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MAIN WAYS OF TANKER INERT GAS SYSTEM MODERNIZATION

Formulation of the problem

Identical inert gas systems are used on all tankers in the world. The operation principle of these systems is based on the combustion of diesel fuel in an inert gas generator. This system is autonomous and it is not connected to the fuel processing circuit. Inert gases that are produced during combustion in the generator are processed and fed into the cargo holds of the tanker. When a hold is being filled, they push the air out, thereby reducing the total oxygen concentration to a working value of less than 8%. The removal of air from the hold is due to the pressure of inert gases, which is 20% above the atmospheric pressure. In this case, during delivering of a new cargo there will be no conditions for a fire or explosion inside the hold.

Analysis of the inert gas systems operation on tankers shows that in most cases the process of creating a fire- and explosion proof micro-atmosphere inside the hold is not economically efficient. The main reason for this deficiency is the very long duration of the ventilation process. On average, it takes time from 25 to 34 hours. When carrying out such work in port, payment for a lie idle of a tanker is expressed in a large unprofitable payment equivalent.

Double reduction of the cargo holds ventilation time on a tanker on average can lead to savings of about 100,000 USD per year. Basically, this amount consists of two components - reduction of payment for the vessel berthing and reduction of the cost of fuel that is burned during the inert gas system operation.

The main reason for the long duration of the ventilation process in the tanker holds is the imperfection of the technologies used. The displacement of air from the working volume of a cargo hold occurs by means of natural convection and diffusion processes only without using any compulsory arrangements to increase the speed of the mass exchange process between air and inert gases.

Analysis of the recent research and publications

Analysis of the structural dimensions of tankers cargo holds shows that they are not universal. On different tankers the cargo holds always differs from each other. Despite this fact the technological circuit for the production and supply of inert gases is standard on all tankers. Its design on different ships differs only in the geometric layout of the main components and devices. An example of an inert gas circuit is shown in Figure 1.

The technological circuit of inert gases with a volumetric capacity of 1500 m^3/h works as follows: diesel fuel is taken through the filter system from the fuel tank by the fuel pumps 1. Two pumps are connected according to the parallel connection scheme. Usually, only one pump is running, and the second is a backup. Behind the fuel pumps in the fuel supply line 3, a bypass pipeline 4 is installed. In case of pressure oscillations in the fuel pipeline 3 or in case of necessity for the inert gas generation system the quick stop a of bypass valve is activated. In this case, the fuel flow can be directed back to the tank for storage, or partially discharged into the fuel line before the pumps 1. Then diesel fuel is fed to the nozzle 5 through the fuel line 3. It is installed on the top cover of the inert gas generator 6. The fuel is ignited with the use of spark plug at the top of the chamber. The gases generated during combustion are directed from the central combustion chamber to the scrubber - an external cylindrical channel 8. In the scrubber temperature decreases to 60 °C and the inert gases are cleaned of soot and various fuel particles.

Air is supplied to the inert gas generator through a separate line by means of two air compressors 2. These blowers are connected according to the parallel connection scheme. Due to their work, a working pressure is created that ensures all the movement of inert gases.

To remove the sludge residue in the lower part of the inert gas generator, a drain line is installed. After cleaning in the scrubber, inert gases enter the main line 8 with a hydraulic gate 9. This unit prevents the inert gases from flowing backward from the cargo holds towards the generator. This device uses seawater as a working fluid. On line 8, a pneumatic accumulator 10 is installed. Its operation eliminates pressure oscillations in line 8. A complete description of the operating principles of the hydraulic lock 9 and pneumatic accumulator 10 are well represented in [1-3].

