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MONITORING OF THE INERTIZATION OF CARGO TANKS OF LNG CLASS VESSELS

The results of monitoring the inertization of cargo tanks of vessels intended for the transportation of liquefied natural gas are given. It is determined that the mandatory stage of cargo operations in the port of unloading of liquefied natural gas is the inertization of tanks. It is noted that on gas-carrying vessels, the following sources of inert gases can be: flue gases of vessel's auxiliary boilers; gases generated in the inert gas generator during the burning of liquid fuel in them; directly chemically pure inert gas (usually nitrogen). It is also stated that the inertization of cargo tanks is carried out by one of two methods: either dilution of the gas atmosphere (which is the process of mixing two environments), or replacement of the gas atmosphere (in which the gases supplied to the tank form a dividing layer and gradually displace the residual vapors cargo). The stability and integrity of the dividing layer determines the inertization quality of cargo tanks. Control of the state of the dividing layer in the cargo tank is impossible with optical or visual means of control, which is caused by the opaque environment inside the tank. In this regard, it is proposed to determine the integrity of the separating layer, as well as the level at which it is located in the cargo tank, by measuring the concentration of inert gas in the volume of the tank. Research was carried out on a gas carrier with a cargo capacity of 42,563 m^3. Inertization of the vessel's cargo tanks was ensured with the help of nitrogen, which was generated by an inert gas generator using the Pressure Swing Adsorption technology. Nitrogen concentration monitoring in the volume of the cargo tank was performed at levels corresponding to 5 %, 20 %, 50 %, 80 % and 95 % of the tank depth. Research on determining the effect of nitrogen pressure entering the cargo tanks for their inertization on the stability and integrity of the dividing layer was carried out in the range of 0.95–1.05 MPa. The duration of the experiment was 210 minutes, fixation of nitrogen concentration values was performed every 30 minutes. As a result, optimal pressure values were established, according to which the inertization is ensured in the minimum time. The critical pressure values at which the separation layer breaks down were also determined.

Keywords: *cargo tanks, inertization of cargo tanks, inertization using nitrogen, concentration of inert gas, gas carrier vessel.*

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1. Introduction

Natural gas currently occupies a dominant position among other fuels in many countries around the world. Natural gas is used in automobile, rail and marine engines, as well as in stationary power engineering to meet domestic needs. Today, natural gas is a commodity that is sold all over the world and is supplied either in a gaseous state (via pipelines) or in a liquefied state (by special sea-going gas carriers) [1, 2]. As a rule, the main customers/consumers of gas are located at a great distance from its deposits. In these cases, the method of transporting liquefied natural gas (LNG) by sea and ocean routes is more economical compared to pipelines. Therefore, natural gas in liquefied form is transported by LNG-class sea vessels. Currently, the number of gas carriers that transport liquefied gas is constantly growing. This is due to the energy dependence of a number of countries (primarily Europe, Canada, China and Japan) and the impossibility of supplying them with gas fuel via continental pipelines [3, 4].

Liquefied natural gas is the best form for transporting and storing gas on vessels. However, all equipment for storing, transmitting and using gas must be designed to constantly maintain the required cryogenic conditions. In addition, all technological operations for preparing cargo tanks of gas carriers for LNG transportation, loading LNG onto a gas carrier, transporting LNG from the loading port to the unloading port, unloading LNG, cleaning cargo tanks after unloading LNG must be carried out in accordance with the developed recommendations and ensure structural reliability, fire and explosion safety, environmental friendliness and energy efficiency. This is a necessary requirement for the safe and reliable operation of LNG-class vessels providing for the transportation of liquefied gas [5, 6]. A mandatory stage of cargo operations at the LNG unloading port is tank inertization. After unloading is complete, some cargo always remains in the cargo holds of gas carriers. This is due to the inevitable increase in LNG temperature during unloading. At the same time, some of the remaining LNG, transported as cargo, evaporates and (due to the properties of the gas) occupies the entire free volume of the cargo tank. Inertization of cargo tanks is aimed at preventing this effect. During inertization, an inert gas is supplied to the cargo tanks with a pressure increased compared to the pressure of the remaining cargo vapor [7, 8].

