operating modes and coordinating the operation of tanks with regasification systems and BOG the use.

Modern thermal insulation solutions and methods for assessing heat input and BOG formation

The efficiency of liquefied natural gas storage is largely determined by the design of the thermal insulation system of the tanks. Its main task is to reduce the heat flow from the environment to the cryogenic product, maintain an acceptable temperature field in the structural elements and limit the intensity of the BOG formation.

Modern storage systems use multilayer thermal insulation structures, which may include polyurethane foam, perlite, fiberglass, composite and other materials with low thermal conductivity. The choice of thermal insulation depends on the tank type, its geometry, fastening method, permissible mass of the structure, resistance to cyclic thermal loads and durability requirements.

Thus, for membrane tanks, the thermal insulation system simultaneously performs the functions of thermal protection, load transfer to the ship's hull and the tightness maintaining of the cargo circuit. In such structures, special attention is paid to the joints of thermal insulation panels, membrane attachment points and pipeline passage areas. These zones can form local thermal bridges and increase the unevenness of the temperature field.

In self-supporting tanks, thermal insulation is located around the outer surface of the tank, while its temperature deformations must be taken into account. For spherical and prismatic tanks, the uniformity of the thickness of the thermal insulation, the tightness of the vapor barrier layer and the minimization of heat input through the supporting elements are important. Even with high efficiency of the main thermal insulation array, a significant portion of the heat load can come through structural components, fittings, pipelines and supports.

A separate direction of improvement is the use of vacuum and multilayer thermal insulation systems. They provide low values of effective thermal conductivity, but require stable vacuum, reliable sealing and more complex control of the technical condition. For large-sized ship and floating tanks, the use of such systems is limited by structural complexity, cost and requirements for maintainability.

The estimation of heat input can be performed at different levels of detail. At the initial stage, one-dimensional stationary models, in which the heat input is determined through the total thermal resistance of the thermal insulation layers, are used. It allows to estimate the average heat input and compare several options of the thermal insulation design.

For a multilayer system, the total thermal resistance can be defined as

$$R_{\Sigma} = \frac{1}{\alpha_{\text{ext}} \cdot A} + \sum \frac{\delta_i}{\lambda_i \cdot A} + \frac{1}{\alpha_{\text{in}} \cdot A},$$

where α_{ext} – heat transfer coefficient from the external environment, W/(m²·K); α_{in} – heat transfer coefficient from the inside of the tank, W/(m²·K); δ_i – thickness of a separate layer, m; λ_i – thermal conductivity coefficient of the corresponding material, W/(m·K); A – heat exchange area, m².

With a known total thermal resistance, the heat flow is defined as

$$Q = \frac{T_{\text{ext}} - T_{\text{LNG}}}{R_{\Sigma}}.$$

This representation is convenient for preliminary engineering calculations; however, it does not take into account the spatial non-uniformity of the temperature field, local thermal bridges, changes in solar load and dynamics of the liquefied natural gas level.

For a more detailed analysis, two- and three-dimensional heat conductivity models are used. They allow to study the temperature distribution in the structure, determine areas of increased heat flow and assess the influence of joints, supports and pipeline passages. Such models can be implemented using the finite element or finite volume method.

Non-stationary modeling is necessary in cases where external conditions and operating modes change over time. Such factors include daily fluctuations in air temperature, changes in solar radiation, fluctuations in sea water temperature, changes in the tank filling level, and uneven regasification mode. In this case, the heat balance must take into account the heat capacity of the structural layers and the liquefied natural gas itself.

Specialized process modeling software packages can be used to model the storage, vaporization, compression, and regasification processes. For example, Aspen HYSYS allows to create thermodynamic models of liquefied natural gas flows, evaluate phase equilibrium, the operation of compressors, heat exchangers, and re-liquefaction systems. It is advisable to use it to study the relation between heat input, BOG formation, and the operation of auxiliary equipment.

