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SELECTION OF OPTIMAL SCHEMES FOR THE INERTING PROCESS OF CARGO TANKS OF GAS CARRIERS

Recommendations are given for choosing the optimal schemes for the process of inerting cargo tanks of ships carrying liquefied gases. It was determined that one of the tasks that arise during the transportation of hydrocarbon cargoes (crude oil, petroleum products, and liquefied gases) is to ensure fire safety and prevent accidental explosions of cargo vapors in cargo tanks. Processes that occur during cargo operations on ships transporting oil products and liquefied gases are considered. The critical composition of the mixture of oxygen (entering the cargo tanks with air) and cargo vapors (remaining in the tanks after the cargo is unloaded) is indicated, at which a flash and explosion may occur. It was determined that the main technological operation that prevents spontaneous ignition of cargo vapors in cargo tanks is their inerting using nitrogen. The main advantages and disadvantages of the schemes for inerting cargo tanks are considered and determined: cascade, semi-cascade and parallel. The effective use of these schemes is based on the consumption of nitrogen, the amount of which is necessary for inerting, as well as the duration of the inerting process. The results of determining these indicators for a group of gas carriers with a cargo capacity of 38,646–62,233 m^3 are given. At the same time, it is stated that the lowest consumption of nitrogen is necessary to ensure the process of inerting according to the cascade scheme. It was established that semi-cascade and parallel inerting schemes require an increase in the amount of nitrogen by 1.74–2.42 times and by 1.28–1.83 times, respectively. It was also established that the cascade scheme of inerting requires more time for its implementation. The duration of inerting according to the semi-cascade and parallel scheme is reduced and is 0.43–0.64 and 0.58–0.75 times in comparison with the cascade scheme.

Keywords: *cargo tanks, explosiveness of cargo tank atmosphere, inerting of cargo tanks, inerting using nitrogen.*

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1. Introduction

Sea transport is the most common type of transport that provides cargo transportation between countries and continents. Sea transport ships are the only means of transport that provide transoceanic cargo transportation [1–3]. In addition, sea ships transport almost all types of cargo:
– bulk (including grain and fertilizers) – using Bulk Carrier class ships;
– general (including machinery and equipment) – on General Cargo class ships;
– ro-ro (including cars) – on Ro-Ro type ships;
– large-tonnage – using Heavy Lift class ships;
– container – using Container Ship;
– liquid – on Oil Product/Crude Oil/Chemical Tanker ships [4–6].

There are also Liquefied Petroleum Gas Ship (LPG-ship) and Liquefied Natural Gas Ship (LNG-ship) classes, which provide transportation of the corresponding types of gas [7, 8].

Natural gas is currently the most environmentally friendly of all fossil fuels. Natural gas does not contain nitrogen, and the sulfur content in natural gas is minimal compared to all petroleum fuels. This ensures that natural gas does not produce fuel nitrogen oxides and produces minimal sulfur oxides. Also, when burning natural gas, potential emissions of solid particles are several orders of magnitude lower than when burning liquid and solid fuels. In addition to low emissions of nitrogen oxides, sulfur oxides, carbon oxides, and unburned hydrocarbons, natural gas produces much fewer greenhouse gases when burning [9–12]. This promotes the active use of natural gas as an energy source and the gradual replacement of fuels (petroleum products, coal, peat) by natural gas. The need for gas carriers is primarily due to the fact that natural gas deposits (continental or offshore) are located at a great distance from large gas consumers. In this regard, gas delivery via conventional gas pipelines becomes either unprofitable or impossible. Under such conditions, natural gas is initially liquefied and then transported by gas carrier ships. This solves the problem of transporting large volumes of natural gas over long (in some cases transatlantic) distances [13, 14].

Liquefaction of natural gas is explained by the following. When cooled to a temperature at which natural gas passes into a liquid state, its volume decreases by approximately 600 times. In a liquid state, natural gas is pumped into cargo tanks of gas carriers and transported to special terminals [15, 16]. This increases the profitability of its transportation from large remote fields over long distances.

