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# DETERMINING PERFORMANCE CHARACTERISTICS OF JET WATER-GAS EJECTORS FOR AN OPENING IN A VERTICAL FENCING STRUCTURE

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***The object of this study is jet water-gas ejectors (JWGEs) in the system for ensuring fire safety of ships. The problem that was solved: in the event of a fire, in the shortest possible time, a high temperature rises in the area of the exit from the ship's emergency room and a large amount of smoke spreads throughout the ship's premises. These factors require immediate sealing of the emergency room, which limits the immediate access of emergency teams to the interior. Installation of a local air support system based on JWGE in the doorway could make it possible to shield thermal energy and localize smoke gases in the emergency room without sealing it to ensure prompt access of emergency teams. The main results that were achieved relate to the adequacy of theoretical studies on the processes of localization of flue gases in the emergency room without its sealing confirmed by the experimental method. The investigated problem was solved by optimizing processes: the intensity of smoke emission from the working characteristics of jet water-gas ejectors; the rate of change of the natural indicator of the weakening of the environment at the start of JWGE system; speed of reaching the required temperature from the time in the adjacent room. Special feature of the results was the formation of an air curtain, obtained by the selection of a part of high-temperature flue gases into the JWGE housing, their heat and mass exchange treatment and output back into the flow. This created conditions under which thermal energy shielding occurs with a fairly high efficiency of 85–88 %. And it was also established that the decrease in the intensity of gas exchange through the open hole, in which the JWGE works, occurs already at the 0.3 MPa regime in the fire pipeline. The scope and conditions of practical use of the reported results are shipbuilding and ship fire safety design***

***Keywords: water-gas jet ejector, combustion products, gas-air medium, flow movement***

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## 1. Introduction

When fighting a fire on a ship (vessel), the primary task is to localize the ignition [1]. The crew must close doors, hatches, and turn off ventilation [2]. This localization technique does not necessarily solve the task, namely:

– some time passes from the moment the fire starts to the moment the emergency room is sealed, during which high-temperature smoke gases spread to the adjacent rooms and make it difficult to fight the fire;

– it is often necessary to open the emergency room, for the need to introduce an emergency party (reconnaissance group), establish the characteristics of the fire, evacuate the victims, enter fire extinguishing equipment, etc.

This, in turn, complicates firefighting and leads to depressurization of the emergency room. When the room in which the fire develops is opened, smoky gaseous combustion products escape from it. The combustion products have an average temperature above 250 °C and can become a source of fire spread outside the premises and have a harmful effect on the human body. At the same time, air with a normal oxygen content enters the open door, which in turn contributes to fanning the fire and increasing the intensity of burning.

According to requirements [3, 4], the fire protection of the ship should include measures to limit the spread of fire and smoke from the emergency room, as well as to prevent draft and gas exchange with adjacent rooms.

However, in practice, when designing ships, measures to limit the spread of fire and smoke from the emergency room, as well as to prevent draft and gas exchange with adjacent rooms, are practically not implemented. The reason is the lack of technical means.

Therefore, the question arises regarding the need to find technical solutions that will make it possible to meet the requirements for the design of the ship's fire protection system.

Therefore, the relevance of research is due to the importance of investigating the processes that form conditions under which the release of high-temperature flue gases from the ship's emergency room with an open hatch will decrease.

## 2. Literature review and problem statement

Attempts to protect ship hatches from smoke and high temperatures were made repeatedly. There is a well-known technical solution for the safe evacuation of personnel from the power compartment (PC), which is used on some ships [5]. So, to ensure this, a watch and ladder irrigation system is provided, which is a pipeline with sprinklers connected to the water fire protection system. The principle of operation of the system is based on the supply of coarsely dispersed water spray (0.6...1.2 mm) in the area of emergency ladders [5]. The main disadvantage of this technique is that this method cools the structure of the staircase and slightly cools the gas-air environment but does not exclude the spread of smoke gases through the open hatch outside the emergency room. Also, the implementation of this design solution on ships with a displacement of 1,000–2,500 tons is rather difficult to implement. The difficulty is the fact that the EVs of such ships are cluttered with equipment and in the lower part do not have continuous platforms, and the exit from the PC is not protected by structural means.

There is a known technical solution [6], which is a means of reducing the intensity of the spread of smoke and toxic gases outside the emergency room, and includes two parallel U-shaped collectors, which are placed parallel to the emergency hatch, one internal along the perimeter of the emergency hatch and the other external – at a distance of 0.1–0.15 m from the inner one. The collectors are connected to the water fire protection system and are equipped with centrifugal jet sprinklers with an inclination to the plane of the collectors at an angle of 30°. Curtains are fixed between the collectors on rotary rods that can rotate around their longitudinal axis and are irrigated when the working fluid is supplied.

A significant drawback of these technical solutions [5, 6] is that during their application, sprayed water is used in an open manner, which causes significant damage to the ship's electrical equipment and the failure of necessary systems.

There is a known technique of air support in emergency rooms during a fire [7], which involves ejecting hot flue gases from the upper part of the emergency PC into the body of a jet water-gas ejector. In the case, they are processed on the highly developed heat-mass exchange surface of the working fluid. After processing, the cooled inert mixture with increased moisture content and low oxygen percentage is fed to the lower part of the room. The disadvantage of the specified technique and device [7] is that the device was not intended to create air support in the opening of the emergency room and is not efficient enough to form a support flow.

An option to overcome the difficulties may be to design a ship's hatch with the installation of an air support system based on JWGE in its slot. This is the approach used in works [8, 9], which evaluate the efficiency of jet water-gas ejectors (JWGE) as technical means of smoke localization in the emergency room, as well as prevention of draft and gas exchange with adjacent rooms.

In works [8, 9], a technique for reducing the intensity of the exit of smoke gases through open openings (doors) from the emergency room is theoretically substantiated. Thus, the reduction in intensity occurs due to the creation of air support, which is formed by the flow of steam-gas-air mixture directed into the emergency room by the system based on JWGE. The essence of the theoretical justification is reduced to the task of reducing gas exchange through an open hole during a fire and finding conditions under which gas exchange with the environment is absent (airtight room). To this end, a special case of the zonal model of fire development processes and the formation of gas exchange in the ship's emergency room with an opening in which the JWGE works was developed.

However, the adequacy of the theoretical justification of the specified technique must be confirmed by experimental studies.

All this gives reason to assert that it is expedient to carry out a study aimed at establishing the regularity of distribution of a cooled vapor-gas-air environment with an increased moisture content, obtained by processing flue gases in jet water-gas ejectors installed in a semi-limited (open on one side) volume of the ship's space.

## 3. The aim and objectives of the study

The purpose of my work is to determine the regularity of the formation of the air curtain obtained by the selection of a part of the high-temperature flue gases into the JWGE housing, their heat and mass exchange treatment and output back into the flow. This will confirm that the JWGE kit is an effective means of reducing the intensity of smoke entering the adjacent room, which makes it possible to change the direction of movement of smoke gases, thereby ensuring their effective shielding.

