International Journal of Innovative Technology and Exploring Engineering (IJITEE)
ISSN: 2278-3075 (Online), Volume-9 Issue-4, February 2020

New Forced Ventilation Technology for Inert Gas System on Tankers

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Abstract: ***This investigation is devoted to the development of a new technology for cargo holds ventilation on tankers. The quality criterion for this process is the value of the residual oxygen concentration inside the hold. The long duration of the process and its high cost directly determine the quality of tanker operation. They directly affect the duration of the operating mode and the speed of tanker loading with a new type of cargo. Time reduction of the inertization of cargo holds and the use of information technology to monitor its current performance can increase the income from the operation of the tanker. It was stated that forced ventilation should be used during the supply of inert gases to the cargo holds of the vessel. When inert gases enter the cargo hold as a jet there could be increased a convective transfer between air and inert gases. In this case, inside the enclosed volume of the hold, the oxygen concentration decreases to standard values in a shorter period of time. A new forced ventilation technology has been developed for the vessels inert gas system. Its use is supplemented by information technologies that give an ability to control the basic parameters of the process.***

Keywords - forced ventilation technology, information processing of data stream, oxygen concentration, tanker's cargo holds.

I. INTRODUCTION

On all tankers, regardless of their design, the system for inert gases production and supply is used. With this system, the main requirements for the creation and maintenance of a safe atmosphere from the point of view of fires and explosions in cargo holds are provided. The inert gases system is always used on tankers before receiving a new type of cargo. The use of an inert gas system is mandatory and has been regulated by various prescriptive documents since 1978 [1, 2, 3, 4].

Reduction of the working time of the inert gases system directly determines the income from the operation of the tanker.

Revised Manuscript Received on February 28, 2020.
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This system must maintain an atmosphere with an oxygen content less than 8% by volume in any part of the cargo hold. It should create excessive pressure (20% more than atmospheric) to counteract the influx of outside air into the hold.

The rate of decrease in oxygen concentration inside the cargo holds of a tanker reduces the time required to obtain a new type of cargo. Process time reduction of the tanker inertization improves such logistic indicators of its operation as: the duration of the ship mooring in the port, the working time of cargo operations, the number of passages for identical periods of time. The generator when burning marine diesel produces inert gases during the operation of the system.

Time reduction of the inert gasses' generator operation will make it possible to reduce fuel consumption and reduce emissions of harmful substances into the atmosphere.

II. PROBLEM STATEMENT

The main principles of the inert gases system operation on tankers are based on the combustion of marine diesel fuel inside inert gases generator. This device on the tanker is a separate unit and is not included in the fuel system of the vessel. Combustion products (inert gases) obtained during fuel burning, after cleaning and lowering the temperature, are sent to the cargo holds of the tanker. As they enter the hold, they displace air and thus create a safe micro-atmosphere.

Imperfection of the technologies that are used for the process of the tanker holds ventilating with inert gases is the main reason of its long duration. The displacement of air from the entire working volume of the tankers hold occurs due to the processes of natural convection and diffusion only. Currently, tankers do not use any forced mechanisms to increase the speed of the mass transfer process between air and inert gases.

The upward forced movement of air inside the hold of a tanker is caused always by the action of buoyancy force from inert gases supplied to the hold. This force appears due to different values of the concentration and density of inert gases and air due to the interconnected processes of heat and mass transfer. The temperature stratification of the flow of inert gases mixed with air along the height of the hold is also one of the factors affecting the rate of air displacement from the hold of a vessel. It is the only one who implements the mechanism of energy transfer from inert gases to air. When the temperature changes from 20 to 80 ^{0}C density of air changes by 17 % from 1.204 to 0.9994 kg/m^3 [5].

It was shown by Jaluria [6], that in case of forced convection, the flow field in a restricted volume ceases to depend on the heat transfer mechanisms and the current temperature field.

This fact directly indicates the feasibility of using the forced supply of inert gases into the hold of the vessel.