Inertization of cargo tanks of vessels carrying liquid oil or liquefied gas cargoes ensures a reduction in the oxygen content in these tanks to a level that guarantees the impossibility of any ignition of the cargo itself, the remaining cargo vapor, or the mixture of gases in the tank. The source of inert gases may be:

1) flue gases of vessel auxiliary boilers [9, 10];

2) gases generated in an inert gas generator by burning liquid fuel in them [11, 12];

3) directly chemically pure inert gas (usually nitrogen) [13, 14].

In the first two cases, obtaining inert gas (the functions of which are performed by carbon dioxide CO_2) is associated with the combustion of oil fuel. This has an additional negative impact on the environment, and also increases the operating costs of the fuel itself [15, 16]. In the third case, nitrogen generators provide for the release of nitrogen N_2 from the air, while pure oxygen O_2 is returned to the atmosphere. Nitrogen generators can be part of the vessel equipment of gas carriers. Nitrogen can also be supplied to cargo tanks from coastal LNG receiving stations. This method (due to its higher productivity) is also used under the condition of a shortened mooring of the gas carrier and when it is necessary to leave the port faster. The type and characteristics of the inert gas that can be used to inert cargo tanks are 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 parameters [17, 18]. Some cargoes may react with carbon dioxide CO_2 or other components of the inert gas generated by the vessel's inert gas system. There are also cargoes that require very low oxygen content during the inertization. This is one of the additional reasons why nitrogen is used to ensure inertization of cargo tanks on gas carriers. Nitrogen is a chemically inactive (inert) gas. It can only react chemically with certain elements at high pressures and temperatures in the presence of a catalyst. Therefore, under normal conditions, nitrogen does not react with cargoes carried by gas carriers. Nitrogen can be obtained using a special vessel installation that separates it from the air or from shore supply stations. 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 vessel's system are significantly inferior to nitrogen. Since inert gases are obtained in marine conditions 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 vessel's system, depending on its characteristics, ranges from 0.1 % to 5 % by volume. This level is certainly sufficient for the safety of gas carriers, but the safety margin for this safety is significantly less than when inertization of cargo tanks with nitrogen [19, 20].

It should also be noted that the inert gas distribution system and the cargo tank gas vent system must provide for:

– means for supplying inert gas to cargo tanks during unloading, deballasting, and tank cleaning operations, as well as for additional gas supply to tanks [21, 22];
– means for releasing gases in the tanks into the atmosphere during cargo loading and ballasting [23, 24];
– additional inlet or outlet pipes for inertization [25, 26];
– means of isolating individual tanks from the inert gas main to perform degassing [27, 28];
– means of protecting tanks from excessive pressure or vacuum [29, 30].

Inertization of cargo tanks is performed using one of two methods:

1) dilution of the gas atmosphere, which is the process of mixing two media (Fig. 1, *a*);

2) replacement of the gas atmosphere, in which the gases supplied to the tank do not mix with those removed, but form a two-layer structure and gradually displace the vapors of the remaining cargo (Fig. 1, *b*).

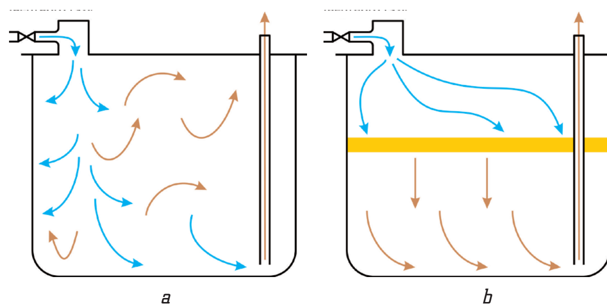

Fig. 1. Removal of cargo vapor residues by the method of:
a – dilution; *b* – displacement

The dilution method assumes that the incoming inert gas is mixed with the initial tank atmosphere to obtain a homogeneous gas mixture throughout the tank volume. As a result, the concentration of gas in the initial atmosphere progressively decreases. The intensity of gas replacement depends on the volume of incoming gas, its velocity at inlet and the dimensions of the tank. For complete gas replacement, it is necessary that the incoming stream of inert gas at inlet have a velocity sufficient to reach the bottom of the tank.