To achieve the goal, the following tasks were set:

– to determine the ratio of the consumption characteristics of JWGE and the opening in the case of fire;

– to determine the shielding properties of JWGE in the opening to the adjacent room as a parameter for optimizing the change in the natural indicator of the attenuation of the medium when the JWGE system is started from time $t$;

– to determine the dynamics of temperature decrease of the heated gases as a parameter for optimizing the average volume temperature in the adjacent compartment at time point $t$.

## 4. The study materials and methods

As a working hypothesis, it was assumed that the design of the current model of JWGE has two direct-flow spray heat exchangers located on both sides of the opening (door). The inlet parts of the heat exchangers were located above the upper section of the hole and were connected to each other by an inlet manifold with a slotted hole. The cross-sectional area of the slit opening was 0.07 m$^2$, which corresponded to two cross-sectional areas of the heat exchanger housing. The total cross-section of the original parts was 0.03 m$^2$. In the current model of JWGE, the output parts were not connected to the collector, but were directed towards the opening of the model of the emergency room.

It was considered necessary to build a measuring system of a model of a ship's room for the hardware of conducting experimental studies of the shielding of flue gases and thermal energy of JWGE in front of the opening to the emergency room on a full-scale model (scheme in Fig. 1).

The model of the ship's room consisted of two compartments:

1. Fire compartment (1×1×1 m) – intended for placement of a model fire, sensors of control and measuring equipment, and equipped with an opening (0.35×0.2 m) in a vertical partition.

2. Adjacent compartment (1×1×1 m) – intended for placement of a working model of JWGE and sensors of control and measuring equipment.

In accordance with the methodology for calculating the structural characteristics of a jet water-gas ejector [9], operating models of JWGE were determined and built.

JWGEs have cylindrical bodies made of galvanized steel sheet 1 mm thick with a cross-section diameter of 165 mm and the length of the working part of the body of 300 mm. In the upper part of the case there is a multi-jet nozzle, which has 14 nozzles with a section of 0.7 mm on a disk. The nozzles are connected to the working fluid supply system, which consists of a water tank, a centrifugal pump, a system pressure control device (manometer) and a connecting pipeline. In the lower part, the case is equipped with a separator, which consists of a system for removing the vapor-gas-air environment from the case and a system for removing the spent working fluid.

The set of active models of JWGE (Fig. 1, item 6), intended for use on openings in vertical fences, consists of two JWGEs, located vertically and symmetrically with respect to the opening. A system for collecting and removing the spent working fluid is located under the heat exchanger housings.

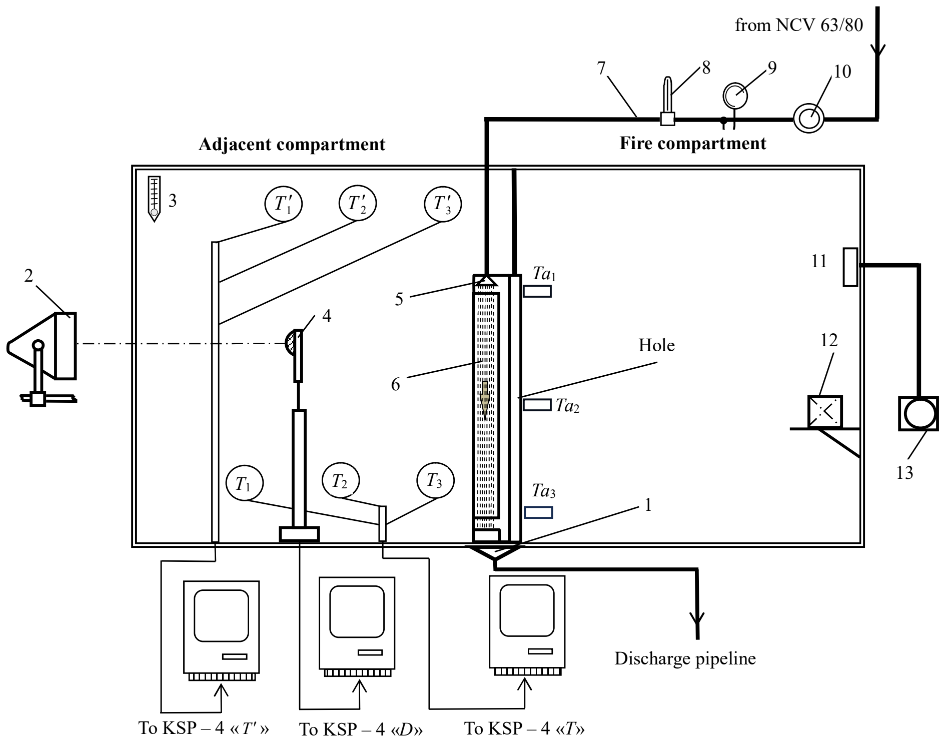


Fig. 1. Measuring system for the experimental model of shielding the flue gases and thermal energy of the jet water-gas ejector in front of the opening to the emergency room: 1 — water collector; 2 — light source; 3 — laboratory mercury thermometer; 4 — selenium photocell; 5 — spraying device; 6 — jet water and gas ejector; 7 — pipeline of working fluid; 8 — laboratory mercury thermometer; 9 — sample manometer; 10 — flow meter; 11 — airflow speed generator; 12 — smoke source (fire source); 13 — exhaust fan

To measure the transparency of the gas-air environment in the model of the ship's room, a system for measuring the transparency of the gas-air environment (Fig. 1) was used, which includes a selenium photocell 4, a light source 2, and a self-recording device of the KSP-4 "*D*" type. An incandescent lamp of the KPZH 220-500 type was used as a light source.

The system of temperature measurements includes a standard thermometer and three thermocouples located in the volume of the ship's room. The thermocouples are connected to a KSP-4 "*T*" self-writing device. The measurement of the temperature field at 6 points (Fig. 1, pos. $T_1$–$T_3$, $T_1'$–$T_3'$) of the model of the ship's room was carried out by the thermoelectric method, with the help of chromel-copel thermocouples.

The measurement of the velocity of the air-gas environment was carried out using a digital thermoanemometer ATT-1004, which works on the principle of cooling a heated thread with an air flow. The sensor of the device was placed inside the hole model, at the indicated points (Fig. 1, pos. $Ta_1$–$Ta_3$). The thermal anemometer provides fast and accurate measurements even at a low air flow speed (at $\upsilon$=0.2 m/s). The measured values of the velocity of the air-gas medium are stored in the device's memory automatically.

Control over the volumetric flow rate of the working fluid is carried out with the help of a flow meter (Fig. 1, item 10) using the readings from the scale of the device before starting and after stopping the water curtain.