One of the methods of forced supply of inert gases can be the use of conical nozzles. The creation of high-pressure jets will increase the convective transfer zone and enhance the mass transfer process. The main focus of researches connected with the use of inert gases jets movement mechanism inside the tanker's cargo hold should be aimed to the solution of the problem of the ventilation time reduction for cargo holds of a tanker.

The duration of the tanker inertization process is always determined by the operation of only one measuring device - a gas analyzer. In most cases, oxygen concentration is monitored at one point, which corresponds to the exit of air from the cargo hold. The measurements are carried out without considering the specifics of the hold design and the degree of flue gases distribution inside its volume. In this case, the measurements which were obtained do not correspond to the real indicators of the ventilation process. Recommended target points for sampling should be located inside the hold and there should be several points. Processing the information data stream should be carried out in a continuous mode and reflect the real oxygen concentration not only at the exit from the hold, but inside it too.

III. METHODOLOGY

The modern theory of heat and mass transfer is based on the consideration of fluid or gas flows in relation to the transfer of energy and mass during natural or forced convection and diffusion [6, 7, 8, 9, etc.]. Main part of publications, when considering convection theory, usually depict problems on heat and mass transfer processes in not restricted regions without the presence of rigid boundaries [10, 11, 12]. Much less research publications are devoted to the description of the process with mixed convection or diffusion of gases in closed volumes, when the walls that restrict the flow possess a significant unsteady effect onto the mechanism of heat or mass transfer [6, 13, 14]. Basically, these publications deal with flows within cylindrical pipes or between flat vertical and horizontal walls with different temperatures. More complex forms of the geometry of heat and mass fluxes are rarely considered.

In the theory of heat and mass transfer, the use of two types of convection is accepted - natural, when the processes of mass and heat transfer are inextricable and forced, when the emerging flow field is determined not by heat transfer mechanisms, but by the hydrodynamics of the emerging flows [6]. In the first case, it is important to estimate the kinetic energy that inert gases transmit to the airflow during displacement from the hold. If the density of the environment is equal to ρ_a, and the density of inert gases is equal to ρ the energy that inert gases transfer to air equals

$$\frac{\rho V_z^2}{2} \approx gz(\rho_a - \rho)$$

ρ - density of inert gases, kg/m^3; V_z - velocity component inside the hold in the vertical direction, m/s; g - acceleration of gravity, m/s^2; z - vertical coordinate, m; ρ_a - density of the environment, kg/m^3;

In case of natural convection this estimation can be used when it is necessary to obtain the maximum numerical value of the velocity of air displacement from the hold of the vessel V_z.

In application to inert gas ventilation of a cargo hold, the closest are the results of Elder [14]. This research considers case with thermal convection in a three-dimensional rectangular volume with an open top. The experiment was carried out in the range of Rayleigh parameters 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 shown in Figures 1 and 2. During the experiments [14] it was found that:

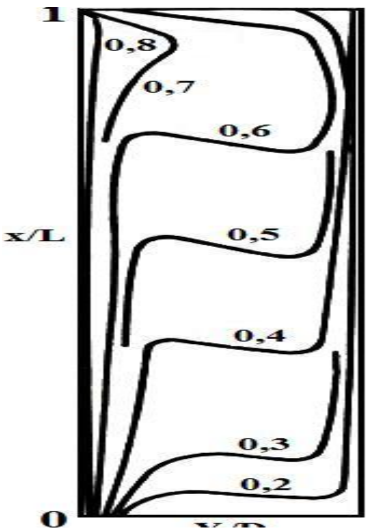

Fig. 1. Temperature distribution [14]

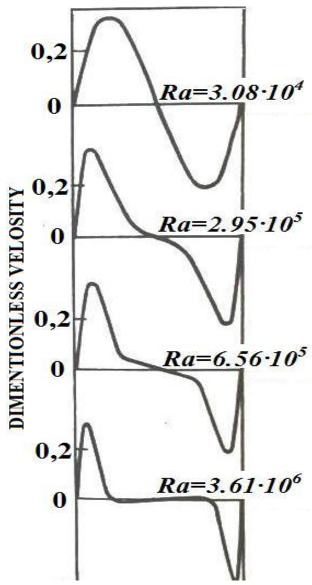

Fig. 2. Speed distribution [14]

- at Rayleigh numbers Ra $<10^3$ in a rectangular volume a single cell with weak stationary circulation appears.