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One of the main tasks in the transportation of hydrocarbon cargoes (both crude oil and petroleum products, and gases in a liquefied state) is to ensure fire and explosion safety [17, 18]. Moreover, the attention of classification societies and international organizations, insurance, ship-owning and shipbuilding firms and companies from different countries is riveted to ensuring the solution of this problem [19, 20].

A fire of an explosive nature in a closed cargo space can be caused by the presence of three elements that make up the so-called «combustion triangle»: ignition sources, a combustible substance and a sufficient amount of oxygen. Sources of ignition may be:

1) a spark that occurs when metal objects come into contact;

2) spontaneous ignition of flammable vapors as a result of an increase in their temperature;

3) hot surfaces of cargo heating steam coils (for oil tankers);

4) accumulation of static electricity charge, associated, in particular, with friction of the moving medium against the walls of the pipeline, as well as with friction of the ship's hull against the surface of the water [21, 22].

If the first three factors are subject to certain control, then the occurrence of static electricity discharges, especially for large-volume cargo tanks, is practically impossible to avoid.

At all stages of operation of both oil tankers and gas carriers, it is impossible to avoid the presence in cargo tanks of the second component necessary for ignition – flammable vapors.

Depending on the type of cargo, its temperature and operations, a certain amount of flammable cargo vapors is located in the unfilled space of the cargo tank. These vapors are a mixture of volatile fractions – individual hydrocarbons from the class of normal paraffins (methane, ethane, propane, etc.). Each of these gaseous hydrocarbons has its own flammability limits corresponding to a certain concentration in the air, and each of them is explosive. The most common way to prevent spontaneous combustion of hydrocarbon vapors is inerting and degassing cargo tanks [23, 24].

Inerting and degassing of cargo tanks of gas carriers can be achieved in various ways, and different cargoes require different versions of these technological operations. Inerting and degassing processes are related to the environmental safety of ships and their impact on the environment [25–27]. Carrying out inerting and degassing of cargo tanks in the waters of sea ports has a harmful effect on the atmosphere, and over time (due to the deposition of hazardous products that form during inerting and degassing), also on the marine and continental environment. This requires inerting and degassing to be carried out in the shortest possible time and with minimal emissions of harmful substances [28, 29]. The number of ships intended for the transportation of liquefied gas increases year after year. This is due to both the increase in the extraction of minerals and the annual increase in energy consumption by all countries of the world [30–32]. Transportation of liquefied gases (most of which are flammable substances) requires a sequence of technological operations that ensure the loading of such cargo on board gas carriers, their safe storage and maintenance of their characteristics during sea and ocean passages, as well as unloading at the destination port. Transportation of liquefied gases requires separate conditions for the preparation of cargo tanks and equipment for each type of cargo, maintenance of separate transportation conditions, as well as cleaning of cargo tanks from cargo residues after it is loaded onto shore receiving complexes.

Optimization of the inerting process of cargo tanks of oil tankers and gas carriers has been studied by many researchers. At the same time, solutions have been proposed that ensure a change in the method of filling tanks, an increase in the productivity of the ship's inert gas system, a change in the thermodynamic characteristics and chemical components of inert gases [33–35]. However, the issues of determining the optimal methods of inerting cargo tanks by filling them with nitrogen remain not fully resolved. In this regard, *the aim of research* is to select optimal inerting schemes for cargo tanks of gas carriers.

The set goal can be achieved by solving the following auxiliary tasks:

1) analysis of inerting schemes for cargo tanks of gas carriers;

2) selection of criteria that characterize the efficiency and feasibility of the process of inerting cargo tanks.

2. Materials and Methods

The object of research is the process of inerting cargo tanks of gas carriers.

The sequence of the technological chain of receiving cargo (oil, oil products or liquefied gas) at the port of loading – transportation of cargo by sea or ocean routes – unloading of cargo at the port of delivery ends with mandatory cleaning of cargo tanks. As a rule, it is performed according to the scheme «inerting – degassing – repeated inerting». Due to the fact that after unloading, oil tankers and gas carriers carry out return transitions in ballast, the quality of tank cleaning operations after unloading becomes very important. This is due to the fact that the explosion safety of cargo tanks and, consequently, the safety of the ship, the ship's crew and the environment depend on its implementation [36, 37].