A stopwatch was used to measure time.

Processing of the test results was carried out in accordance with the theory outlined in works [10–13], based on a scheme with uniform duplication of experiments in the following sequence:

1. For each row of the planning matrix, the average arithmetic value of the optimization parameter is calculated:

$$\bar{y}_j = \frac{1}{n}\sum_{u=1}^{n} y_{ju}, \qquad (1)$$

where $n$ is the number of parallel experiments; $y_{ju}$ is the result of a separate experiment.

2. The variance $S_j^2$ of each experiment of the planning matrix and the mean square deviation $S_j$ are determined:

$$S_j^2 = \frac{1}{n-1}\sum_{u=1}^{n}\left(y_{ju} - \bar{y}_j\right)^2, \qquad (2)$$

$$S_j = \sqrt{\frac{1}{n-1}\sum_{u=1}^{n}\left(y_{ju} - \bar{y}_j\right)^2}. \qquad (3)$$

3. Using the Cochran criterion, the hypothesis of homogeneity of variances of experiments is tested:

$$G = \frac{S_{\max}^2}{\sum_{1}^{N} S_j^2}, \qquad (4)$$

where $G$ is the Cochrane criterion, and if the value $G_l$<$G_t$ for the accepted level, then the model is considered adequate. When $G_l$>$G_t$, the hypothesis of adequacy is rejected; $S_{\max}^2$ – the largest of all variances;

$N$ is the number of experiments or the number of rows in the planning matrix.

The numbers of degrees of freedom $f_1$=$n$–1 and $f_2$=$N$ are associated with this criterion.

4. If the variances of the experiments are homogeneous, then the reproducibility variance of the experiment is calculated:

$$S_{\{\bar{y}\}}^2 = \frac{1}{N(n-1)}\sum_{j=1}^{N} S_j^2. \qquad (5)$$

5. The coefficients of the regression equation are determined by the following formulas: the free term $b_0$ is determined from the formula:

$$b_0 = \frac{1}{N}\sum_{j=1}^{N}\overline{y}_j. \qquad (6)$$

The regression coefficients characterizing linear effects are calculated as a function of:

$$b_j = \frac{1}{N}\sum_{j=1}^{N}\overline{y}_j x_{ij}. \qquad (7)$$

The regression coefficients characterizing the effects of interaction are determined from the formula:

$$b_{il} = \frac{\sum_{j=1}^{N} y_j x_{ij} x_{lj}}{nN}, \qquad (8)$$

where $il$ – numbers of factors; $x_{ij}$, $x_{lj}$ – coded values of factors $i$ and $l$ in the $j$-th experiment.

6. The variance of the regression coefficients is determined:

$$S^2_{\{b_j\}} = \frac{S^2_{\{\overline{y}\}}}{nN}. \qquad (9)$$

7. The value of the confidence interval is set $\Delta b_j$:

$$\Delta b_j = \pm t_\tau \cdot \sqrt{S^2_{\{b_j\}}} = \pm t_\tau \cdot S_{\{b_j\}}, \qquad (10)$$

where $t_\tau$ is the tabular value of the Student's criterion for the number of degrees of freedom with which $S^2_{\{\overline{y}\}}$ was determined and the selected level of significance; $S_{\{bj\}}$ is the squared error of the regression coefficient.

With uniform duplication of experiments, the number of degrees of freedom depends on $f=(n-1)\,N$, where $N$ is the number of experiments in the planning matrix, and $n$ is the number of parallel experiments.

8. The statistical significance of the regression coefficients is checked.

The coefficient is significant if its absolute value is greater than the confidence interval. The confidence interval is given by the upper and lower limits $b_j+\Delta b_j$ and $b_j-\Delta b_j$.

The coefficient is significant if its absolute value is greater than the confidence interval.

9. Checking the adequacy of the model.

Adequacy variance or residual variance characterizes the dispersion of empirical values $\overline{y}$ relative to the estimated values $\tilde{y}$, determined from the found regression equation. Adequacy variance is determined from the formula:

$$S^2_{ad} = \frac{\sum_{j=1}^{N}\left(\overline{y}_j - \tilde{y}_j\right)^2}{f}, \qquad (11)$$

where $\overline{y}_j$ is the average arithmetic value of the optimization parameter in the $j$-th experiment; $\tilde{y}_j$ is the value of the optimization parameter, calculated by the model for the conditions of the $j$th experiment; $f$ is the number of degrees of freedom $((N-(k+1))$, $k$ is the number of factors).

10. Verification of the hypothesis of adequacy of the found model.

Testing of this hypothesis is carried out by Fisher's $F$ test:

$$F_l = \frac{S^2_{ad}}{S^2_{\{y\}}}. \qquad (12)$$

If the value is $F_l<F_t$ for the accepted level of significance and corresponding numbers of degrees of freedom, then the model is considered adequate. When $F_l>F_t$, the hypothesis of adequacy is rejected.

The use of the Cochrane and Fisher tests assumes a normal distribution of the results of the experiment.

The processing of the results of the tests carried out in the model of the ship's room was carried out according to the following methodology:

a) the dependence derived from the Lambert-Bouger-Behr law [14] was used when determining the natural attenuation index of the medium by the photoelectric method:

$$\mu' = \frac{1}{r}\ln\frac{E_0 - E_f}{E_1 - E_f}, \qquad (13)$$

where μ' is the natural attenuation index of the medium, $m^{-1}$; $r$ is the distance from the light source to the photocell, m; $E_0$, $E_1$ – energy illuminance of the photocell, when light passes through the smoke-free and smoke-free volume, respectively, mV;

$E_f$ is the background value of the energy illuminance of the photocell, mV.

Considering that $E_f$=0 and assuming $E_0$=100 mV and $E_1=E_n(t)$ ($E_n(t)$ is the energy illumination of the photocell at time $t$, then expression (13) after substituting the above-mentioned data will take the following form:

$$\mu'_n(t) = \frac{1}{r}\ln\frac{100}{E_n(t)}, \qquad (14)$$

where $\mu'_n(t)$ is the natural attenuation index of the medium of the $n$-th experiment, $m^{-1}$;

b) calculation of liquid flow rate for the current JWGE model:

$$Q'_d = Q'_{d_2} - Q'_{d_1}, \qquad (15)$$

where $Q'_{d_1}, Q'_{d_2}$ is the reading of the device before starting the JWGE and after its stop, respectively, kg;

c) consumption characteristics of the input and output parts of the heat exchanger housing take the form:

$$G_{in} = Q'_d \rho_{fg}, \qquad (16)$$

$$G_{com} = Q'_d \rho_{im}, \qquad (17)$$

where $Q_f$ – volume flow rate of the working fluid ($m^3$/s); $\rho_{fg}$, $\rho_{im}$ – density of flue gases and inert mixture, kg/$m^3$;