The displacement method requires a stable horizontal interface between the light gas (which enters the upper part of the tank) and the heavier cargo residues (which are displaced from the bottom of the tank through the gas outlet pipe). This method requires that the inert gas supplied to the tank have a relatively low velocity. In addition, it is necessary that the density of the inert gas exceed the density of the cargo residue vapors. Only if these conditions are met can the replacement process be ensured.

The efficiency of the inertization for cargo tanks of gas carriers is reduced to two options:

1) by reducing the time required to ensure it;

2) by reducing the consumption of inert gas required to perform it.

As a rule, these two options are mutually exclusive. Reducing the inertization time is achieved by increasing the amount of gas supplied to the cargo tank – this method is typical of the dilution method. Reducing the consumption of inert gas increases the time of the inertization – this method is typical of the replacement method.

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It should also be noted that the inertization for cargo tanks of gas carriers is carried out with constant monitoring of the following parameters:

- concentration, pressure and moisture content of inert gas;
- concentration and pressure of vapors of cargo residues;
- temperature of the atmosphere inside the cargo tank;
- temperature of the liquid phase of cargo residues;
- chemical composition of gases at the outlet of the cargo tank.

In this case, for the substitution method, the most important thing is monitoring the concentration, pressure and moisture content of the inert gas; for the dilution method, the chemical composition of the gases at the outlet of the cargo tank.

The inertization efficiency of LNG class cargo vessels has been studied by many researchers. The following were studied:

- the effect of changing the direction of inert gas flow into the cargo tank [31, 32];
- the relationship between the intensity of gas exchange and the opening angle of the nozzle through which the inert gas is supplied to the cargo tank [33, 34];
- the effect of the composition of the fuel burned in the inert gas generator on the chemical composition of the cargo tank atmosphere [35, 36];
- changing the inertization time for different methods of connecting groups of cargo tanks and the sequence of filling them with inert gases [37, 38].

However, the issues of the state of the cargo tank atmosphere, monitoring the concentration of inert gases, as well as the state of the cargo residues located in the lower part of the tank, require further study and development of a method for their control.

In this regard, *the aim of research* is to monitor the concentration of gases in the cargo tank when ensuring the inertization using the substitution method.

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

1) selection of a gas concentration control scheme in cargo tanks of gas carriers;

2) selection of criteria that characterize the efficiency of the cargo tank inertization.

2. Materials and Methods

The object of research is the inertization of cargo tanks of gas carriers.

A necessary condition for the high-quality implementation of the inertization of cargo tanks of gas carriers is the provision of a stable layer separating the cargo vapors remaining in the tank and the inert gas that is supplied to it. This layer is formed at the boundary between the inert gas and the vapors of the remaining cargo and is a mixture of these components (Fig. 2).

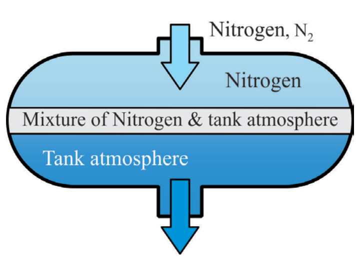

Fig. 2. Formation of a separating layer between cargo vapors and inert gas during inertization of cargo tanks of gas carriers

In case of maintaining a stable separating layer in a cargo tank, a "piston" effect is achieved. Due to this, a gradual but constant displacement of cargo residues is achieved. A rupture of the separating layer surface facilitates the entry of cargo vapors from the lower part of the tank to the upper part. In this case, a mixture of inert gas and cargo vapors is formed above the surface of the separating layer, the concentration of which in the total volume constantly fluctuates. This increases the inertization time of cargo tanks and leads to an increase in the consumption of inert gas, and also (due to an increase in the energy consumption for generating inert gas) reduces the energy efficiency of the inertization.