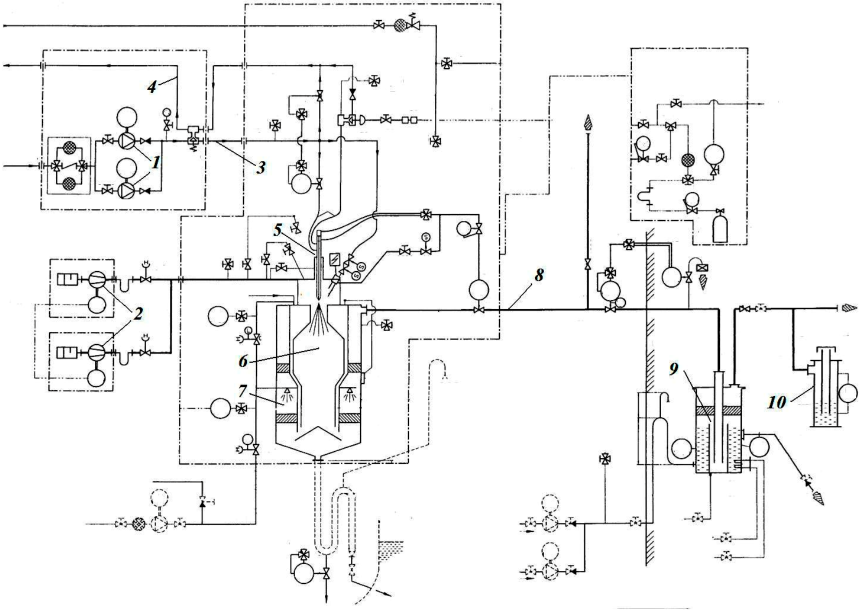

Figure 1. The tanker inert gas production and supply circuit
1 – fuel pumps; 2 – compressors; 3 – fuel supply line; 4 – bypass fuel line with valve; 5 – nozzle; 6 – generator; 7 – scrubber; 8 – supply line; 9 – hydraulic lock; 10 – pneumatic accumulator.

The modern theory of heat and mass transfer is based on the consideration of liquid or gas flows, taking into account the transfer of energy and mass in the course of natural or forced convection and diffusion [4-6]. All the used relations that are directed mainly to determine a connection between the flow of a fluid in the volume under consideration and the mechanisms underlying thermal conductivity [6].

In most scientific works on the theory of convection, heat and mass transfer processes are usually considered in an unrestricted region without the presence of rigid boundaries. Only a small number of works describe the process of mixed convection or diffusion of gases in confined spaces, when the walls restricting the flow have a significant nonstationary effect on the mechanism of heat or mass transfer [6–8]. In these works, flows within cylindrical pipes or between flat vertical and horizontal walls with different temperatures are mainly considered.

When applied to the ventilation of a cargo hold with inert gases, the closest are the results of paper [7] where thermal convection in an open-top three-dimensional rectangular volume is considered. The experiment was carried out in the range of Rayleigh numbers from 100 to 10^8. For the case of heat transfer from one heated wall to another, dimensionless temperature and velocity profiles were obtained. They are presented in Figure 2. During the experiments [7], it was found that:

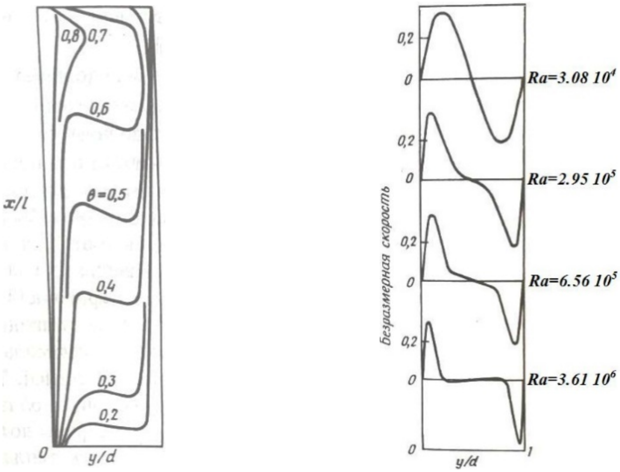

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Figure 2. The distribution of temperature and velocity in a rectangular closed area. [7]

a – distribution of isotherms describing the temperature field along the height of the entire region;

b – variation of the velocity isolines across the width of the region at various Rayleigh numbers.