At the same time, Aspen HYSYS does not replace a detailed spatial calculation of the thermal insulation structure. Therefore, the most complete approach involves combining a heat transfer model in the tank shell with a process model of the movement and BOG processing. The results of the thermal calculation can be used as an initial heat load for the tank model in the process environment.

In modern research, considerable attention is also paid to systems for handling already formed BOG. The main solutions include its use as fuel, compression and supply to the gas network, recondensation and re-liquefaction. The choice of a specific method depends on the BOG amount, the operating mode of the unit, the presence of gas fuel consumers and energy costs for its processing [7–10].

Re-liquefaction systems allow the BOG to be returned to the liquid phase, but require significant electrical energy costs for compression and cooling. The efficiency of such systems is determined by the refrigeration cycle scheme, the temperature and pressure of the BOG, the composition of the natural gas and the performance of the equipment [7, 9, 10].

The BOG use as a fuel reduces the need for its re-liquefaction, but links the gas balance with the load of the ship's power unit. With a low fuel demand, the excess BOG still requires compression, recondensation or another method of disposal.

Recondensation, in turn, is effective if there is a sufficient flow of supercooled liquefied natural gas. In this case, the BOG after compression is mixed with the liquid phase and condensed due to its cold potential. For floating storage and regasification units, the feasibility of such a solution depends on the mode of liquefied natural gas withdrawal and regasification performance.

A separate direction is the use of the cold potential of liquefied natural gas and BOG in integrated energy systems. Cold energy can be used for pre-cooling of working environments, maintaining low-temperature processes or reducing the energy consumption of auxiliary equipment [11].

Analysis of current approaches shows that effective BOG management should combine two complementary directions: reducing its formation by improving thermal insulation and thermal regime of tanks, as well as energy-efficient treatment of already formed gas. Further research should be directed to quantitative assessment of heat input, determining the influence of properties of thermal insulation materials and forming an integrated model of the tank and BOG handling system.

Purpose, objectives and research methodology

The purpose of the study is a computational and analytical assessment of the impact of reducing heat input on the BOG formation during storage of liquefied natural gas on floating storage and regasification facilities.

To achieve this goal, the following tasks have been defined:

– analysis of the relation between the heat input to the cryogenic tank and the intensity of BOG formation;

– assessment of the impact of the BOG formation daily coefficient on its accumulation during the operating cycle;

– determination of the change in the volume and BOG mass at different levels of thermal load;

– assessment of the impact of reducing BOG formation on the load of compression, recondensation, re-liquefaction and fuel preparation systems;

– determination of the potential change in the methane equivalent indicator;

– formation of the starting points for further mathematical and software modeling of thermal processes in liquefied natural gas tanks.

The research methodology is based on a combination of thermodynamic analysis, parametric calculation estimation and comparison of operating modes. The main initial parameter is the daily BOG formation coefficient, which characterizes the fraction of the volume of liquefied natural gas that passes into the gas phase during one day.

For the calculation, a model configuration of a floating storage and regasification unit with a total tank capacity of 178,000 m^3 was adopted. This capacity corresponds to the modern large-tonnage class of gas carriers and allows to estimate the order of magnitude for an industrial liquefied natural gas storage system.

The duration of the basic operating cycle is taken to be eight days. This period is used as an approximate interval between consecutive supplies of liquefied natural gas for a terminal with a given annual productivity. To assess the scalable effect, the results of one cycle can be aggregated for a monthly or annual period without assuming continuous storage of one batch of cargo for a long time.

The calculations consider daily BOG formation rates of 0.02; 0.05 and 0.10 %/day. The first two values characterize the current level of thermal insulation efficiency, while the value of 0.10 %/day is used as a comparative mode for systems with higher heat input.

The BOG volume in the liquid phase equivalent during one operating cycle is determined by the ratio

$$V_{\mathrm{BOG}} = V_0 \cdot r_{\mathrm{BOG}} \cdot \tau,$$

where V_{BOG} is the volume of liquefied natural gas that has turned into BOG as, m³; V_0 is the initial volume of liquefied natural gas in tanks, m³; r_{BOG} is the daily BOG formation rate, fraction per day; τ is the duration of the operating cycle, days

The mass equivalent of the formed BOG is determined by the formula

$$m_{\mathrm{BOG}} = V_{\mathrm{BOG}} \cdot \rho_{\mathrm{LNG}},$$

where m_{BOG} is the mass of liquefied natural gas converted into BOG, kg; ρ_{LNG} is the density of liquefied natural gas, kg/m³.