c) second flow rate of liquid, kg/s:

$$Q_p = \frac{Q'_d}{t}, \qquad (18)$$

where $t$ is the working time of JWGE, s;

d) amount of burnt combustible material during the experiment:

$$\Delta g_n = g_n^b - g_n^e, \qquad (19)$$

where $\Delta g$ is a change in the mass of the combustible material during the experiment, kg; $g_n^b$ – initial mass of combustible material in the experiment, kg; $g_n^e$ – final mass of the combustible material in the experiment, kg;

e) based on the conditions of widespread use on ships, data on smoke formation of diesel fuel were used in the calculations. Smoke-generating capacity of diesel fuel, $m^3/kg$ – 13.23;

f) JWGE ejection coefficient:

$$K_{\text{in}} = \frac{G_{\text{in}}}{G_{\text{WF}}}, \tag{20}$$

$$K_{\text{com}} = \frac{G_{\text{com}}}{G_{\text{WF}}}, \tag{21}$$

where $G_{\text{in}}$ and $G_{\text{com}}$ are the mass flow rates of the gas-air environment of the input and output parts of the JWGE housing, $m^3/s$; $G_{\text{WF}}$ – flow rate of working fluid per second, $m^3/s$;

g) evaluation of the effectiveness of the shielding of flue gases of JWGE was performed based on the relative change in the attenuation coefficient of the environment in the room:

$$F_{\mu} = \frac{\mu_0' - \mu_t'}{T} \cdot 100\,\%, \tag{22}$$

where $\mu_0'$ is the average value of the natural indicator of the attenuation of the environment to the shielding of flue gases in the adjacent room, $m^{-1}$; $\mu_t'$ is the average value of the natural indicator of the attenuation of the environment in the adjacent room after the time since the start of operation of JWGE, $m^{-1}$;

h) assessment of the intensity of temperature reduction of heated gases in the fire and adjacent compartments is made in comparison with the efficiency of JWGE operation in the emergency room:

$$F_t = \frac{T - T_{\text{med}.i}}{T} \cdot 100\,\%, \tag{23}$$

where $T$ is the average volumetric temperature in the measuring compartment at time $t$, created by the exemplary version of JWGE, °C; $T_{\text{med}.i}$ is the average volume temperature in the measuring compartment at time $t$ in the $i$-th experiment;

i) the evaluation of the effectiveness of reducing the temperature of the heated gases of JWGE was performed based on the relative change of the average volume temperature in the model of the ship space over time:

$$F_{\text{tef}} = \frac{T_{\text{med.fir}.i} - T_{\text{med.mea}.i}}{T_{\text{med.fir}.i}} \cdot 100\,\%, \tag{24}$$

where $T_{\text{med.fir}.i}$ is the average volume temperature in the fire compartment at time $t$ in the $i$-th experiment, °C; $T_{\text{med.mea}.i}$ is the average volume temperature in the measuring compartment at time $t$ in the $i$-th experiment, °C.

## 5. Results of experimental studies on the prevention of draft and gas exchange with adjacent rooms

### 5. 1. Determining the ratio of consumption characteristics of JWGE and the opening during a fire

In order to study the effectiveness of JWGE in the hole, it was assumed to study the ratio of the consumption characteristics of JWGE and the opening in the event of a fire. For the possibility of varying the consumption characteristics of the JWGE, three working pressures of water supply to the JWGE spraying device were chosen: 0.3 MPa, 0.4 MPa, and 0.5 MPa.

During the experiment, before launching the set of the operational model of JWGE (Fig. 1), the initial parameters of the state of the air environment in the model of the ship's room were measured: pressure, humidity, and temperature of the gas-air environment. Then manually (through the door of the fire compartment) with the help of an ignition source (torch) the combustible load was ignited. After ignition and self-burning, the torch was removed while the doors of the fire compartment remained closed.

After that, 2 minutes after the ignition of the combustible load, the set of the current model of JWGE was put into operation, for which pump 9 was turned on (Fig. 1). With the help of a special valve on manometer 9, the set pressure of the working fluid was set. The temperature of the working fluid was controlled by thermometer 8.

The start of the experiment is considered to be the time of starting the recorders of KSP-4 "*D*", KSP-4 "*T*'", and KSP-4 "*T*"" devices. The measurement of the velocity of the gas-air environment was carried out using thermal anemometers (in Fig. 1, items $Ta_1$–$Ta_3$). The height of the gas exchange rate between the emergency and adjacent rooms was controlled by the location of the thermal anemometers. Control over the volumetric flow rate of the working fluid was carried out with the help of a flow meter (Fig. 1, item 10) using the readings from the scale of the device before starting and after stopping the JWGE.

5 minutes after the start of the experiment, the stopwatch, instrument recorders, and a set of the current JWGE model stopped. After stopping the set of the operating JWGE model, readings were taken from the flow meter 10. Data on the flow rate of the working fluid, pressure, and speed were entered in the research log (Table 1).

Based on the results of the research and the obtained data, the ejection coefficients of the current model of JWGE were calculated at the selected pressures of the working fluid according to the procedure using formulas (15) to (19). The results of the calculations are given in Table 1. The averaged values of measurements of gas phase velocities in the hole during operation of JWGE are represented by the diagram in Fig. 2.

It should be noted that during firefighting, a large number of consumers are connected to the ship's fire main. This sometimes leads to a decrease in the normal working pressure in the fire main from 0.8 MPa to the critical minimum values of 0.3 MPa.

Then, based on the data from Table 2, it can be seen that under the mode of the lowest ejection coefficient, which corresponds to the pressure in the fire main of 0.3 MPa, a minimum rarefaction is formed in the inlet part of JWGE, and in the outlet – a minimum inflation. This means that even with these minimum values of the JWGE characteristics, the effect of reducing the intensity of smoke entering the adjacent room through the hole is achieved. Therefore, the specified cost characteristics of the JWGE are a condition for the minimum achievement of effective operation of the support system.

The diagram (Fig. 1) of gas-air flow velocities in the opening during the operation of JWGE demonstrates that the highest flow velocities occur at the section of the upper edge of the door and the lower one in the absence of the middle part. This indicates the ability of the local support system on the basis of JWGE to take the heated gases of the upper layer from the emergency room, process them, and return them to the room. This indicates the achievement of the effect of localization of flue gases in the emergency room when the door is open.