- at Rayleigh numbers $Ra<10^3$ in a rectangular volume, one cell arises with a weak stationary circulation. The liquid, heated at the wall, rose up, and then descended down near the cold wall. At the width of the entire volume the flow was directed only vertically (excluding turns near the upper and lower boundaries);

- for Rayleigh numbers $10^3<Ra<10^5$, the temperature gradient increased near the walls, and remained constant in the internal flow region. The temperature field for this mode is shown in fig. 2–a.

- speed distribution, shown in fig.2–b, in the range of Rayleigh numbers from $3\cdot10^4$ to $3,6\cdot10^6$ is characterized by a symmetry in relation to the vertical axis of symmetry of the volume considered.

An increase in the Rayleigh number indicates a spatial increase in the width of the core zone of the flow. Smaller velocities are localized in the end region of the flow, and high near rigid vertical walls.

In works [6–8], different Rayleigh numbers are given as the lower boundary for the occurrence of secondary flows in a closed rectangular volume. The total range of variation of the values obtained answers to range from $Ra=2,1\cdot10^5$ to $Ra=3,9\cdot10^5$. More complex flow structures arise according to the data of [7] with Rayleigh numbers equals $Ra>10^6$. In this case, the occurrence of multi-cell structures with weak shear flows at their boundaries is observed.

Formulation of the investigation purpose

All technological circuits of production, processing and supply of inert gases included in the inert gas system of tankers are universal. In most cases they contain the same type of equipment and pipelines. Because of this reason, it can be stated that the main technical problems that arise during their operation are also identical for all tankers. For their description, a universal classification was developed. In accordance with it there are three separate directions that already include specific ship problems.

The first direction is technical, when all emergency problems in the work of the inert gas system are caused by imperfect structures of the technical devices that are used.

The second direction is determined by design errors or by the presence of strong deficiencies in the technologies which are used for supplying inert gases to the internal space of the working volume of the cargo hold.

The third direction is determined by the quality of the measuring and control devices that are used, as well as by the human factor from the crew of the tanker.

In the course of research, during the study of the causes of accidents that occurred in the inert gas systems on tankers an analysis of the emergency reports was done. Finally, it was concluded that the problems most often encountered on ships were associated with technical deficiencies of the inert gas system. These disadvantages include:

- poor fuel separation and, as a result, poor filtration of heavy fractions in the combusted diesel. This is reflected in changes in the production volume of inert gases over time and the breakdown of the combustion process in the working chamber of the inert gas generator;

- poor quality fuel combustion in an inert gas generator. This is reflected in increased soot generation and lowered volumes of the main combustion product produced in the form of carbon dioxide (CO_2);

- violation of the tightness of the scrubber water cooling of inert gases system, as a result of which, at the tanker berthing places, emissions of petroleum products with their emergency spills over the sea surface of the port waters takes places.

A change for the better of all technical shortcomings can be carried out by improving the listed individual technological units or by upgrading the fuel treatment system. This can be achieved by installing additional equipment in the fuel pre-supply line. A simple solution in this case can be the use of a stand-alone technical device – a unit for heavy fuel oil dispersing with the cavitation process use. Due to the crushing of heavy fractions, for example, bitumen or asphaltenes, a result will be achieved in reducing the emergency indicators of the fuel combustion process.

The third direction of the causes of accidents on tankers is metrological. Due to improper installation or poor quality of gas analyzers, the oxygen concentration process of monitoring in the hold may not meet the requirements of regulatory documents. In most cases, this can lead to excessive values of the residual oxygen concentration in the ventilated space. In most cases, the concentration of oxygen or cargo vapors (after shipment) is controlled at the exit from the cargo hold without taking into account the specifics of its design. Recommended places for gases sampling pick up should be located inside the hold and there should be several of them.

The main purpose of research should be to improve the quality and reduce the duration of the ventilation process of cargo holds on tankers. The main factors determining the quality of the implementation of such a process are the current and final oxygen content in the working volume of the hold and the time to achieve the final values of the minimum allowable concentration. Currently, both of these indicators are supported through the use of outdated technologies.