For the preliminary assessment, the density of liquefied natural gas is assumed to be 450 kg/m³. The density value may vary depending on the component structure, temperature and pressure; however, the adopted value is sufficient for a comparative calculation assessment.

The impact of the reduction in heat input is assessed through the relative change in the amount of formed BOG. Under the assumption of a directly proportional relation between heat load and vaporization, reducing the heat input by a given value leads to a corresponding reduction in the BOG volume

$$V_{\mathrm{BOG}}^{\mathrm{red}} = V_{\mathrm{BOG}}(1 - \delta Q),$$

where $V_{\mathrm{BOG}}^{\mathrm{red}}$ is the BOG volume after reducing the heat input, m³; δQ is the relative reduction in the heat input.

To assess the sensitivity, the levels of heat input reduction by 5 and 10% are considered. Such a comparison allows to determine the change in the BOG volume and mass without reference to the specific design of the thermal insulation system.

The methane equivalent indicator is defined as a potential environmental indicator that characterizes the change in the amount of methane associated with a decrease in the BOG formation. For its assessment, the 100-year global warming potential of methane is used in accordance with the recommendations of the Intergovernmental Panel on Climate Change [3].

The next stage of the study involves the detailed analysis of the heat balance of the tanks, taking into account the design of the thermal insulation layers, external climatic loads, the level of tank filling and the regasification mode. It is planned to perform modeling of heat and mass transfer processes using Aspen HYSYS or a similar software environment with subsequent comparison of the results for different thermal insulation options and operating modes.

Calculation and analytical assessment of the BOG formation

For the quantitative assessment, a model configuration of a floating storage and regasification facility with a total tank capacity of 178,000 m³ was adopted. The calculation was performed for one eight-day operating cycle, which is considered (and this has already been discussed) as an approximate interval between consecutive supplies of liquefied natural gas.

The daily volume of liquefied natural gas converted to BOG is determined by the formula

$$V_{\mathrm{BOG}}^{\mathrm{day}} = V_0 \cdot r_{\mathrm{BOG}},$$

where $V_{\mathrm{BOG}}^{\mathrm{day}}$ is the daily volume of liquefied natural gas converted to BOG, m³/day; V_0 is the initial volume of liquefied natural gas, m³; r_{BOG} is the daily BOG formation coefficient.

For a daily coefficient of 0.02% – $V_{\mathrm{BOG}}^{\mathrm{day}} = 178000 \cdot 0.0002 = 35.6$ m³/day. For eight days – $V_{\mathrm{BOG}}^{8} = 35.6 \cdot 8 = 284.8$ m³.

For a daily coefficient of 0.05% – $V_{\mathrm{BOG}}^{\mathrm{day}} = 178000 \cdot 0.0005 = 89.0$ m³/day, $V_{\mathrm{BOG}}^{8} = 89.0 \cdot 8 = 712.0$ m³.

For a daily coefficient of 0.10% – $V_{\mathrm{BOG}}^{\mathrm{day}} = 178000 \cdot 0.001 = 178.0$ m³/day, $V_{\mathrm{BOG}}^{8} = 178.0 \cdot 8 = 1424.0$ m³.

The mass equivalent is determined for a density of liquefied natural gas of 450 kg/m³. The calculation results are given in Table 1.