The reason for the violation of the integrity of the separating layer in a cargo tank may be an increased pressure of the inert gas supplied to the tank or a poor quality of the inert gas. When using nitrogen, this may be the presence of water in the gas, which turns into ice at low temperatures and can rupture the surface of the dividing layer. In the case of using carbon dioxide, the integrity of the surface of the dividing layer can be destroyed due to mechanical impurities and solid unburned particles that are part of the flue gases. The desire to speed up cargo operations and reduce the time the vessel is parked forces the inertization to be performed with the maximum possible inert gas pressure for the cargo system. At the same time, it is the maximum possible pressure of the inert gas supplied to the cargo tanks that is the only indicator recommended by regulatory documents for the performance of cargo operations. At the same time, there are no documents that define the critical pressure in the inertization system – exceeding which leads to a violation of the integrity of the dividing layer. At the same time, this pressure can be different for different cargo, as well as for different amounts of cargo remaining in the bottom of the cargo tank after the technological operation of unloading it.

The presence of a separating layer in a cargo tank cannot be controlled by optical or visual means due to the opaque medium inside the tank. The integrity of the separating layer, as well as the level at which it is located in the cargo tank, can be determined by measuring the concentration of inert gas in the tank volume [39, 40]. According to the requirements of the IMO Code for gas carriers, the cargo tanks of these vessels must have level indicators installed at heights corresponding to 5 %, 50 % and 95 % of the full tank volume [20, 41]. The purpose of these indicators is to control the filling of the volume of cargo tanks. These indicators are located directly on the side surface of the tank in the cargo compartment of the vessel. In addition, level indicators corresponding to 20 %, 50 % and 80 % of the full tank volume are additionally installed. The visualization of the values of these indicators is displayed on the control post located on the cargo deck of the vessel. The main functional purpose of these indicators is to control the uniformity of loading in different tanks during cargo operations in order to ensure the stability of the vessel. It is by the integrated use of these two groups of indicators that it is possible to control the integrity of the separating layer located in the cargo tank. In this case, it is necessary to select the concentration of inert gas at different heights of the cargo tank as the indicator by which this control is carried out. The following studies were carried out to confirm the possibility of such control on a gas carrier with a cargo capacity of 42,563 m^3. After the completion of cargo unloading operations, the inertization of its cargo tanks was ensured (Fig. 3). For this purpose, nitrogen N_2 was supplied to cargo tanks 6, which was generated using Pressure Swing Adsorption (PSA) technology in generator 2.

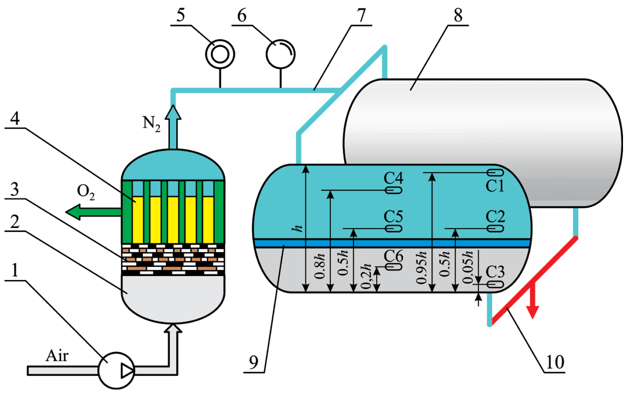

Fig. 3. Inertization of cargo tanks of gas carriers with nitrogen using PSA technology: 1 – compressor; 2 – generator; 3 – filter combination; 4 – adsorption vessels; 5 – flow meter; 6 – pressure gauge; 7 – nitrogen supply line; 8 – cargo tank; 9 – separating layer; 10 – cargo residue removal line

Obtaining nitrogen using PSA technology involves separating nitrogen from air, which is pumped to generator 2 by compressor 1. The PSA nitrogen generator produces nitrogen using a process that consists of the following stages:
- air compression in compressor 1;
- compressed air purification in filters 3 with different flow areas;
- adsorption of water, carbon dioxide and other impurities from air in adsorption vessels 4 and oxygen release;
- nitrogen generation.