The density of inert gases can be calculated as the product of their density under normal conditions (0 °C and 760 mmHg) by the temperature correction according to the expression [9]:

$$\rho_{д.г.} = \frac{G_{д.г.}}{V_{д.г.}} \frac{273}{273+T} = \frac{1+\alpha L_0}{22.4\left(m_{CO_2} + m_{H_2O} + m_{NO_2} + m_{O_2}\right)} \frac{273}{273+T} =$$

$$= \frac{1+\alpha\left(\frac{Q_m}{0.21}\right)}{22.4\left(m_{CO_2} + m_{H_2O} + m_{NO_2} + m_{O_2}\right)} \frac{273}{273+T} \qquad (1)$$

where: $\rho_{д.г.}$ – density of flue gases, kg/m^3; $G_{д.г.}$ – total amount of flue gases generated by burning 1 kg of fuel, kg/kg; $V_{д.г.}$ – volume of flue gases, m^3; T – temperature, ^{0}C; α – coefficient of excess air; L_o – theoretical amount of air required for combustion of 1 kg of fuel, kg/kg; Q_m – the theoretical amount of oxygen required for combustion of 1 kg of fuel, kg/kg; m_i – the molar content of the i-th component of inert gases (calculated using empirical formulas [9]), m^3;

In [6], it was shown that in the case of forced convection, the flow field in a closed volume ceases to depend on the mechanisms of heat transfer and the current temperature field. This fact directly indicates the feasibility of using the forced supply of inert gases in the vessel's hold. The main focus of research on the mechanism of using the supply of inert gas jets into the cargo hold of a vessel should be aimed at solving the problem of reducing the ventilation time of the cargo hold of a tanker.

Taking into account the stated above, the main scientific and technical problem was formulated, which is to develop new principles for the operation of the system for generating and supplying inert gases to the cargo holds of tankers, providing a significant improvement in the quality of vessel operation by changing the technology of hold ventilation and reducing accidents related to the quality and duration of such systems operation.

Description of research

One of the options to eliminate the problem of highly viscous hydrocarbon inclusions in fuel can be the installation of an additional technical unit on the fuel line. This device should perform the functions of a homogenizer and change the fractional composition of the fuel to the desired degree of dispersion. The technical solution in this case may be the cavitation treatment of the fuel. Due to the processes of destruction that occur in a moving stream of small bubbles, an active change in the structure of the whole stream will occur, with its uniform mixing and small particle size of high molecular weight hydrocarbon fractions.

Due to the complexity of the theoretical description of the process of convective-diffusion transfer of inert gases in ship cargo holds, the following assumptions must be used:

- the movement of air and inert gases inside the hold can be considered as the movement of the flow inside the flat channel;
- during the process of thermos-gravitational convection all transfer coefficients should be constant and not dependent on the temperature [10];
- due to the low speeds inside the cargo hold of the tanker, no compressibility effects occur. The air flow-rate at the outlet of the hold can be taken equal to the flow-rate of inert gases into the interior of the hold.

When considering thermo-gravitational convection, the equation describing the change in the density of the mixture of inert gases and air inside the tanker hold can be written as [5, 10, 11]

$$d\rho = \left(\frac{\partial\rho}{\partial T}\right)_P dT + \left(\frac{\partial\rho}{\partial P}\right)_T dP \tag{2}$$

where ρ – density of inert gases, kg/m^3; t – time, s; V – speed, m/s; P – pressure, Pa; η – dynamic viscosity, Pa·s; g – gravitational acceleration m/s^2.

Equation (2) should be supplemented by an equation describing the change in temperature of inert gases during thermo-gravitational convection in the form

$$\frac{\partial T}{\partial t} + \left(\vec{V}\nabla\right)T = \frac{k}{\rho C_p}\nabla T \tag{3}$$

where k – thermal conductivity coefficient, W/(mK); C_p – heat capacity of inert gases at the constant pressure, J/K.