The liquid, heated near the wall moves up and then fell down near the cold wall. Over the width of the entire volume, the flow was directed in vertical direction only (excluding turns near the upper and lower boundaries);

- at Rayleigh numbers $10^3<Ra<10^5$, the temperature gradient near the walls increased and remained constant in the internal region of the flow. The temperature distribution for this mode is shown in Figure 1;

- inside the whole volume velocity distribution shown in Figure 2 in the range of Rayleigh numbers from $3{\cdot}10^4$ up to $3{,}6{\cdot}10^6$ was symmetrical in relation to the vertical axis of symmetry. An increase in the Rayleigh number indicates a spatial increase in the transverse direction of the flow core zone. This zone has small values of velocity in the main region of the flow and high values of flow velocity near rigid vertical walls.

In [6, 13, 14], various Rayleigh numbers are stated as the lower boundary for the appearance of secondary flows in a closed rectangular volume. The general range of the scatter of the obtained values is from $Ra=2.1{\cdot}10^5$ up to $Ra=3.9{\cdot}10^5$. More complex flow structures arise according to [14] for Rayleigh numbers $Ra>10^6$. In this case the appearance of multicellular structures with weak shear flows at their boundaries was observed.

For thermogravitational convection, the equation that describes the change in the density of a mixture of inert gases and air inside the tanker's hold can be written as [15, 16]

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

ρ - density of inert gases, kg/m^3; T - temperature, ^{0}C; P - pressure, Pa;

This equation should be solved together with the equation that describes the change in temperature of inert gases during thermogravitational convection in the form

$$\frac{\partial T}{\partial t} + \bar{V}\nabla T = \frac{k}{\rho C_p}\nabla T$$

V - speed, m/s; k–factor of thermal conductivity, W/(mK); C_p– heat capacity of inert gases at constant pressure, J/K.

In accordance with recommendations of [6] the temperature distribution between rigid walls along the width and height of the cargo hold can be assumed at first approximation as a linear. The boundary conditions in this case should be the temperature of inert gases and air inside the hold. This hypothesis can be confirmed by the results shown in Figure 1, where one can see that vertical distance between isotherms remains constant all the time and isotherms themselves are horizontal over almost the entire width of the region considered.

To characterize the stability of air vertical motion inside the vessel's hold during the supply of inert gas jets, it is necessary to use the dimensionless Richardson criterion

$$Ri = \frac{g\left(\frac{\partial\rho}{\partial z}\right)}{\rho\left(\frac{\partial V_z}{\partial z}\right)^2}$$

In this equation the z coordinate coincides with the vertical axis of symmetry of the vessel's hold. For this coordinate the starting point of reference should correspond to the point of air exit from the hold to the environment, i.e. top wall of the hold.

During upward laminar (with a linear velocity profile) air movement inside the hold due to the supply of inert gases with a continuous density distribution, flow stability will be present if the inequality $Ri>0.25$ is satisfied [6].

The process of air displacement due to the supply of inert gases will lead to a turbulent mode of its movement. In a first approximation, the diagram of the velocity distribution over the hold section for this motion can be written in accordance with [17] as

$$V = 5.75lg\frac{y\sqrt{\frac{\tau}{\rho}}}{\nu} + 5.5$$

V - speed, m/s; y - current coordinate of the cross section of the hold, m; τ - friction stress on the wall, Pa; ρ - density of the two-phase flow of air and inert gases, kg/m^3; ν — kinematic viscosity of a two-phase flow of air and inert gases, m/s^2.