When receiving cargo (crude oil, oil products, liquefied natural or petroleum gas), a concentrated layer of gaseous hydrocarbons is formed above the surface of the liquid. This layer rises together with the liquid without any noticeable change in concentration. The gas mixture leaving the tank at the beginning of cargo reception mainly consists of air and a small amount of hydrocarbons. As the amount of cargo increases, the concentration of hydrocarbons begins to grow. The growth of hydrocarbon concentration continues until the concentrated layer of gaseous hydrocarbons reaches the outlet. In this case, it is necessary that the oxygen concentration in the layer above the cargo surface be such that ignition of cargo vapors is impossible [18, 24]. A theoretical diagram showing the flammability and safety zones of a mixture of hydrocarbon vapors and oxygen is shown in Fig. 1.

Each point of the diagram corresponds to a gas mixture that includes hydrocarbon vapors, oxygen, and an inert gas. The concentration of hydrocarbons C_{CH} and oxygen C_{O2} is determined by the corresponding axes of the diagram, and the concentration of the inert gas C_{IG} as:

$$C_{\mathrm{IG}} = 100 - C_{\mathrm{CH}} - C_{\mathrm{O2}}.$$

Fig. 1 shows how the flammability limits of a gas mixture containing oxygen, hydrocarbons and an inert gas narrow with decreasing oxygen concentration. At an oxygen concentration of less than 11.5 %, ignition is impossible, just as with an over-enriched or depleted gas mixture with hydrocarbons.

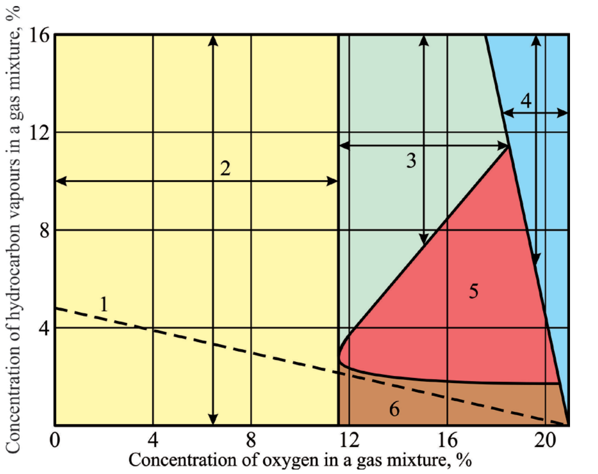

Fig. 1. Diagram of flammability and safety zones of a mixture of hydrocarbon vapors and oxygen: 1 – critical line of mixing processes with air; 2 – low oxygen content zone (no ignition possibility); 3 – enriched mixture zone (no ignition possibility); 4 – line of maximum oxygen content in a mixture of air and hydrocarbon vapors (the mixture is theoretically impossible to achieve on the right); 5 – flammability zone; 6 – lean mixture zone (no ignition possibility)

The diagram consists of five zones (2, 3, 4, 5, 6), as well as a critical line of mixing processes with air 1 and a line of the maximum oxygen content in a mixture of air and hydrocarbon cargo vapors 4.

In zone 2, the oxygen content in the mixture is so low that the possibility of ignition of the mixture is absent. Ignition of the mixture in zone 3 with a high oxygen content is also impossible. Zones 4 and 6 are also explosion-proof. Zone 4 corresponds to a mixture, the formation of which is theoretically impossible. Zone 6 – to a depleted mixture, the concentration of hydrocarbon vapors in which is insufficient for their ignition.

The only explosive zone of all those shown in Fig. 1, is zone 5. In this zone, the concentration of hydrocarbon vapors and oxygen ensures the ignition of the mixture. It is this zone that is dangerous during all cargo operations on ships that transport hydrocarbon cargo (crude oil, oil products, as well as liquefied natural and petroleum gas).

The diagram of flammability and safety zones can also display the processes that occur during cargo operations on oil and gas carriers (Fig. 2).