To characterize the stability of air movement inside the ship's hold during supply process of inert gases jets, it is necessary to use the dimensionless Richardson criterion. With laminar air movement in the hold due to the supply of inert gases with continuous density distribution, flow stability will be present while Ri> 0.25 [6].

The movement of inert gases inside the ship's hold should be considered as continuous. It can be described by the continuity equation

$$\frac{\partial \rho}{\partial t} + div\left(\rho \vec{V}\right) = 0 \tag{4}$$

and equations describing free convection, when motion arises due to the action of Archimedes force, in the field of mass forces action.

The process of air displacement due to the supply of inert gases will lead to a turbulent mode of its movement. In the first approximation, the body of the velocity distribution over the cross section of the hold during such movement can be written in accordance with [12] as follows

$$v = 5.75 lg \frac{y\sqrt{\frac{\tau}{\rho}}}{\nu} + 5.5 \tag{5}$$

where v – velocity, m/s; y – current coordinate of the cross section of the hold, m; τ – friction stress on the wall, Pa; ρ – density of the flow, kg/m^3; ν – kinematic viscosity of the flow, m/s^2.

The duration of the process of displacing air from the cargo holds of a vessel is directly determined by parameters such as the feed rate of inert gases jets and the Prandtl number *Pr*. The higher their values, the stronger the convective transfer, the increase in Archimedean force and the amount of air ejection along the jet action axis [10].

During the experimental studies carried out on the tanker "Cape Dowson" of Columbia Shipmanagement, two technical methods were used to create cavitation in the heavy fuel supply line. They used standard ship pumps.

The first method consisted in the use of a cavitation unit which provided an intense spin of the flow. As shown in Figure 3, cavitation was created in the spiral channels, and the cavitation zone was located in the cylindrical chamber of the fuel processing unit.

The second method was based on the use of Venturi tube. A cavern was created in its cylindrical part. At the exit from this area, the cavity collapsed and provided the necessary degree of fuel dispersion.

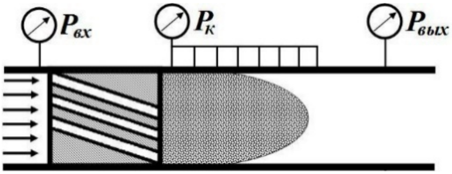

Figure 3. Cavitation unit with spin of the flow

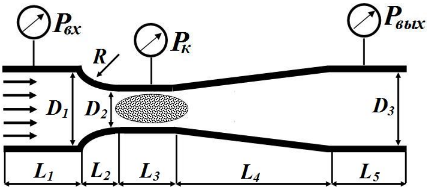

Figure 4. Cavitation unit in the form of a Venturi tube

During conduction of the experiments with the use of cavitation unit for heavy fuel dispersion, operating on the principle of rotation of the flow, was used the estimation of its twisting degree. It was calculated as a dimensionless complex

$$\Gamma_w = \frac{Q}{\Gamma R} = \frac{Q}{(2\pi w R)R} \tag{6}$$

where Q – fuel consumption, m^3/s; Γ – circulation of the fuel flow; R – radius of the pipe, m; w – peripheral velocity of the fuel on the pipe wall, m/s.

All experiments were conducted in the range of variation of the value of Γ_w from 0.02 to 0.8. This corresponded to a change in the volume flowrate in a range from 0.01 to 0.117 m^3/s and the feed rate of the main fuel flow at the entrance to the treatment unit from 15 to 27 m/s.

During the experiments, it was found that when the flow was turned on, the radius of the cavitation zone became close to the pipeline radius. The length of the cavitation zone can be from 0,1 to 5,17 pipe diameters. Graphically, the results of these experiments are shown in Figure 5. The points on the graph correspond to the measurement results, and the straight line corresponds to their linear approximation.

In the experiments, an estimate of the total hydraulic pressure loss ΔP was performed depending on the length of the cavitation cavity. The results are shown in Fig. 6. The corresponding changes in the cavitation numbers, depending on the volume flow-rate, are shown in Fig. 7. All four curves correspond to different values of input relative pressure. The value of this pressure was determined as the ratio of the pressure at the inlet to the cavitation channel $P_{вх}$ to the pressure in the cavity $P_к$ at the moment of its destruction and was respectively equal $\overline{P}_{вх} = 40$, $\overline{P}_{вх} = 70$, $\overline{P}_{вх} = 110$ и $\overline{P}_{вх} = 120$.