In accordance with recommendations of [17], the value of the friction stress τ can be calculated considering the maximum speed (determined from the current flow-rate of inert gas) using the following empirical equation

$$\tau = 0.0225\rho\left(V_{max}\left[\frac{y}{\frac{1}{2}H}\right]^{\frac{1}{7}}\right)^{\frac{1}{4}}\left(V_{max}\left[\frac{y}{\frac{1}{2}H}\right]^{\frac{1}{7}}\right)^{\frac{7}{4}} y^{\frac{1}{4}}$$

V_{max} - maximum value of air velocity, m/s; N - width of the cross section of the cargo hold on the tanker, m.

The duration of the process of air displacement from the vessel's cargo holds is directly determined by such parameters as the flow-rate of the inert gas jets and the Prandtl number Pr. The higher their values, the stronger will be convective transfer, as well as an increase in Archimedean force and the value of air ejection along the axis of action of inert gas jet.

The heat transfer from inert gas to the upward airflow can be estimated using empirical expressions from [6]:

when $2{\cdot}10^4<Gr<2{\cdot}10^5$:

$$Nu = 0.18Gr^{\frac{1}{4}}\left(\frac{L}{z}\right)^{-\frac{1}{9}}$$

when $2{\cdot}10^5<Gr<10^7$:

$$Nu = 0.065Gr^{\frac{1}{3}}\left(\frac{L}{z}\right)^{-\frac{1}{9}}$$

Gr - Grashof parameter; Nu - Nusselt parameter.

These two equations correspond to the range of distances between the walls of the hold L/H from 1 to 40. When using them, it should be considered that at $Gr> 5{\cdot}10^4$ the dependence between the heat transfer process on the width H of the flow among vertical walls is reduced to zero.

IV. RESULTS

The forced supply of inert gas to the tanker's hold for ventilation should be based on the structure of the airflow moving at low speeds inside the rigid walls of the cargo hold that restrict it.

As can be seen in fig. 1 and 2, the main changes in the bodies of velocity and temperature take place in the corner zones of cargo holds only. Because of this reason, the supply of inert gas jets exactly into the core of the ascending airs flow is very important. In this case, the turbulization of a steady flow in the middle part of cargo hold of the tanker will lead to a time reduction of its ventilation.

During forced ventilation of a hold, a very important question is the number of inert gas jets at the bottom of the cargo hold and the opening angle of their torch. Smaller opening angles will lead to a longer jet of inert gases, and therefore increase the zone of turbulization of the core of the air flow along the height of the hold. Large angles will affect the intensification of heat and mass transfer processes in the corner zones of the lower part of the cargo tank.

Three new technological schemes were used during investigation the process of the forced cargo tanks ventilation with the use of inert gas. They are shown in Figure 3.

The first technological scheme (Fig. 3-a) contained only one nozzle for supplying a jet of inert gases into the hold. It was located at the bottom in the center point of the cargo hold. The second scheme (see Fig. 3-b) of ventilation system contained four nozzles for supplying jets of inert gas. They were all located symmetrically. The third scheme (see Fig. 3-c) of the ventilation system contained five sources of jets. Last technological scheme allowed to get the best results.

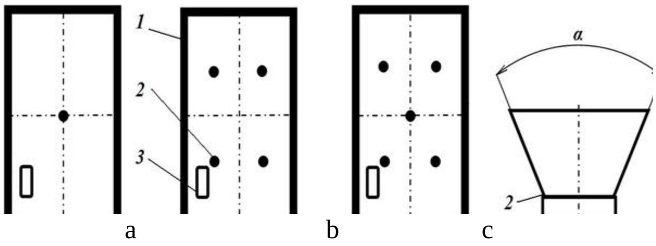

Fig. 3 Location of the jets

1 - hold; 2 - nozzle for inert gas; 3 - the outlet of the hold

During the tanker operation experiments were carried out and data were obtained that describe the process of changing the oxygen concentration inside the cargo hold of a tanker during operation of the inert gas system. At the same time, measurements were carried out in identical cargo holds during the operation of four technological schemes. In the first hold there was used standard inert gas technology. In all other holds there were used three described technological schemes for forced ventilation of the hold. The experimental results are shown in Figure 4. The graph shows that due to the use of nozzles that created jets of inert gases with increased pressure, a reduction in the duration of the inertization of the tanker was obtained. Under the same conditions an additional decrease in the oxygen concentration was achieved for the same ventilation time of the holds.