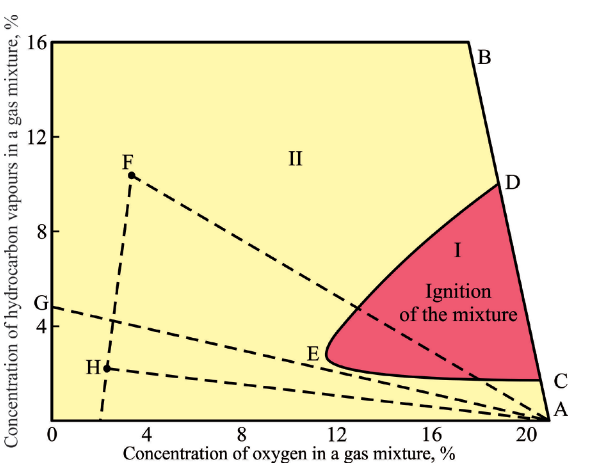

Fig. 2. Processes that occur during cargo operations on oil and gas carriers: FA, HA – dilution of the cargo tank atmosphere with air; GA – critical dilution of the cargo tank atmosphere with air; FH – dilution of the cargo tank atmosphere with inert gas

Ignition of a mixture of hydrocarbon vapors and air is possible in zone I. Zone II defines the safe state of the mixture; ignition and explosion of hydrocarbon vapors are impossible in this zone. Zone I is limited by the straight-line CD and two curved sections DE and CE. The curve DE defines the upper, and the curve CE defines the lower limits of flammability of hydrocarbon vapors. At vapor concentrations above the curve DE or below the curve CE, the mixture does not ignite. A mixture of hydrocarbon vapors with air that does not contain an inert gas is represented by the straight-line AB.

The slope of the straight-line AB shows a decrease in the oxygen content as the hydrocarbon content increases. Mixtures in which the oxygen content is reduced by adding an inert gas are represented by points to the left of the straight-line AB. The further to the left these points are located, the higher the proportion of inert gas and the lower the percentage of oxygen. As inert gas is added to the hydrocarbon vapour/air mixture, the flammability range decreases until point E is reached, where the lower and upper flammability limits coincide.

This point corresponds to an oxygen content of approximately 11.5 %. For practical purposes and taking into account the adoption of a safety factor, an 8 % oxygen content is adopted in the gas mixture contained in the cargo tank. In this case, no mixture containing any hydrocarbon vapours and air can ignite under any circumstances. The expansion of the safe zone (in which ignition and explosion are impossible) is ensured by feeding inert gas with an oxygen content of not more than 5 % into the cargo tanks. In addition, the mixture contained in the tank is displaced using inert gas. This operation is continued until the final oxygen content in the entire tank volume is less than 8 % by volume.

When any inert mixture, such as that represented by point F, is diluted with air, its composition changes along the line FA and thus enters the special zone of flammable mixtures. This means that all inert mixtures in the region above the line GA (critical dilution line) pass through the state of ignition as they are mixed with air, for example, during the process of outgassing. Mixtures represented below the line GA, such as those indicated by point H, do not become flammable when mixed with air. It should be noted that it is possible to change from one mixture, which is represented by point F, to another, which is represented by point H, by supplying additional inert gas.

Inerting of cargo tanks of ships ensures that the oxygen content in them is reduced to a level that ensures the impossibility of any combustion – either of the cargo or of the residual cargo vapors or of the mixture of gases contained in the tank. The exhaust gases of marine diesel engines and marine steam boilers are used as inert gas. The oxygen content in the exhaust gases of steam boilers is significantly lower than in the exhaust gases of diesel engines. However, the volume of these gases is not always sufficient to completely fill all cargo tanks. In addition, the exhaust gases in any case contain oxides of sulfur, nitrogen and carbon, which have a negative impact on the environment. Therefore, the most common source of inert gases on ships are special inert gas generators. The type of gas that can be used to inert cargo tanks is determined by the charterer's requirements regarding the minimum oxygen content in the tank atmosphere, dew point, compatibility of cargo and inert gas and other secondary characteristics [13, 38].