During the experiments, for cavitational dispersion of fuel and the degree of its influence on the system an evaluation of the quality of the process was done. In Figure 7, presenting a comparison of the consumption characteristics for the supplied fuel in two operating modes – normal operation of the inert gases system and with the fuel dispersion process usage.

The experiments were carried out in real operating conditions of the tanker. The total working time of the standard and modernized inert gas system was different. For this reason, the graphs in Figure 8 show only those measurements that correspond to the first six hours of the system's operation. In all three experiments, the consumption of the produced inert gases was at its maximum value – 1500 m^3/h. Dependencies 2 and 3 corresponding to the work of the inert gas system using the process of dispersion of fuel were obtained during different experiments.

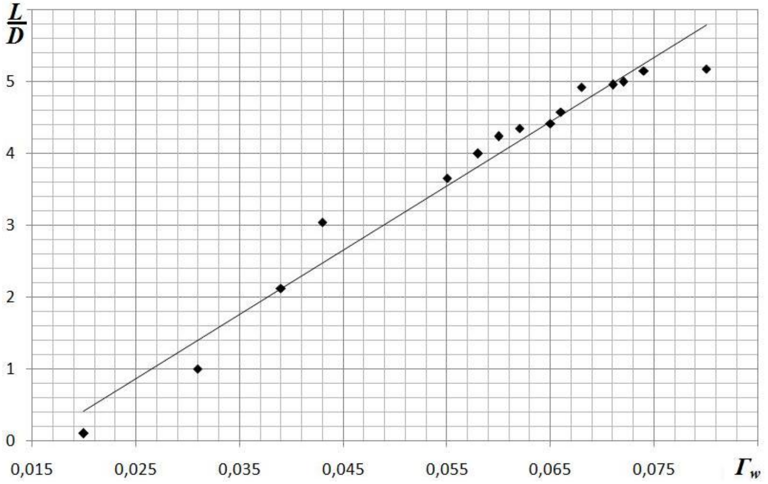

Figure 5. Influence of the degree of flow swirl on the length of the cavitation cavity

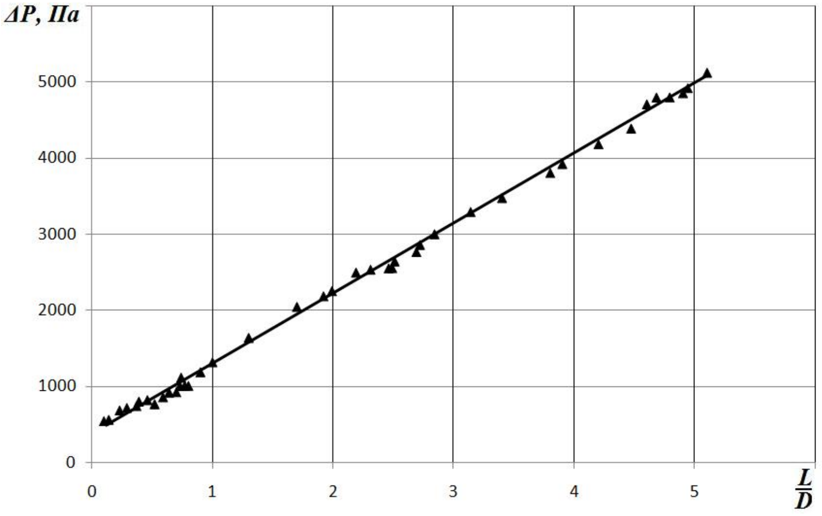

Figure 6. Influence of cavity length on hydraulic losses along the channel length