Figure 5 shows a comparative analysis of the ventilation process of tankers cargo holds with the use of standard and new developed technology. The simulation results obtained with the use of information technology on the vessel are also presented at the diagram. The oxygen concentration values correspond to measurements at the outlet area of air exit from cargo hold to the atmosphere (Fig. 3). The experimental data shown in this graph were obtained simultaneously for two inert gas supply technologies. Two identical cargo holds at the same time were filled with inert gases using a standard technological scheme and using the developed new forced ventilation scheme with five jet sources for inert gas (Fig. 3-c).

The analysis of results that are presented in fig. 5 indicate that the use of a new technological scheme led to a

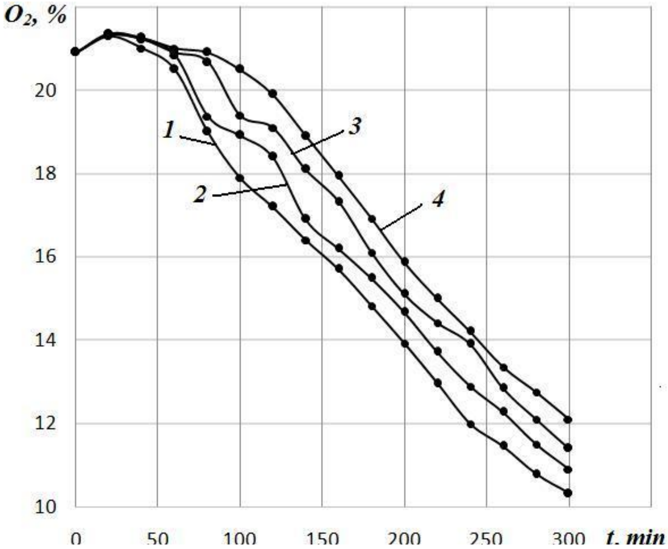

Fig. 4. Decrease in oxygen concentration in the hold

1 - first technological s scheme; 2 - second technological scheme; 3 - third technological scheme; 4 - standard inert gas supply

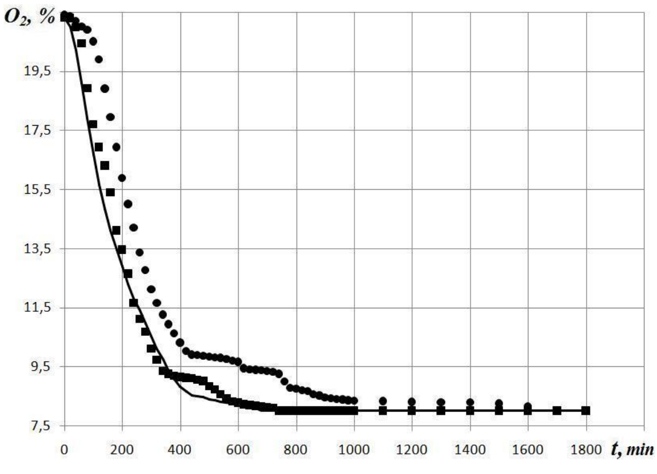

Fig. 5. Change in oxygen concentration during

inertization of tanker cargo holds

● – standard inert gas supply;

■ – forced supply of inert gas;

solid line - numerical calculation.

quantitative, but not qualitative discrepancy in the changes in time of the oxygen concentration inside the hold. The discrepancy between the two experimental curves shows that the use of the process of forced inert gas supply into the hold leads to the most important and main result - reducing the time spent on the ventilation processing of tanker holds before receiving a new type of cargo.