Table 1. BOG formation during an eight-day operating cycle

Daily coefficient of BOG generation, %/day	BOG generation, m³ LNG-eq./day	BOG generation, m³ LNG-eq./cycle	Mass equivalent, t/cycle
0.02	35.6	284.8	128.16
0.05	89.0	712.0	320.40
0.10	178.0	1424.0	640.80

Note: The volume of BOG is given in liquid phase equivalent, i.e. as the volume of liquefied natural gas that has passed into a gaseous state

The obtained values demonstrate a significant dependence of the absolute amount of BOG on the efficiency of the thermal insulation system. At a daily coefficient of 0.02%, 284.8 m³ of liquefied natural gas is converted into BOG during one operating cycle, while at a coefficient of 0.10% this indicator increases to 1424 m³. Thus, a fivefold increase in the daily coefficient causes a corresponding fivefold increase in the load on the BOG handling systems.

To assess the impact of reducing the heat input, two levels of its reduction were considered – and 10%. Given the adopted proportional relation between the heat input and the amount of BOG formed, the calculated reduction is determined by the formula

$$\Delta V_{\text{BOG}} = V_{BOG} \cdot \delta Q ,$$

where ΔV_{BOG} is the reduction in the BOG volume, m³; δQ is the relative reduction in the heat input.

The results are given in Table 2.

Table 2. Effect of heat input reduction on BOG formation over an eight-day cycle

Daily coefficient, %/day	Reducing heat input, %	BOG generation after heat input reduction, m³ LNG-eq./cycle	BOG reduction, m³ LNG-eq./cycle	Mass equivalent reduction, t/cycle
0.02	5	270.56	14.24	6.41
0.02	10	256.32	28.48	12.82
0.05	5	676.40	35.60	16.02
0.05	10	640.80	71.20	32.04
0.10	5	1352.80	71.20	32.04
0.10	10	1281.60	142.40	64.08

From Table 2 it is clear that the absolute effect of reducing the heat input depends on the initial level of BOG formation. For the most effective thermal insulation system with a daily coefficient of 0.02%, a 10% reduction in heat input provides a reduction in BOG by 28.48 m³ per cycle. For an initial coefficient of 0.10%, a similar relative reduction in heat input corresponds to a reduction of 142.4 m³ per cycle. For a visual comparison of the effect of reduced heat input on boil-off gas formation, the calculation results are presented in Fig. 1. The graph illustrates the change in the absolute reduction of boil-off gas volume for three adopted daily coefficients and two levels of heat input reduction.

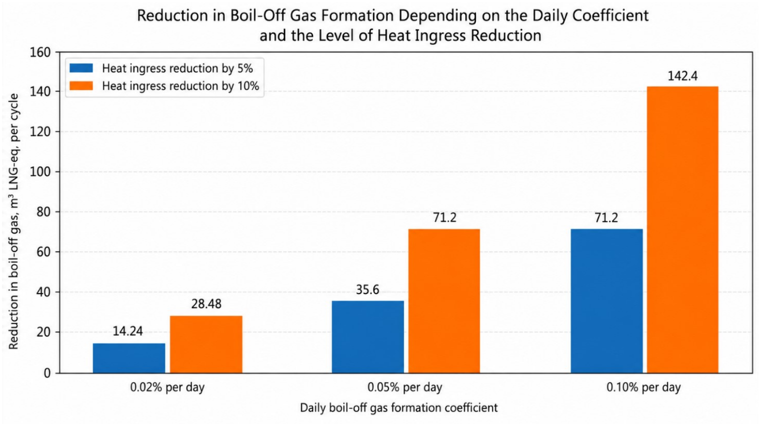

Fig. 1. Reduction of the BOG formation depending on the daily rate and the level of heat input reduction

The graphic comparison confirms that the absolute reduction of the BOG formation increases in proportion to the initial daily coefficient and the level of heat input reduction. For the 0.05%/day mode, a reduction of the heat input by 5–10% corresponds to a reduction of the BOG formation by 35.6–71.2 m³ of LNG-equivalent per one operating cycle.

For a modern system with a daily coefficient of 0.05%, a reduction of the heat input by 5–10% allows to reduce the BOG formation by 35.6–71.2 m³ per one operating cycle, which corresponds to 16.02–32.04 t of liquefied natural gas. This result characterizes not only the preservation of the product, but also the possible reduction of the load on the compressors, heat exchangers, recondensation and re-liquefaction systems.