As a result of this technological process, nitrogen is produced with the desired purity, and oxygen is returned to the atmosphere. PSA nitrogen generators can produce nitrogen with a purity of up to 99.9995 %, which is very important for maintaining fire and explosion safety in the cargo tanks of gas carriers. And also important for preventing the formation of ice plugs and mechanical contamination in the lines through which nitrogen is sent to the cargo tanks. The cargo residues that are displaced by nitrogen from tank 8 are sent through line 10 to another tank, or to the receiving shore line. The separating layer 9, which is formed in the cargo tank, prevents the formation of a mixture of cargo residue vapors (always present in the tank after cargo operations) and the inert gas that is supplied to the tank. The amount and pressure of nitrogen are controlled by flow meter 5 and pressure gauge 6, which are installed on main line 7. The amount and condition of cargo in cargo tanks 8 are controlled by indicators C1...C6, which allow simultaneous determination of the liquid level in the tank and the concentration of vapors of the substance inside the tank.

Monitoring the liquid level is a mandatory indicator when loading and unloading liquefied gas. Determining the composition of vapors of the substance in the tank allows diagnosing both the loading/unloading processes and the degassing/inertization processes. At the same time, depending on the type of cargo and the inertization method, it is possible to simultaneously determine up to ten components of the gas mixture (nitrogen, ammonia, butane, hydrogen, carbon dioxide, isobutane, oxygen, methane, propane, propylene).

During the experiment, the main indicators C1, C2, C3 ensured control of indicators at levels corresponding to 5 %, 50 % and 95 % of the total depth of the tank. Additional indicators C4, C5, C6 ensured control of indicators at levels corresponding to 20 %, 50 % and 80 % of the total depth of the tank.

3. Results and Discussion

One of the objectives of the study was to determine the effect of nitrogen pressure (used as an inert gas) on the integrity of the separating layer. It is this layer that prevents the formation of a mixture of cargo vapors (which remained in the tank) and nitrogen (which is supplied to the tank to ensure the inerting process). This effect can be assessed by diagnosing the nitrogen concentration at different heights of the cargo tank.

The study involved measuring the nitrogen concentration at the following control points of the cargo tank:
- at a height of $0.05h$, which corresponds to 5 % of the total tank height h (using indicator C3);
- at a height of $0.2h$, which corresponds to 20 % of the total tank height h (using indicator C6);
- at a height of $0.5h$, which corresponds to 50 % of the total tank height h (using indicators C2 and C5);
- at a height of $0.8h$, which corresponds to 80 % of the total tank height h (using indicator C4);
- at a height of $0.95h$, which corresponds to 95 % of the total tank height h (using indicator C1) – Fig. 3.

According to the characteristics of the nitrogen generator, the pressure of nitrogen produced in the generator is 0.85–1.20 MPa with an operating range of 0.90–1.10 MPa recommended by the charterer. In this regard, studies to determine the effect of the pressure of nitrogen supplied to cargo tanks for their inertization on the stability and integrity of the separating layer were performed with a value of $p_1=0.95$ MPa (taken as the "base") and a subsequent step-by-step increase in pressure by 0.05 MPa: $p_2=1.00$ MPa, $p_3=1.05$ MPa. The duration of the experiment was 210 min, the nitrogen concentration values were recorded every 30 min. The control of nitrogen pressure supplied to cargo tanks, nitrogen concentration by the height of the cargo tank, and the time of measurement were provided by microcontroller control systems [42, 43]. The results of the studies are presented in Tables 1–3. For better visualization, the results presented in Tables 1–3 were plotted in diagrams – Figs. 4–6.