Data in fig. 5 shows that the value of oxygen concentration equals 8% with forced supply of inert gases was achieved much earlier. In percentage terms, the improvement of the hold ventilation process during the transition from natural to forced ventilation of the hold was 13.5%. Reduction of time spent, ceteris paribus, was 56.47%.

During experiments a comparison of the results of measurements for the flow temperature at the exit from the hold with the use of standard and forced ventilation was done. It was found that stabilization of temperature in the case of using new technology occurs earlier too. The temperature gradient equals 17 ^{0}C was achieved in a time less by 38.18% compared with the standard operation of ventilation of a tanker's cargo hold.

V. DISCUSSION

Technology that is currently used on tankers during measurements of oxygen concentration inside the working volume of cargo hold has several disadvantages. One of the main disadvantages is the fact, that temperature or oxygen concentration is measured at one point, which corresponds to the flow exit from the hold. The second drawback is the lack of information technology to control and monitor the working process of the inert gas system.

Due to these two reasons during inertization of the tanker, the quality of control over the process of ventilation of the holds remains very low. Under real conditions of the vessel's operation, the measured values of oxygen concentration do not always correspond to their actual values inside the hold. Actually, the parameters of fire and explosion safety inside the hold on all tankers are measured indirectly only. To control the composition of the micro-atmosphere inside the cargo hold, it was proposed to use a set of measuring gauges and implement information technology for processing and visualizing process data.

The general structure of the information technology used for tanker inertisation is shown in Figure 6. The user receives information from several sources. The first, most basic source is the measurements made by ship's measuring devices. These devices include: flow-rate meters, temperature sensors, pressure sensors, and gas analyzer that is used to measure oxygen concentration.

The second source is the store of main modules for monitoring and modeling providing based on information that has been stored from previous tanker inertization processes.

The third source is user-generated arrays of initial values that must be used during monitoring the operation of the inert gas system. These values include all geometric dimensions of the cargo hold (overall linear dimensions, linear dimensions of rigid surfaces of walls and their tilt angles for non-standard forms of the holds body, etc.), physical constants of the process, as well as environmental parameters.

The structuring of the information flow is based on continuous operational processing of current parameters of the tanker cargo hold ventilation process. All information flows with obtained values of simulation results and data of measurements are directed to the local storage. After this, a set of temporary files is formed that contain all information necessary for the user. Based on the processing of these temporary files, at each moment of time, an appropriate array of numerical data is generated. Such arrays contain specific values of the controlled parameter (oxygen concentration in hold, pressure, temperature, speed, etc.). After formation of data arrays, all values of technologically important parameters are automatically compared with similar results of their measurements. The maximum value of the error should not exceed 3%.

Visualization of main indicators of the inert gas system operation on the user's screen is shown in Figure 7. It supposed the mandatory display of four indicators: time elapsed since the start of the vessel's cargo hold ventilation; percentage degree of the process completion; drop in oxygen concentration during inertization of the tanker; distribution of oxygen concentration inside the hold, which is obtained by measurement and modeling.

To improve the quality of measuring the concentration of oxygen inside the hold during researches, a new arrangement of measuring gauges was developed. This diagram with main relative dimensions is shown in Figure 8. The left side of this drawing corresponds to a one half of