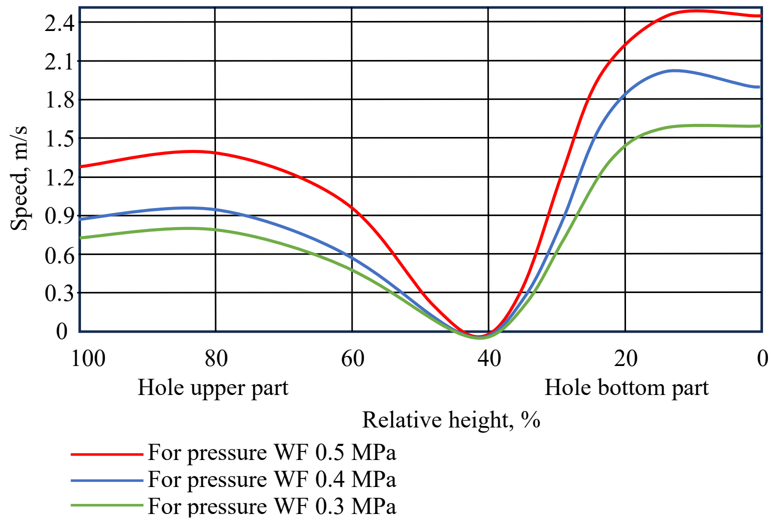


Fig. 2. Diagram of gas-air flow velocities in the hole during the operation of a jet water-gas ejector

Table 1

Determining the performance characteristics of current JWGE model

| Pressure | $P_l$, MPa | 0.3 | 0.4 | 0.5 |
|---|---|---|---|---|
| Inlet part, 0.07 m$^2$ | Measurement 1 | 11 | 17.5 | 29.5 |
| | Measurement 2 | 9 | 18 | 27.5 |
| | Measurement 3 | 11 | 12 | 29.5 |
| | Average value of measurements for the inlet part of JWGE | 11.6 | 15 | 27.83 |
| | $\omega_{in}$, m/s | 0.67 | 0.78 | 1.22 |
| Outlet part, 0.03 m$^2$ | Measurement 1 | 30 | 45 | 55 |
| | Measurement 2 | 31.5 | 54 | 65 |
| | Measurement 3 | 36 | 50 | 57 |
| | Average value of measurements for the outlet part of JWGE | 36.9 | 48.3 | 60.4 |
| | $\omega_{com}$, m/s | 1.53 | 1.91 | 2.33 |
| Mass flow rate of the gas-air environment of the input and output parts of the housing, m$^3$/s | $G_{in}$, m$^3$/s | 0.043 | 0.052 | 0.07 |
| | $G_{com}$, m$^3$/s | 0.046 | 0.057 | 0.085 |
| Consumption of working fluid per second, m$^3$/s | $G_{WF}$, m$^3$/s | 0.000248 | 0.000287 | 0.000331 |
| Ejection coefficient | $K_{in}$ | 173 | 181 | 211 |
| | $K_{com}$ | 185 | 199 | 257 |
| | Mean value $K$ | 186 | 195 | 234 |

**5. 2. Determining shielding properties of jet water-gas ejectors in the opening to the adjacent room**

As a parameter for optimizing the process of reducing the intensity of smoke entering the adjacent room through the hole, the natural attenuation index μ' was adopted when the time $t$ changed from 1 to 300 s.

The organization of the experiment was similar to that described in chapter 5. 1. At the beginning of each experiment, the parameters characterizing the state of the gas-air environment in the model of the ship's room and the working fluid were determined. The controlled factor was the energy illuminance of the photocell, the readings of which were taken using a system for measuring the transparency of the gas-air medium (Fig. 1), which includes a selenium photocell 4, a light source 2, and a self-recording device of the KSP-4 "*D*" type. The results of experimental studies are given in Table 2.

Experiments on experimental studies of the shielding properties of JWGE in the opening to the adjacent room were performed three times.

Statistical processing of the results of experimental studies was carried out in the Mathcad 11 environment, the results of which are given in Table 3.

The model was checked for adequacy for the time point $t$=120 s.

When determining the optimization of the process of reducing the intensity of smoke entering the adjacent room through the opening, the natural medium attenuation index μ' was adopted.

The selected optimization parameter depends on the following factors [8, 9]:

$$\mu' = f\left(\alpha, K, \omega, G_l, G_g, V, H, \varphi\right), \quad (25)$$

where α is the angle of inclination of the support flow to the plane of the door, °; $K$ – JWGE ejection coefficient; ω – speed of air flow, m/s; $G_l$, $G_g$ – volume flow rate of liquid and gas, respectively, m$^3$/s; $V$ – volume of the adjacent compartment model, m$^3$; $H$ – door height, m; φ – air humidity in the model of the ship space, kg/m$^3$; $m$ – mass of combustible load, kg.

The factors $G_l$, $G_g$ are determined by the characteristics of JWGE nozzle; they were taken as constant and excluded from consideration.

The factor ω was assumed to be constant.

Factors $V$, $H$, φ are fixed during experiments and were excluded from consideration. Therefore, two factors α, $K$ were considered to be the most significant, the influence of which had to be tested experimentally, i.e.:

$$\mu' = f\left(\alpha, K\right), \quad (26)$$

The homogeneity of the variances of the experiments was confirmed by the Cochren criterion: the calculated value of the Cochren criterion is less than the tabulated value (Table 3).

The test of the hypothesis of the adequacy of the theoretical model was carried out according to the Fisher criterion (12): the calculated value is $F_l$=0.011, the tabular value is $F_t$=18.5. The calculated value is less than the tabular value, therefore, the model is adequate.

Optimization of the process of reducing the intensity of smoke entering the adjacent room was carried out in the values of the natural attenuation index μ'. For this purpose, the experimental values of the energy illuminance of the photocell $E$1mid. were recalculated into the value of the natural index of attenuation of the environment according to formula (13). The results of the calculation are given in Table 4.

Table 2

Results of experimental studies on the process of reducing the intensity of smoke entering the adjacent room through the opening (energy illumination of the photocell)