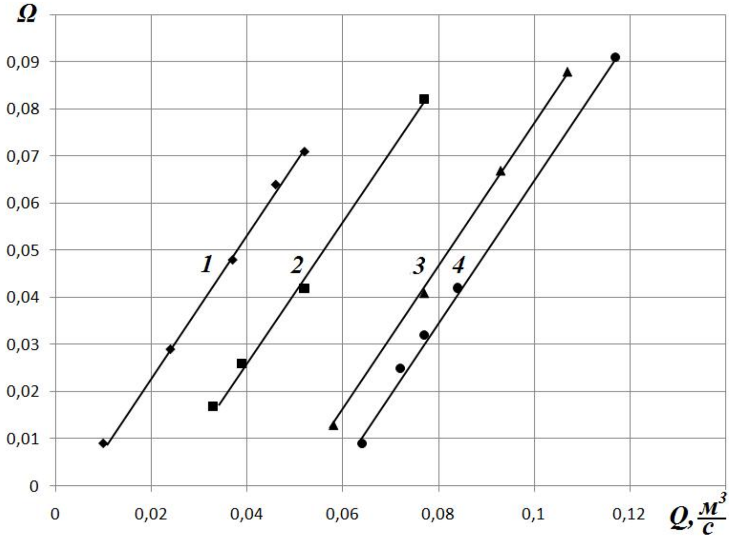

Figure 7. Dependence of the cavitation number Ω on the volume flow rate Q when the input pressure changes.
1 – $\overline{P}_{вх}$ = 40; 2 – $\overline{P}_{вх}$ = 70; 3 – $\overline{P}_{вх}$ = 110; 4 – $\overline{P}_{вх}$ = 120.

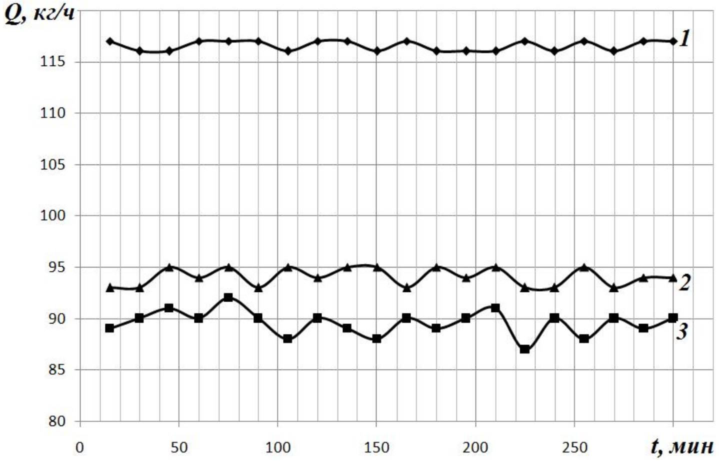

Figure 8. Evaluation of the operation quality of an inert gas system in terms of fuel consumption

1 – system operating in usual mode; 2, 3 – system operating with fuel processing

Analysis of the results lets make a conclusion that dispersion of the fuel provides a significant improvement in the operation quality of the inert gas system. As can be seen in Figure 8, less fuel is required to generate an identical volume flow-rate of inert gases. In the first case (comparison of curves 1 and 2 in Fig. 8), the average consumption of fuel was reduced from 116,55 kg/h to 89,55 kg/h, which is 23,1% as a percentage. In the second case (comparison of curves 1 and 3 in Fig. 8), the average consumption of fuel was reduced from 116,55 kg/h to 94,05 kg/h, which is 19.3% as a percentage.

Flow fluctuations in fig. 8 are not caused by changes in the performance of the inert gas system, but by the accuracy of the ship's digital differential manometer, according to which the fuel consumption was measured. The magnitude of these fluctuations for all three curves of the graph is: 0.4% first curve, 2.8% second curve, 1.1% third curve.