Table 1

Change in nitrogen concentration at injection pressure $p_1=0.95$ MPa

Time, min	Nitrogen concentration at different heights of a cargo tank				
	$0.95h$	$0.8h$	$0.5h$	$0.2h$	$0.05h$
30	100	28	0	0	0
60	100	58	26	19	0
90	100	77	62	44	32
120	100	100	75	61	47
150	100	100	94	84	76
180	100	100	100	89	84
210	100	100	100	100	100

Note: the time it takes to complete the inertization is highlighted in green

Table 2

Change in nitrogen concentration at injection pressure p_2 = 1.00 MPa

Time, min	Nitrogen concentration at different heights of a cargo tank				
	0.95*h*	0.8*h*	0.5*h*	0.2*h*	0.05*h*
30	100	57	28	0	0
60	100	72	59	34	0
90	100	100	77	59	42
120	100	100	85	76	58
150	100	100	100	84	77
180	100	100	100	100	100
210	100	100	100	100	100

Note: the time it takes to complete the inertization is highlighted in green

Table 3

Change in nitrogen concentration at injection pressure p_3 = 1.05 MPa

Time, min	Nitrogen concentration at different heights of a cargo tank				
	0.95*h*	0.8*h*	0.5*h*	0.2*h*	0.05*h*
30	100	76	52	37	19
60	100	96	73	68	56
90	100	100	100	85	47
120	100	78	72	63	33
150	78	62	58	52	46
180	88	77	72	61	39
210	76	63	43	37	19

Note: the time at which the separation layer is destroyed is highlighted in red

Comparison of the results presented in Tables 1, 2 and Fig. 4, 5 indicate that an increase in the injection pressure from 0.95 MPa to 1.00 MPa accelerates the inertization process. In this case, the inertization time is reduced from 210 min to 180 min. Such an increase in pressure does not affect the stability and integrity of the separating layer, as evidenced by 100 % nitrogen concentration over the entire height of the cargo tank at the final moment of the studies. Comparison of the results presented in Tables 1, 3 and Figs. 4, 6 indicate that an increase in the injection pressure from 0.95 MPa to 1.05 MPa leads to a gradual destruction of the stability and disruption of the integrity of the separating layer. This is confirmed by a decrease in the nitrogen concentration in the upper part of the cargo tank over a certain period of time (150–180 min) and fluctuations in the nitrogen concentration values over the height of the cargo tank (150–210 min). In this case, a gradual mixture of cargo residue vapors and nitrogen occurs. This worsens the process of inertization of cargo tanks and requires that it be repeated. This increases nitrogen consumption, increases energy consumption for its production or receipt, and increases the vessel's idle time. It is also necessary to take into account that cargo residues displaced from cargo tanks by nitrogen are subsequently burned in the territory of coastal cargo complexes. This has a negative impact on the ecology of the port territory and coastal waters. The technology for conducting the research was agreed upon with the technical department of the shipping company, which ensures technical supervision of the vessel and its power plant. In addition, the sequence of experiments and the expected results were discussed and approved with the charterer's representatives. During the experiments, all requirements for the safe operation of vessel's auxiliary equipment, as well as the requirements of the IMO Code for gas carriers and the MARPOL requirements for the prevention of environmental pollution were met [44–46].