| Time, s | Measurement 1 | Measurement 2 | Measurement 3 | $E1mid.(t)$, mV |
|---|---|---|---|---|
| | $E1(t)$, mV | $E1(t)$, mV | $E1(t)$, mV | |
| Experiment 1 | | | | |
| 0 | 0.2 | 0.2 | 0.2 | 0.2 |
| 30 | 1 | 1 | 1.2 | 1.1 |
| 60 | 7 | 8 | 8.1 | 7.7 |
| 90 | 18 | 18.5 | 19.3 | 18.6 |
| 120 | 43 | 45 | 38 | 42 |
| 150 | 55 | 54 | 62 | 57 |
| 180 | 62 | 66 | 67 | 65 |
| 210 | 84 | 86 | 85 | 85 |
| 240 | 84 | 85 | 89 | 86 |
| 270 | 88 | 88 | 88 | 88 |
| 300 | 90 | 89 | 88 | 89 |
| Experiment 2 | | | | |
| 0 | 0.2 | 0.2 | 0.2 | 0.2 |
| 30 | 0.5 | 0.8 | 0.8 | 0.7 |
| 60 | 2.4 | 2.6 | 2.2 | 2.4 |
| 90 | 6.4 | 6.5 | 7.2 | 6.7 |
| 120 | 15 | 14 | 13 | 14 |
| 150 | 22 | 21 | 23 | 22 |
| 180 | 38 | 39 | 38.5 | 38.5 |
| 210 | 43 | 45 | 46 | 44.7 |
| 240 | 57 | 56 | 58 | 57 |
| 270 | 68 | 69 | 65.5 | 67.5 |
| 300 | 64 | 66 | 65 | 65 |
| Experiment 3 | | | | |
| 0 | 0.5 | 0.2 | 0.5 | 0.4 |
| 30 | 4 | 3.5 | 4.5 | 4 |
| 60 | 20 | 22 | 21 | 21 |
| 90 | 36 | 40 | 38 | 38 |
| 120 | 64 | 68 | 72 | 68 |
| 150 | 75 | 72 | 75 | 74 |
| 180 | 85 | 85 | 85 | 85 |
| 210 | 98 | 97 | 99 | 98 |
| 240 | 98 | 98 | 98 | 98 |
| 270 | 100 | 100 | 100 | 100 |
| 300 | 100 | 100 | 100 | 100 |
| Experiment 4 | | | | |
| 0 | 0.2 | 0.2 | 0.5 | 0.3 |
| 30 | 2 | 2 | 5 | 3 |
| 60 | 14 | 15 | 16 | 15 |
| 90 | 34 | 32 | 30 | 32 |
| 120 | 64 | 59 | 57 | 60 |
| 150 | 70 | 65 | 63 | 68 |
| 180 | 80 | 85 | 84 | 83 |
| 210 | 95 | 95 | 98 | 96 |
| 240 | 97 | 97 | 94 | 96 |
| 270 | 100 | 99 | 95 | 98 |
| 300 | 100 | 100 | 100 | 100 |

The dependences of the natural index of environmental attenuation on time are shown in Fig. 3.

The effectiveness of reducing gas exchange through the opening was evaluated based on the relative change in the natural rate of attenuation of the environment in the room (14). Thus, during the evaluation, results were obtained that indicate the ability of the JWGE system to screen gas exchange with a fairly high efficiency of 85–88 %.

Table 3

Results of statistical processing of the experiment

| Experiment No. | Factor | | Response function | $\overline{y}_i$, mV | $S_j^2$ | $s_j$ | Cochren criterion | $S_{\{y\}}^2$ |
|---|---|---|---|---|---|---|---|---|
| | $x_1$, ° | $x_2$ | $y_j$, mV | | | | | |
| 1 | 60 | 0.3 | 43 | 42 | 13 | 3.61 | $G_l$=0.372; $G_t$=0.7679; $G_l$<$G_t$ | 10.75 |
| | | | 45 | | | | | |
| | | | 38 | | | | | |
| 2 | 60 | 0.1 | 15 | 14 | 1 | 1 | | |
| | | | 14 | | | | | |
| | | | 13 | | | | | |
| 3 | 0 | 0.3 | 64 | 68 | 16 | 4 | | |
| | | | 68 | | | | | |
| | | | 72 | | | | | |
| 4 | 0 | 0.1 | 64 | 60 | 13 | 3.61 | | |
| | | | 59 | | | | | |
| | | | 57 | | | | | |

Table 4

Recalculation of the experimental values of energy illumination of the photocell into the values of the natural index of attenuation of the medium

| Time, s | | 0 | 30 | 60 | 90 | 120 | 150 | 180 | 210 | 240 | 270 | 300 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Experiment 1 | $E1$mid.($t$), mV | 0.2 | 1.1 | 7.7 | 18.6 | 42.0 | 57.0 | 65.0 | 85.0 | 86.0 | 88.0 | 89.0 |
| | μ′, m⁻¹ | 6.2 | 4.5 | 2.6 | 1.7 | 0.9 | 0.6 | 0.4 | 0.2 | 0.2 | 0.1 | 0.1 |
| Experiment 2 | $E1$mid.($t$), mV | 0.2 | 0.7 | 2.4 | 6.7 | 14.0 | 22.0 | 38.5 | 44.7 | 57.0 | 67.5 | 65.0 |
| | μ′, m⁻¹ | 6.2 | 5.0 | 3.7 | 2.7 | 2.0 | 1.5 | 1.0 | 0.8 | 0.6 | 0.4 | 0.4 |
| Experiment 3 | $E1$mid.($t$), mV | 0.4 | 4.0 | 21.0 | 38.0 | 68.0 | 74.0 | 85.0 | 98.0 | 98.0 | 100.0 | 100.0 |
| | μ′, m⁻¹ | 5.5 | 3.2 | 1.6 | 1.0 | 0.4 | 0.3 | 0.2 | 0.0 | 0.0 | 0.0 | 0.0 |
| Experiment 4 | $E1$mid.($t$), mV | 0.3 | 3.0 | 15.0 | 32.0 | 60.0 | 68.0 | 83.0 | 96.0 | 96.0 | 98.0 | 100.0 |
| | μ′, m⁻¹ | 5.8 | 3.5 | 1.9 | 1.1 | 0.5 | 0.4 | 0.2 | 0.0 | 0.0 | 0.0 | 0.0 |

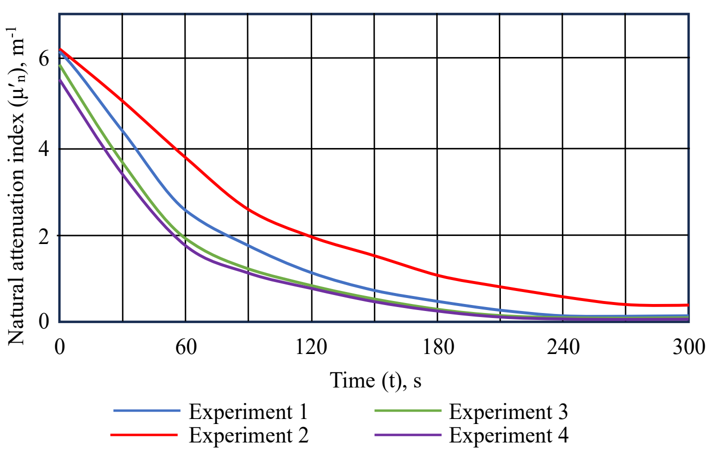


Fig. 3. Dependence of the natural index of environmental attenuation on time

**5. 3. Determining the dynamics in a temperature decrease of heated gases**

When studying the dynamics of temperature reduction of heated gases, the average volumetric temperature in the adjacent compartment at time $t$, which varies from 1 to 300 s, is taken as an optimization parameter. The results of experimental studies are given in Table 5, and the dynamics of temperature changes in the adjacent room – on the graph in Fig. 4.

Statistical processing of the results of experimental studies was carried out in the Mathcad 11 environment, the results of which are given in Table 5.

Analogous to chapter 5. 2, the model was checked for adequacy for the time point $t$=120 s.