Ventilation of tanker holds by means of forced supply of inert gases should be based on the fact that a change in velocity, vorticity and temperature diagrams is observed in the corner zones of the cargo tank only. For this reason, it is necessary to supply jets of inert gases exactly to the body of the ascending air flow. The turbulization of a steady flow in the middle of the cargo hold of the tanker will lead to a reduction of the time required for its ventilation. The results of these studies are shown in Figure 9, where it can be seen that the minimum oxygen concentration in the hold was obtained at a jet opening angle of 30^0. At this angle, the distance of action of the jet of inert gas, and hence the zone of convective interaction with air, was maximum. As can be seen in all graphs, the nature of the change over time in the concentration of oxygen inside the hold in all four cases remained almost identical. This result allows to make a conclusion that the influence of the angles of opening of the inert gas jets onto the nature of the displacement of air from

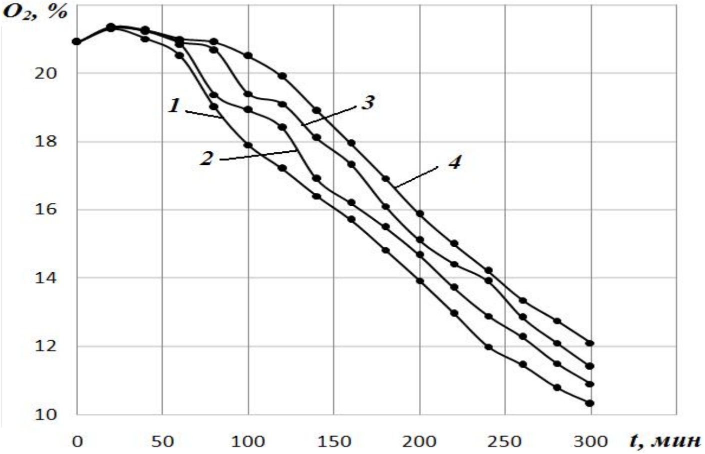

Figure 9. Changes in the concentration of oxygen in the hold
Inert gas jet opening angle: 1 – 30^0; 2 – 90^0; 3 – 160^0; 4 – standard supply of inert gases

the hold is not basic, and the process itself depends mainly on the degree of density stratification of inert gas within the working space of the cargo hold.

During the experiments, it was found that the use of forced supply of inert gas leads to the main result – reduction of the time that is spent on the ventilation treatment of the tanker holds before receiving a new cargo. The receiving of the stationary value of oxygen concentration equals 8% with the forced supply of inert gas was observed approximately in 740 minutes after the start of the process of the hold ventilation. A similar amount of concentration during the standard ventilation of the hold over this period of time was greater and amounted to 9,25%. Its stabilization to the stationary value was observed approximately in 1700 minutes after the start of the process of ventilation of the hold. In percentage terms, the improvement of the hold ventilation process during the transition from standard to forced ventilation of the hold was 13,5%. The reduction of time spent, ceteris paribus, was 56,47%.

By analogy with the process of oxygen concentration changing within the working volume of the hold, temperature stabilization was observed as well. Its stationary values in the four measured sections at the height of the hold were obtained in 960 minutes after the start of the process of inert gas supplying to the vessel's hold.

In comparison of the results of measurements of the temperature at the exit of the hold with standard and forced ventilation, it was found that stabilization in the latter case also occurs earlier. The temperature gradient, that equals –17 °C was achieved in time less than 38,18% compared with the standard ventilation operation of the cargo hold of the tanker.

Conclusions

1. Modernization of the inert gas system on tankers implies research in two directions. The first direction corresponds to a constructive change in the processing technology for a heavy fuel in the inert gas generation system. The second direction should be based on the use of technology of tanker holds forced ventilation.

2. During the operation of the inert gas system, the quality of operation of the fuel dispersion unit, which is used to generate them, was evaluated. With an error of less than 2.8%, it was found that while maintaining the volume flow-rate of the inert gas, the total fuel consumption is reduced up to 23.1%.

3. The use of the process of forced supply of the inert gas leads to a reduction in the time spent on the ventilation processing of the holds of the tanker before receiving new cargo.

In percentage terms, the improvement of the hold ventilation process during the transition from standard to forced ventilation of the hold was 13.5%. The reduction of time spent, ceteris paribus, was 56.47%.

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