To assess the long-term scale, the results of one cycle can be aggregated by the number of consecutive operating cycles. In this case, it is not assumed that one batch of liquefied natural gas will be stored continuously for a month or a year. The scaling reflects the total effect of repeated cycles of reception, storage and regasification.

With an estimated number of 44 operating cycles per year for a mode with a daily coefficient of 0.05% and a reduction in heat input by 10%, the annual reduction in the BOG formation will be

$$\Delta V_{\text{BOG}}^{\text{year}} = 71.2 \cdot 44 = 3132.8 \text{ m}^3 \text{ LNG-eq./year}.$$

The mass equivalent of such a reduction is

$$\Delta m_{\text{BOG}}^{\text{year}} = 32.04 \cdot 44 = 1409.76 \text{ т/рік}.$$

The given scaling shows that even a relatively small reduction in heat input within one operating cycle can have a noticeable cumulative effect over the long-term operation of a floating unit.

Estimation of methane equivalent

The BOG is formed mainly from the light components of liquefied natural gas, among which methane dominates. Therefore, a decrease in the amount of BOG can affect not only the energy balance of the unit, but also its potential environmental performance. At the same time, the amount of formed BOG should not be directly identified with the actual methane emissions, since under operating conditions the gas can be used as fuel, sent for recondensation, re-liquefaction or supplied to the onshore gas system.

Within the framework of the study, the methane equivalent indicator was used as a comparative indicator of the potential environmental effect of reducing the BOG formation. Its definition is based on the mass equivalent of the reduced BOG and the global warming potential of methane.

The general expression for the assessment can be given in the form

$$E_{\text{CO}_2-\text{eq}} = \Delta m_{\text{BOG}} \cdot x_{\text{CH}_4} \cdot f_{\text{rel}} \cdot GWP_{\text{CH}_4},$$

where $E_{\text{CO}_2\text{-eq}}$ is the methane equivalent indicator, t CO_2-eq; Δm_{BOG} is the mass equivalent of reduced BOG, t; x_{CH_4} is the mass fraction of methane in BOG; f_{rel} is the fraction of gas that can potentially be lost to the environment; GWP_{CH_4} is the global warming potential of methane.

According to the Intergovernmental Panel on Climate Change, the 100-year global warming potential of fossil methane is 29.8 relative to carbon dioxide [3].

To compare the calculation modes, a limit methane-equivalent indicator is adopted, for which x_{CH_4}=1 and f_{rel}=1. This approach does not characterize the actual emissions of a particular floating unit, but shows the maximum potential climate equivalent of the corresponding mass of methane. In real conditions, the indicator value should be adjusted taking into account the component composition of BOG and the actual share of its losses.

For a mode with a daily coefficient of BOG formation of 0.05%, a 5% reduction in heat input provides a reduction in the mass equivalent of BOG by 16.02 t per eight-day cycle. The marginal methane equivalent indicator will be

$$E_{\text{CO}_2-\text{eq}}^{5} = 16.02 \cdot 29.8 = 477.40 \text{ t CO}_2\text{-eq./cycle}.$$

For a 10% reduction in heat input, the mass equivalent of BOG reduction is 32.04 t per cycle

$$E_{\text{CO}_2-\text{eq}}^{10} = 32.04 \cdot 29.8 = 954.79 \text{ t CO}_2\text{-eq./cycle}.$$

The results for the considered daily coefficients are given in Table 3.

The data in Table 3 show that the methane equivalent effect directly depends on the initial intensity of the BOG formation and the relative reduction in the heat input. At a lower daily coefficient, the absolute effect is smaller, but the direct relation between the heat load, the BOG mass and the limiting methane equivalent indicator remains.

To assess the actual environmental effect, it is necessary to take into account the real BOG composition, the proportion of methane used as fuel, its combustion efficiency, the presence of unburned methane in the exhaust gases, the operation of the recondensation and re-liquefaction systems. Therefore, the given values should be used primarily to compare the design regimes and determine the potential direction of change in environmental indicators.