Nitrogen, which is either generated on board the ship or supplied from the shore, can be used as an inert gas. Like any inert gas, nitrogen is chemically inactive. It can enter into chemical reactions with some elements only at high pressures and temperatures in the presence of a catalyst. Therefore, under normal conditions, nitrogen does not react with cargoes transported by gas carriers. Nitrogen obtained for industrial purposes contains no more than 0.0005 % oxygen, which is an unconditional guarantee of the impossibility of any combustion in cargo tanks. In terms of quality and composition, inert gases generated by the ship's system are significantly inferior to nitrogen. Due to the fact that in marine conditions, inert gases are obtained by burning fuel in a special installation, they always contain mechanical impurities, soot, water vapor, carbon dioxide, and fuel combustion products. The oxygen content in inert gases generated by the ship's system, depending on its characteristics, ranges from 0.1 % to 5 % by volume. This level is certainly also sufficient for the safety of gas carriers, but the safety margin for this safety is significantly less than when inerting cargo tanks with nitrogen [14, 39].

There are two main methods for changing the tank atmosphere:

– Displacement Method;
– Dilution Method.

The Displacement Method is based on the difference in density between the gas in the tank and the gas supplied to the tank (Fig. 3).

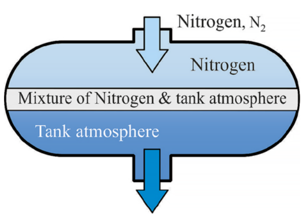

Fig. 3. Displacement Method

The Displacement Method ensures a clear separation of the nitrogen layer and heavier cargo vapors. However, it is necessary to avoid abrupt changes in the rate of nitrogen supply to the tank, supply nitrogen to the upper part of the tank, and avoid gas turbulence in the tank.

The Displacement Method is considered to be very effective. Due to the fact that the density of most commercial gases is significantly higher than the density of nitrogen, this method is widely used on gas carriers. The use of the atmosphere substitution method can be performed simultaneously for all cargo tanks (if necessary).

The process flow charts that ensure the inerting of cargo tanks by replacing the tank atmosphere with nitrogen depend on the design features of gas carriers. The main ones include cascade, semi-cascade and parallel [7, 34].

Inerting (blowing) by cascade means that the tanks are purged one after another, the atmosphere of one tank is displaced into another tank and thus all the tanks are filled (Fig. 4).

When cascading, nitrogen is supplied to the top of a tank and then discharged from the bottom of that tank to the top of the second tank and further. This procedure allows for significant savings in the total amount of nitrogen required for complete purging of all cargo tanks.Cascade tank purging is the most effective purging scheme. If a stable separating layer was initially formed between nitrogen and cargo vapors, then 1.1–1.3 volumes of nitrogen are usually required to completely change the tank volume.

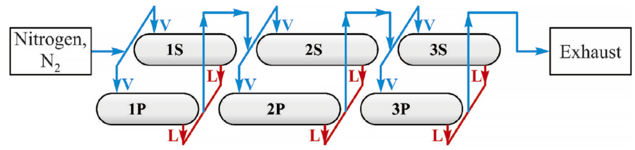

Fig. 4. Schematic diagram of cascade tank blowing: S – Startboard; P – Port Side; L – Liquid line; V – Vapor line

Very often, the ship's cargo system does not allow for all tanks to be connected in series. In this case, the so-called semi-cascade purging method can be used. Typically, the cargo gas system is divided into two separate groups, which allows for cascade purging of one group of tanks in series and the second group in parallel (Fig. 5).

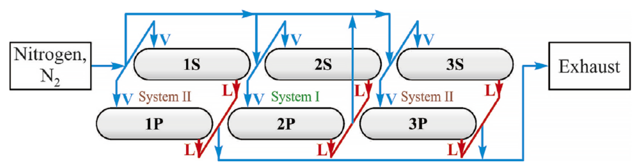

Fig. 5. Schematic diagram of semi-cascade tank blowing: S – Startboard; P – Port Side; L – Liquid line; V – Vapor line

In the diagram shown in Fig. 5, the first system contains tanks 2 of the left and 2 of the right side (2S and 2P) in one group, the second system contains tanks 1 of the left and 1 of the right side (1S and 1P), as well as tanks 3 of the left and 3 of the right side (3S and 3P). The groups are included in the system in parallel, but the tanks of the second group are purged in cascade. In terms of time, such a purging scheme works quite well, since it is possible to significantly increase the speed of the supplied nitrogen, but the nitrogen consumption in this case also increases significantly.