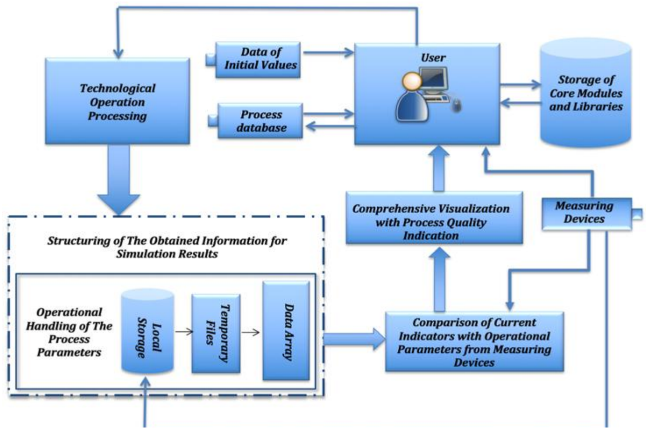

Fig. 6. General structure of the information technology

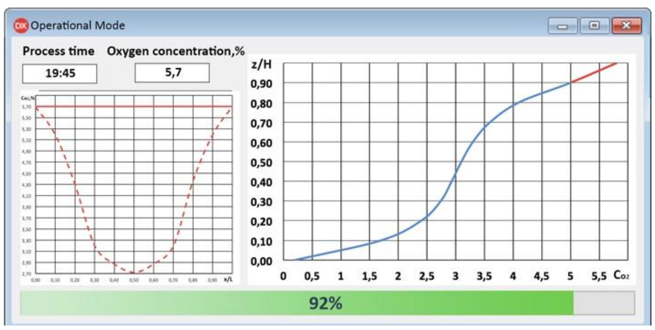

Fig. 7. User screen with main indicators

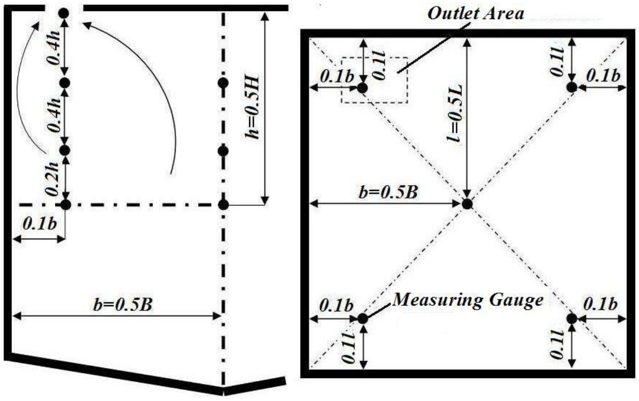

Fig. 8. Measuring scheme for oxygen concentration inside a cargo hold

vertical cross-section of the cargo hold. The right side of the figure shows a longitudinal section through the cross section of a cargo hold. In the schematic drawing, for the overall dimensions of the hold and the additional dimensions for arranging the measuring gauges, the following notation is used: H – hold's height, h - half of the hold's height, B – hold's width, b - half of the hold's width, L – hold's length, l - half of the hold's length.

VI. CONCLUSION AND FEATURE SCOPE

As a result of the research, a new technology was developed for the forced ventilation of cargo holds of a tanker during operation of standard inert gas system. It is based on the use of high-pressure jets to intensify mass transfer processes. Finally, with its use the main result was achieved. It consists in reducing the duration of the process of air removal from the cargo hold.

Transition from natural to forced inert gas ventilation of cargo holds of a tanker led to a reduction in the operation cycle time by 56.47%.

Supply of inert gas jets for tank ventilation should be provided in the central part of the cargo hold of the tanker. In this case, their mixing with air is characterized by increased turbulization and leads to the appearance of characteristic mixing zones in the regions of the hold angular zones. Due to the presence of these regions, the oxygen concentration decreases to a minimum value over shorter periods of time compared with the case of a standard inert gas supply from the top of the hold.

The main aspect of further researches should be related with improvement of individual elements of the inert gas system on tankers. The main elements of this system are fuel preparation unit and the inert gas supply unit inside the cargo hold.

The quality of fuel preparation can be improved by using new methods for its dispersing. One of these methods can be fuel processing with the use of cavitation.

Introduction of new methods for inert gases supplying to the cargo hold of a vessel by analogy with present researches can also lead to an increase in the quality of ventilation process. One of such methods may be the use of technology with a swirling flow of inert gases and air over the entire height of the vessel's cargo hold.

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