Reducing the BOG formation at the storage stage has a systemic advantage, since it reduces the amount of gas that must be further processed, compressed, burned or returned to the liquid phase. As a result, the environmental effect may occur not only through a reduction in potential methane losses, but also through a reduction in energy consumption of auxiliary equipment.

Table 3. The marginal methane equivalent indicator of reduction in BOG generation for an eight-day cycle

Daily coefficient of BOG generation, %/day	Reduce in heat input, %	Mass equivalent of reduced BOG, t/cycle	Limit methane equivalent, t CO_2-eq./cycle
0.02	5	6.41	191.02
0.02	10	12.82	382.04
0.05	5	16.02	477.40
0.05	10	32.04	954.79
0.10	5	32.04	954.79
0.10	10	64.08	1909.58

Note: The value is calculated as a marginal benchmark assuming that all the mass equivalent of the reduced BOG corresponds to methane. The indicators are not an estimate of the actual emissions of a specific unit

Discussion of results

The results of the calculation and analytical assessment show that the amount of BOG formation is determined by the simultaneous action of two main factors, namely: the initial daily coefficient of BOG formation and the duration of the operating cycle. With the same capacity of the tanks, even a relatively small change in the daily coefficient significantly affects the absolute volume of liquefied natural gas that passes into the gas phase.

For a model unit with a capacity of 178,000 m³ for an eight-day cycle, BOG formation is from 284.8 to 1424.0 m³ LNG equivalent, depending on the adopted daily coefficient. This range shows that the characteristics of the thermal insulation system directly affect not only the BOG amount, but also the performance of the equipment required for its further processing.

Reducing the heat input by 5–10% provides a proportional reduction in BOG generation. For a mode with a daily coefficient of 0.05% per day, which can be used as a baseline for a modern storage system, the reduction in heat input corresponds to a BOG reduction by 35.6–71.2 m³ of LNG equivalent per eight-day cycle. In mass terms, this is 16.02–32.04 t of liquefied natural gas.

The given values characterize not only the amount of stored product. The reduction in the BOG volume can reduce the load on compressors, heat exchangers, recondensation and re-liquefaction systems. Accordingly, the reduction in heat input can affect the auxiliary energy consumption, the duration of equipment operation and the overall energy balance of the floating unit.

The largest absolute effect is observed for modes with a higher initial daily coefficient of BOG formation. At the same time, this does not mean that systems with a lower coefficient are of less engineering interest. At the current level of thermal insulation, further reduction of heat input may be important for ensuring a more stable thermal mode, reducing the cyclicality of the operation of auxiliary equipment and increasing operational flexibility.

The use of an eight-day operating cycle allows the calculation to be linked to the mode of regular receipt and regasification of liquefied natural gas. Scaling of results to a monthly or annual period is performed by aggregating consecutive cycles, rather than by assuming long-term continuous storage of one batch of product. This approach reflects the operation of a terminal with a recurring supply schedule more correctly.

The methane equivalent indicator determined in the paper should be used as a comparative indicator. Its value characterizes the potential environmental effect of reducing the BOG mass, but is not an estimate of the actual emissions of a particular unit. To proceed to the actual assessment, it is necessary to take into account the BOG composition, the share of its use as fuel, combustion efficiency, the presence of unburned methane in exhaust gases and the operation of re-liquefaction systems.

The obtained dependencies also justify the feasibility of further transition from parametric estimation to detailed modeling of the heat balance of tanks. For this, it is necessary to take into account the geometry of the tanks, the properties of thermal insulation materials, local thermal bridges, ambient temperature, solar load, tank filling level and variable regasification performance.

Further modeling is advisable to perform in two stages. At the first stage, it is necessary to determine the spatial distribution of temperatures and heat flows in the tank structure. At the second stage, the obtained heat input values can be used in the Aspen HYSYS process model or a similar software environment to evaluate the BOG formation, the operation of compressors, heat exchangers and systems for its further use.