If it is not possible to connect the tanks in series, then purging is performed in parallel, and the scheme takes the form shown in Fig. 6.

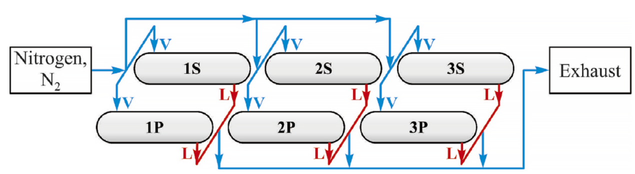

Fig. 6. Schematic diagram of blowing tanks in parallel: S – Startboard; P – Port Side; L – Liquid line; V – Vapor line

In this case, nitrogen is supplied simultaneously to all tanks via a common gas line, the tank atmosphere is removed to the ventilation column or to the shore gas removal system via a common line, also simultaneously from all tanks. The main disadvantage of this method is the significant nitrogen consumption for purging tanks, but the high rate of nitrogen supply to tanks allows for a reduction in the total time of tank purging.

Nitrogen can also be used to dilute the atmosphere of a cargo tank. In this case, nitrogen is supplied to the tank at a high rate, which facilitates uniform mixing (dilution) of the tank atmosphere with nitrogen (Fig. 7).

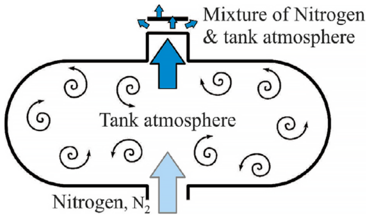

Fig. 7. Method of diluting the tank atmosphere with nitrogen

When changing the tank atmosphere by diluting with nitrogen, it is necessary to supply nitrogen to the lower part of the cargo tank, to provide turbulence of gases in the cargo tank. The main task when using this method is to provide more complete and rapid mixing of the tank atmosphere with nitrogen. This is achieved quite simply by supplying nitrogen to the lower part of the tanks at a high speed. The mixture is removed from the upper part of the tank through the gas main. This method requires a large amount of nitrogen. Therefore, it is applicable only when the reduction in the time of the ship's stay in port dominates over the costs of nitrogen [40–42].

3. Results and Discussion

The studies to determine the most rational method of cargo tank inerting were carried out based on statistical data on ensuring this operation on gas carriers of various cargo capacities. Processing and analysis of information on cargo tank inerting was performed for gas carriers with cargo tank volumes of 38,646 m^3, 42,427 m^3, 42,563 m^3, 72,312 m^3, 88,248 m^3, 88,274 m^3, 88,302 m^3, 145,673 m^3, 146,817 m^3, 162,233 m^3. During the studies, these ships were grouped into three: less than 50,000 m^3, 50,000–100,000 m^3, more than 100,000 m^3. All ships were carrying the same cargo between the ports of the Middle East and China. All ships were capable of performing cascade, semi-cascade and parallel schemes of cargo tank inerting. After each transportation and unloading of liquefied gas in the port, the process of cargo tank inerting was performed. Cargo tanks were inerted using nitrogen. The ship's generation system was used to produce nitrogen. For each ship, after the first transportation, the degassing process was performed according to a cascade scheme. The second transportation was completed with inerting according to a semi-cascade scheme, the third – according to a parallel scheme. During the study period, each of the ships made more than ten transportations of liquefied gas. This provided the necessary array of experimental data, and also allowed to draw conclusions about the correctness of the experiments.

It is advisable to compare cascade, semi-cascade and parallel schemes of cargo tank inerting using nitrogen based on two indicators:

1) nitrogen consumption required to ensure this process;
2) duration of the inerting process.