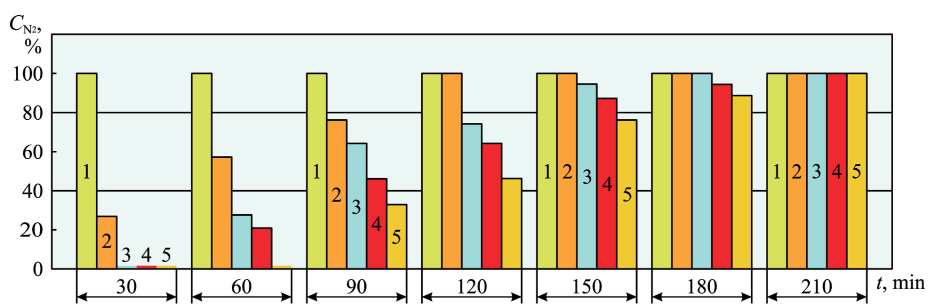

Fig. 4. Change in nitrogen concentration at different heights of a cargo tank at a discharge pressure of p_1 = 0.95 MPa: 1 – 0.95*h*; 2 – 0.8*h*; 3 – 0.5*h*; 4 – 0.2*h*; 5 – 0.05*h*

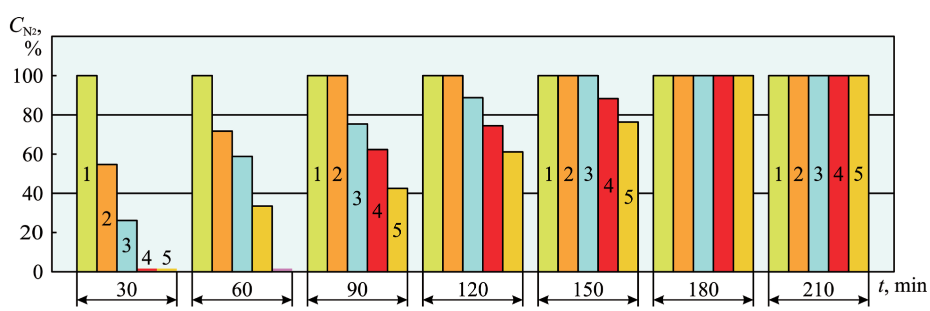

Fig. 5. Change in nitrogen concentration at different heights of a cargo tank at a discharge pressure of p_2 = 1.00 MPa: 1 – 0.95*h*; 2 – 0.8*h*; 3 – 0.5*h*; 4 – 0.2*h*; 5 – 0.05*h*

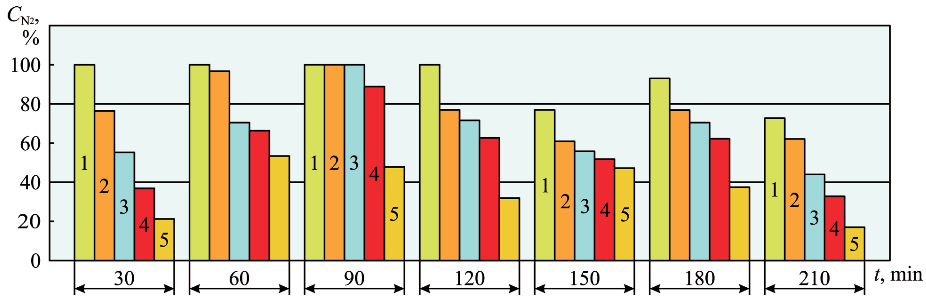

Fig. 6. Change in nitrogen concentration at different heights of a cargo tank at a discharge pressure of p_3 = 1.05 MPa: 1 – 0.95h; 2 – 0.8h; 3 – 0.5h; 4 – 0.2h; 5 – 0.05h