When determining the optimization of the dynamics of the temperature reduction of heated gases in the adjacent room, the average volume temperature was taken.

As in the previous section, the selected optimization parameter depends on the following factors [8, 9]:

$$T_{mid} = f\left(\alpha, K, \omega, G_l, G_g, V, H, \varphi\right). \quad (27)$$

So, as in the previous section, two factors α, $K$ were considered the most significant, the influence of which had to be checked experimentally, i.e.:

$$T_{mid} = f\left(\alpha, K\right). \quad (28)$$

The homogeneity of the variances of the experiments was confirmed by the Cochren criterion: the calculated value of the Cochren criterion is less than the tabular value (Table 6).

The purpose of this experiment was to obtain a linear model, which makes it possible to assert the influence of factors on the optimization parameter. The values of the coefficients in this equation are determined using the values of the response functions obtained as a result of the experiment.

Coefficients of the regression equation:

– the free term $b_0$ is determined from formula (6): $b_0$=24.33;

– regression coefficients characterizing linear effects are determined from formula (7): $b_1$=2.17; $b_2$=–4.8.

Table 5

The average volume value of the temperature in the measuring and firing compartments

| Time | Temperature in the upper part of the adjacent room, °C | | | | Temperature in the lower part of the adjacent room, °C | | | |
|---|---|---|---|---|---|---|---|---|
| | Measurement 1 | Measurement 2 | Measurement 3 | $T_{mid}$ top AC | Measurement 1 | Measurement 2 | Measurement 3 | $T_{mid}$ bottom AC |
| Experiment 1 | | | | | | | | |
| 0 | 36 | 38 | 40 | 38 | 15 | 17 | 16 | 16 |
| 30 | 86 | 89 | 89 | 88 | 18 | 19 | 20 | 19 |
| 60 | 170 | 174 | 169 | 171 | 21 | 20 | 25 | 22 |
| 90 | 210 | 215 | 205 | 210 | 30 | 27 | 24 | 27 |
| 120 | 206 | 204 | 208 | 206 | 26 | 27 | 26 | 26 |
| 150 | 150 | 154 | 149 | 151 | 26 | 21 | 25 | 24 |
| 180 | 120 | 121 | 125 | 122 | 20 | 22 | 27 | 23 |
| 210 | 110 | 110 | 112 | 111 | 24 | 21 | 18 | 21 |
| 240 | 105 | 105 | 105 | 105 | 20 | 19 | 21 | 20 |
| 270 | 90 | 89 | 97 | 92 | 18 | 19 | 20 | 19 |
| 300 | 86 | 83 | 89 | 86 | 18 | 16 | 17 | 17 |
| Experiment 2 | | | | | | | | |
| 0 | 37 | 39 | 36 | 37 | 19 | 19 | 14 | 17 |
| 30 | 110 | 112 | 111 | 111 | 24 | 21 | 18 | 21 |
| 60 | 193 | 196 | 194 | 194 | 27 | 24 | 23 | 25 |
| 90 | 280 | 283 | 281 | 281 | 36 | 32 | 31 | 33 |
| 120 | 275 | 278 | 276 | 276 | 34 | 31 | 31 | 32 |
| 150 | 164 | 166 | 165 | 165 | 26 | 28 | 30 | 28 |
| 180 | 135 | 139 | 137 | 137 | 26 | 24 | 28 | 26 |
| 210 | 120 | 123 | 129 | 124 | 23 | 22 | 27 | 24 |
| 240 | 118 | 107 | 120 | 115 | 20 | 21 | 25 | 22 |
| 270 | 93 | 103 | 95 | 97 | 20 | 21 | 19 | 20 |
| 300 | 90 | 91 | 95 | 92 | 18 | 17 | 19 | 18 |
| Experiment 3 | | | | | | | | |
| 0 | 25 | 25 | 25 | 25 | 13 | 13 | 13 | 13 |
| 30 | 65 | 64 | 65 | 65 | 14 | 13 | 14 | 14 |
| 60 | 106 | 105 | 106 | 106 | 17 | 16 | 15 | 16 |
| 90 | 150 | 148 | 149 | 149 | 18 | 17 | 17 | 17 |
| 120 | 150 | 148 | 149 | 149 | 18 | 18 | 18 | 18 |
| 150 | 110 | 108 | 109 | 109 | 18 | 18 | 19 | 18 |
| 180 | 96 | 95 | 95 | 95 | 18 | 18 | 18 | 18 |
| 210 | 86 | 85 | 87 | 86 | 17 | 17 | 18 | 17 |
| 240 | 85 | 82 | 82 | 83 | 15 | 15 | 15 | 15 |
| 270 | 78 | 77 | 78 | 78 | 14 | 15 | 15 | 15 |
| 300 | 73 | 72 | 72 | 72 | 13 | 14 | 14 | 14 |
| Experiment 4 | | | | | | | | |
| 0 | 28 | 29 | 33 | 30 | 15 | 16 | 14 | 15 |
| 30 | 78 | 75 | 87 | 80 | 16 | 17 | 15 | 16 |
| 60 | 125 | 120 | 130 | 125 | 18 | 19 | 17 | 18 |
| 90 | 165 | 160 | 155 | 160 | 20 | 20 | 20 | 20 |
| 120 | 160 | 162 | 152 | 158 | 20 | 21 | 22 | 21 |
| 150 | 125 | 124 | 135 | 128 | 21 | 21 | 21 | 21 |
| 180 | 110 | 115 | 105 | 110 | 20 | 20 | 20 | 20 |
| 210 | 100 | 100 | 100 | 100 | 18 | 19 | 20 | 19 |
| 240 | 100 | 97 | 97 | 98 | 17 | 18 | 16 | 17 |
| 270 | 80 | 83 | 92 | 85 | 16 | 16 | 16 | 16 |
| 300 | 80 | 80 | 80 | 80 | 14 | 16 | 15 | 15 |

Regression equation: $y$=24.33+2.17$x_1$−4.8$x_2$.

According to the model built, the $x_2$ factor (JWGE ejection coefficient) has the greatest influence on the optimization parameter.