These indicators depend on the cargo capacity of gas carriers. To assess the efficiency of cargo tank inerting systems, it is possible to introduce the following notations: G_c, G_s, G_p – nitrogen consumption required to ensure inerting according to cascade, semi-cascade and parallel schemes, respectively; t_c, t_s, t_p – duration of the inerting process according to cascade, semi-cascade and parallel schemes, respectively.

If to take the nitrogen consumption G_c and the duration t_c of the inerting process according to the cascade scheme as basic values, then the relative values of these quantities for all inerting schemes are determined as:

– for the cascade scheme $\bar{G}_c = G_c/G_c = 1$, $\bar{t}_c = t_c/t_c = 1$;
– for the parallel scheme $\bar{G}_p = G_p/G_c$, $\bar{t}_p = t_p/t_c$;
– for the semi-cascade scheme $\bar{G}_s = G_s/G_c$, $\bar{t}_s = t_s/t_c$.

Generalized values of the relative nitrogen consumption and relative duration of inerting for different groups of gas carriers are given in Table 1.

Table 1

Comparison of inerting schemes for cargo tanks of gas carriers using nitrogen

Cargo capacity of gas carrier, m^3	Relative nitrogen consumption			Relative inerting duration		
	1	2	3	1	2	3
I – less than 50000	1.0	2.37–2.42	1.58–1.83	1.0	0.43–0.57	0.58–0.65
II – 50000–100000	1.0	1.95–2.19	1.41–1.62	1.0	0.55–0.61	0.66–0.71
III – more than 100000	1.0	1.74–1.91	1.28–1.34	1.0	0.59–0.64	0.71–0.75

Note: 1 – inerting according to the cascade scheme; 2 – inerting according to the parallel scheme; 3 – inerting according to the semi-cascade scheme

For better visualization, according to the results of Table 1, diagrams were constructed, which are shown in Fig. 8. In this case, Fig. 8 shows the data for the maximum values of the corresponding quantities of Table 1.

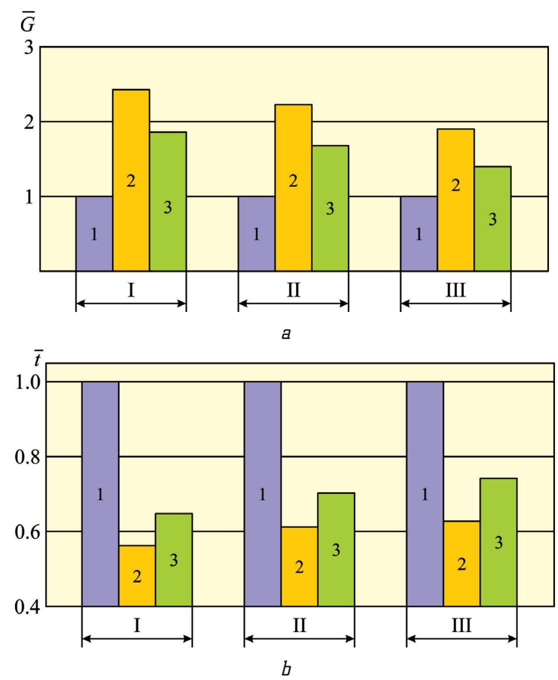

Fig. 8. Relative nitrogen consumption (*a*) and relative duration of the inerting process (*b*): 1 – cascade scheme; 2 – parallel scheme; 3 – semi-cascade scheme; I – cargo capacity less than 50,000 m^3; II – cargo capacity 50,000–100,000 m^3; III – cargo capacity more than 100,000 m^3

All studies were carried out in compliance with the requirements of the following international maritime documents: International Maritime Dangerous Goods Code, Equipment of Ships Carrying Liquefied Gases in Bulk, International Safety Management Code.

All studies on the inerting of cargo tanks were carried out either during the ship's ballast passages or in the port of unloading. In this case, all the main operating parameters of the main and auxiliary engines, the parameters in the systems that ensure their operation, as well as all the main parameters in the inert gas generation system were monitored and maintained in the required range. In addition, the ship's list and trim, as well as its stability, were constantly monitored.