Thus, it is advisable to consider the reduction of heat input to tanks as a component of the comprehensive optimization of the floating storage and regasification unit. The effect of such a reduction is manifested in the reduction of liquefied natural gas losses, the reduction of the load on auxiliary equipment and the potential improvement of environmental indicators.

Research limitations and directions for further work

Further development of the study involves refining the heat balance of liquefied natural gas tanks and quantitatively assessing the impact of heat input on the BOG formation.

It is advisable to pay special attention to the analysis of the characteristics of thermal insulation systems and their impact on the daily coefficient of BOG formation. The level of detail of such an analysis will be determined by the availability of technical data on the design of tanks and thermal insulation materials.

A separate direction is the modeling of heat and mass transfer processes using Aspen HYSYS or similar software. Such modeling can be used to assess the relation between heat input, BOG formation, tank operation mode and load on auxiliary equipment.

It is also advisable to study variable operating modes, in particular, different operating cycle durations, tank filling levels, regasification performance and ambient temperature conditions.

Further refinement of the environmental assessment should include consideration of the BOG component structure, the proportion of its use as fuel, combustion efficiency and operating modes of re-liquefaction systems.

The obtained results can be used to further improve the methodology for assessing heat losses, select areas for increasing energy efficiency and justify technical solutions for floating storage and regasification units.

Conclusions

1. It was established that the intensity of the BOG formation during the storage of liquefied natural gas is determined by the amount of heat input, the daily evaporation coefficient and the operating cycle duration.

2. For a model floating storage and regasification unit with a capacity of 178,000 m^3 per eight-day cycle, the BOG formation is 284.8–1424.0 m^3 in terms of the volume of the liquid phase, depending on the adopted daily coefficient of 0.02–0.10% per day.

3. For a mode with a daily coefficient of BOG formation of 0.05% per day, a reduction in heat input by 5–10% corresponds to a reduction in BOG formation by 35.6–71.2 m^3 per eight-day cycle. The mass equivalent of such a reduction is 16.02–32.04 tons of liquefied natural gas.

4. Reducing the BOG formation can help reduce the load on compressor, heat exchange and other auxiliary equipment, as well as reduce energy costs for compression, recondensation or re-liquefaction.

5. The methane equivalent indicator should be used as a comparative indicator of the potential environmental effect. To determine the actual emissions, it is necessary to additionally take into account the BOG composition, its use, combustion efficiency and the operation of re-liquefaction systems.

6. The use of an eight-day operating cycle allows to link the calculation to the recurring processes of receiving, storing and regasifying liquefied natural gas. It is advisable to assess the monthly or annual effect by aggregating consecutive operating cycles.

7. Further research should be directed towards clarifying the heat balance of tanks, analyzing the impact of the characteristics of thermal insulation systems, and modeling the relation between heat input, BOG formation, and the operation of auxiliary equipment using Aspen HYSYS or similar software.

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Розрахунково-аналітична оцінка зменшення утворення випарного газу на плавучих установках зберігання й регазифікації

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У статті розглянуто проблему утворення випарного газу під час зберігання зрідженого природного газу на плавучих установках зберігання й регазифікації. Актуальність дослідження зумовлена зростанням ролі LNG-інфраструктури у світовій енергетиці, необхідністю підвищення енергоефективності кріогенних систем і зменшення навантаження на допоміжне обладнання. Метою роботи є розрахунково-аналітична оцінка впливу зменшення теплоприпливу на інтенсивність утворення випарного газу і пов'язані з цим експлуатаційні й екологічні показники. У роботі застосовано термодинамічний аналіз, параметричне порівняння розрахункових режимів й оцінку метан-еквівалентного показника. Встановлено залежність між тепловим навантаженням на резервуар, кількістю утвореного випарного газу й навантаженням на системи його оброблення. Отримані результати можуть бути використані для подальшого моделювання теплових процесів, удосконалення систем зберігання зрідженого природного газу й обґрунтування технічних рішень для плавучих регазифікаційних комплексів.

***Ключові слова**: зріджений природний газ, випарний газ, плавуча установка зберігання й ре газифікації, тепло приплив, теплоізоляція, енергоефективність.*

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