The limitations of the study include the need for continuous quality control of nitrogen produced by the inert gas generator. Given that the source of nitrogen generation is air, there is a possibility of moisture getting into the nitrogen volume. Subsequently (due to low temperatures in the nitrogen supply system), the moisture turns into ice. Ice getting onto the surface of the separating layer contributes to the destruction of its integrity, which forces inertization to be repeated. In addition, there may be situations when the separating layer is located in the upper part of the cargo tank. Such situations occur in the case of increased temperature in the cargo tank and the associated increased vaporization of cargo residues. Reducing the distance between the separating layer and the inlet pipe through which nitrogen is supplied to the cargo tank can also lead to the destruction of the separating layer. Therefore, in the case of an increase in temperature in the cargo tank, it is necessary to reduce the nitrogen injection pressure, which increases the inertization time. Another disadvantage of the proposed method is associated with the metrological support of the inertization. An increased number of control points (there are six of them in the proposed study) increases the accuracy of measurements and contributes to a higher level of diagnostics of the cargo tank atmosphere. At the same time, the probability of failure of concentration control indicators and distortion of information increases. First of all, this is due to the possibility of damage to relatively long capillary tubes through which gases from the cargo tank enter the measuring devices. In addition, the capillary tubes are located in different temperature zones (in the internal and external contour of the cargo tank). This can also contribute to the distortion of the information received.

The development of the proposed method is primarily associated with the accumulation of statistical information regarding the most rational nitrogen injection pressure for a particular cargo. The availability of such information is relevant from the point of view of high repeatability of the technological operation for inertization of cargo tanks. As a rule, liquefied gas is transported under long-term contracts, while LNG-class vessels perform several transitions between the same ports with the same cargo. Therefore, a one-time determination of the rational nitrogen injection pressure in the inertization system can be used for subsequent transportation of liquefied gas. In addition, the results obtained on one vessel can be used on vessels of similar or similar tonnage.

4. Conclusions

The paper shows that inertization of cargo tanks after unloading the transported cargo is a mandatory technological process, which can be ensured by filling the tanks with nitrogen, which is either generated on board the vessel or supplied from the shore.

It is also shown that one of the methods of inertization of cargo tanks is the substitution method. In this case, inert gas is supplied to the upper part of the cargo tank, ensuring the formation of a separating layer, which consists of a mixture of inert gas and vapors of the remaining cargo. This separating layer creates a "piston" effect and, if the required pressure of the inert gas is maintained, gradually displaces the remaining cargo from the cargo tank.

It was revealed that high-quality implementation of the inertization is possible only if the stability and integrity of the separating layer is ensured, by means of which the formation of a mixture between the vapors of the cargo remaining in the tank after unloading and the inert gas supplied to the cargo tank is prevented. The range of inert gas pressure supplied to the cargo tank to ensure the inertization recommended by the charterer does not determine its most rational values. Such values, at which the inertization can be performed in the shortest time while simultaneously maintaining the stability and integrity of the separating layer. Reducing the inert gas injection pressure slows down the inertization and increases its duration. Increasing the inert gas injection pressure accelerates inertization and reduces the time it takes to complete, but this creates the risk of destroying the integrity of the separating layer. This leads to the formation of a mixture of inert gas and vapors of cargo residues throughout the entire volume of the cargo tank and forces repeated inertization.

Ensuring the shortest inertization time while simultaneously maintaining the stability and integrity of the separating layer is possible by controlling the inert gas injection pressure depending on the change in its concentration along the height of the cargo tank.

The following should also be indicated as a result of the study:

1. Increasing the nitrogen injection pressure from 0.95 MPa to 1.00 MPa (with the recommended range of 0.9–1.1 MPa) accelerates the inertization. At the same time, the inertization time is reduced from 210 to 180 minutes. Such an increase in pressure does not affect the stability and integrity of the separating layer, as evidenced by 100 % nitrogen concentration over the entire height of the cargo tank at the final moment of its measurement.

2. Increasing the injection pressure from 0.95 MPa to 1.05 MPa leads to a gradual destruction of stability and disruption of the integrity of the separating layer. This is confirmed by a decrease in the nitrogen concentration in the upper part of the cargo tank over a certain period of time (150–180 min) and fluctuations in the nitrogen

concentration value along the height of the cargo tank (in the time interval of 150–210 minutes).

3. The most rational value of nitrogen injection pressure can be determined experimentally, provided that the condition of the cargo tank atmosphere is constantly monitored.

Technological operations for inertization of cargo tanks should be carried out in compliance with international requirements for the operation of gas carriers and environmental protection.

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

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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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