The studies were coordinated with the technical department of the shipping company that owned the ships, as well as with the charterer.

Inerting of cargo tanks of gas carriers is one of the components that ensure the safe operation of ships of this class. The inerting process technology is identical on all gas carriers, as well as when transporting any cargo. Therefore, the results of the studies obtained on one ship or a group of ships can be implemented on all ships of a similar class.

The efficiency of the inerting scheme can be assessed by two criteria: either by the consumption of inert gas required to ensure it, or by the duration of its implementation. The final choice of the inerting scheme depends on the voyage assignment, environmental requirements at the port of cargo unloading, the characteristics of the ship's inert gas generation system, as well as the possibility of obtaining inert gas from the shore technical supply line.

The disadvantages of the cargo tank inerting process primarily include an increase in the berthing time of gas carriers after completion of cargo operations. According to the requirements of some charterers, inerting must be carried out precisely in the ports of berthing. After that, the atmosphere of the cargo tanks is monitored by the charterer's representatives. This increases the safety level of the ship during the ballast transition to the port of loading, but at the same time the total duration of the voyage increases.

The conducted study is also characterized by the following dilemma. On the one hand, each cargo transported by gas carriers has its own physical characteristics. In addition, cargo tanks on different ships have their own geometric characteristics. This leads to the fact that for the same ship, when transporting different cargoes, the hydraulic resistance that must be overcome when providing inerting changes. Thus, the inerting scheme recommended for one cargo may be less effective for another. On the other hand, as a rule, gas carriers provide transportation of cargoes in accordance with long-term charter contracts. In this case, the same cargo is transported over several voyages (the number of which can reach 10, and in some cases exceed 20). This increases the demand for the results of the studies. In addition, there are «series of ships» with virtually identical characteristics, and the operation of these ships can be carried out with the same charter assignment. Thus, recommendations developed for one ship can be effectively used on other ships that transport the same cargo between the same ports.

4. Conclusions

The need for gas fuel and the impossibility of some countries to obtain such fuel via continental gas pipelines facilitate the transportation of liquefied gases by sea and ocean routes by gas carriers. Navigational passages of these ships (both with cargo and in ballast) are impossible without inerting cargo tanks. The main task of the inerting process is to reduce the oxygen concentration in the tank atmosphere to a level at which ignition of the vapors of the gases in them is impossible. Inerting of cargo tanks can be ensured by filling them with an inert gas. One of the safest methods is the use of nitrogen. Nitrogen can be produced in special generators installed on ships; in addition, nitrogen can be obtained from shore supply stations. Inerting of cargo tanks with nitrogen is carried out according to the following schemes: cascade, semi-cascade, parallel. It is advisable to compare inerting schemes when using nitrogen based on two indicators: the nitrogen consumption required to ensure this process; duration of the inerting process.

The results of experimental studies carried out on gas carriers with a cargo capacity of 38,646–62,233 m^3 show that:

– the lowest nitrogen consumption is required when providing inerting using a cascade scheme. In this case, inerting using a semi-cascade scheme increases nitrogen consumption by 1.74–2.42 times. In the case of a parallel inerting scheme, nitrogen consumption increases by 1.28–1.83 times;

– the cascade scheme is characterized by the longest inerting process time. The duration of inerting using a semi-cascade and parallel schemes decreases and is 0.43–0.64 and 0.58–0.75 relative to the time required for inerting using a cascade scheme.

The choice of inerting scheme depends on the voyage assignment, the requirements of coastal authorities and the capabilities of the unloading port to provide the ship with nitrogen, as well as the characteristics of the ship's inert gas generation system.

In all cases, the inerting process must be carried out in accordance with the requirements of international classification societies for environmental protection, as well as international and national regulations for the transport of dangerous goods.

Conflict of interest

Author declares that he has no conflict of interest in relation to this study, including financial, personal, authorship, or any other, that could affect the study and its results presented in this article.

Financing

The study was conducted without financial support.

Data availability

The manuscript has no associated data.

Use of artificial intelligence

The author confirms that he did not use artificial intelligence technologies when creating the presented work.

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