Variance of regression coefficients according to (9):

$$S^2_{\{b_j\}}=0.215.$$

The value of the confidence interval according to (10):

$$\Delta b_j=\pm 1.067.$$

Table 6

Results of statistical processing of the experiment

| Experiment No. | Factor | | Response function | $\bar{y}_j$, °C | $S_j^2$ | $s_j$ | Cochran criterion | $S^2_{\{\bar{y}\}}$ |
|---|---|---|---|---|---|---|---|---|
| | $x_1$, ° | $x_2$ | $y_j$, °C | | | | | |
| 1 | 60 | 0.3 | 26 | 26 | 0.33 | 0.6 | $G_l$=0.387; $G_g$=0.7679; $G_l$<$G_t$ | 2.583 |
| | | | 27 | | | | | |
| | | | 26 | | | | | |
| 2 | 60 | 0.1 | 31 | 32 | 3 | 1.7 | | |
| | | | 34 | | | | | |
| | | | 31 | | | | | |
| 3 | 0 | 0.3 | 16 | 18 | 3 | 1.7 | | |
| | | | 19 | | | | | |
| | | | 19 | | | | | |
| 4 | 0 | 0.1 | 19 | 21 | 4 | 2 | | |
| | | | 23 | | | | | |
| | | | 21 | | | | | |

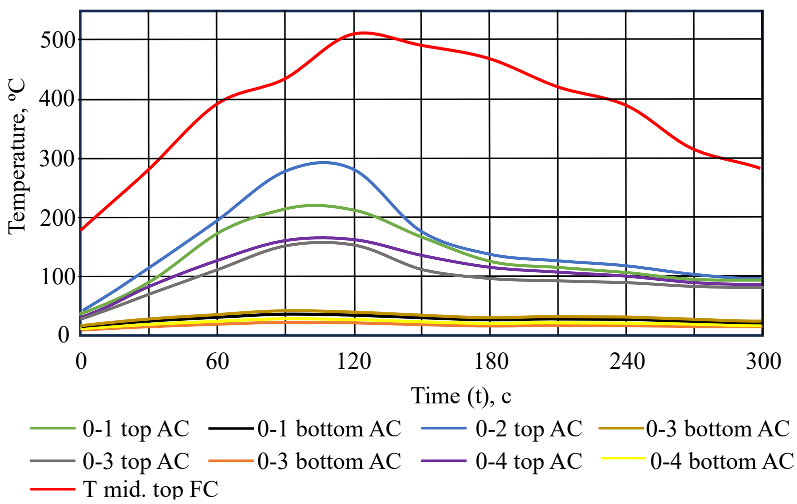


Fig. 4. Dynamics of temperature changes over time at a working fluid pressure of 0.3 MPA: top AC – temperature in the upper part of the adjacent compartment; bottom AC – temperature in the lower part of the adjacent compartment; Tmid FC – the temperature in the upper part of the fire compartment

The coefficients are significant because the value of the confidence interval is less than the absolute value of the regression coefficients.

Adequacy variance according to (11): $S_{ad}^2 = 1.76$.

The test of the hypothesis of the adequacy of the found model is carried out according to Fisher's criterion (12): $F_l$=0.69, $F_t$=18.5. The calculated value is less than the tabular value, therefore, the model is adequate.

## 6. Discussion of results of experimental studies on the prevention of draft and gas exchange with adjacent rooms

The main result was achieved in the work, namely, the adequacy of theoretical studies of the processes of forming the thermal energy shielding effect and the localization of smoke gases in the emergency room without its sealing was confirmed by the experimental method.

The results can be explained by solving main three problems.

First, the effectiveness of reducing the intensity of smoke entering the adjacent room through the hole was experimentally proven. This is explained by the definition of the dependence of the ratio of the consumption characteristics of JWGE and the opening during a fire. The results of calculating the ejection coefficients of the current JWGE model at the selected pressures of the working fluid are given in Table 1. The averaged values of measurements of gas phase velocities in the hole during operation of JWGE are represented by the diagram in Fig. 2.

Secondly, the effectiveness of the shielding properties of jet water-gas ejectors in the opening into the adjacent room was experimentally proven. The effectiveness of reducing gas exchange through the opening was assessed based on the relative change in the natural attenuation of the environment in the room (14). The results are represented by the dependence of the natural indicator of the attenuation of the environment on time, which is shown in Fig. 3.

Thirdly, the dynamics of lowering the temperature of the heated gases in the adjacent compartment were experimentally proven.

During the experiment, a linear model was built, which is expressed by the dynamics of temperature changes over time at the pressure of the working fluid (Fig. 4). The model makes it possible to state that the main factor affecting the optimization parameter is the JWGE ejection coefficient, the results of the statistical processing of the experiment are shown in Table 6.

Research into the application of JWGE installed in the semi-limited (open on one side) volume of the ship space according to the specified methods was carried out for the first time. The creation of a local support system on the basis of JWGE and its installation in the area of the door space made it possible to obtain results from the formation of an air curtain. Obtaining an air curtain is carried out by taking a part of high-temperature flue gases into the JWGE housing, their heat and mass exchange treatment and output back into the flow. This created conditions under which the output of high-temperature flue gases from the ship's emergency room with an open hatch was reduced. The advantages of this method include, first of all, the ability to influence the progress of a fire in an emergency room without using sprayed water in an open manner.

The solutions obtained during the research on providing local support on the basis of JWGE and its installation in the area of the door space give reason to claim the creation of a new effective method for limiting the spread of fire and smoke from the emergency room, as well as preventing draft and gas exchange with adjacent rooms and systems for its implementation. This makes it possible to develop technical solutions during the design of the general safety system of the ship (vessel) aimed at new firefighting methods. Such methods may include optional sealing of an emergency room equipped with the specified local support system by closing the door.

The research was aimed at confirming the adequacy of theoretical studies by experimental method [8, 9]. According to them, the output part of the JWGE is able to ensure the creation of equilibrium in the doorway in order to reduce the intensity of air entering the emergency room from the adjacent room. Therefore, the results are adequate only for proving the workability and effectiveness of the method for preventing the spread of smoke on the ship based on the JWGE system installed in the doorway. These results cannot be used to determine the effectiveness of the system of local support based on JWGE in horizontal ceilings (hatches).

The development of this research may consist in taking into account the limitations and devising an experiment aimed at proving the adequacy of theoretical studies on preventing the spread of smoke on the ship based on the JWGE system installed in horizontal ceilings (hatchways).

## 7. Conclusions

1. The JWGE set is an effective means of reducing the intensity of smoke entering the adjacent room through the opening. This is evidenced by the determined ratio of the consumption characteristics of JWGE and the opening in the event of a fire. Thus, the launch of the support system allows for 2 minutes of work in a completely smoky room with a volume of 0.65 $m^3$ to achieve visibility of up to 2.5 meters at a pressure in the main line of 0.3 MPa.

In addition, it was established that the intensity of smoke removal by the device depends on the operating characteristics of JWGE and the start-up time of the installation:

– when the location of the fire source is from the topmost point, the intensity of gas exchange with the adjacent room is maximum during free burning;

– when the JWGE is started at the working fluid pressure mode of 0.3 MPa, the smoke in the adjacent room does not decrease significantly (compared to the modes of 0.4 and 0.5 MPa). Since the intensity of smoke removal is the same for all experiments, the volume of the zone filled with hot flue gases has the smallest value; with JWGE operating modes of 0.4 and 0.5 MPa, the smoke in the adjacent room is significantly lower;

– when placing the fire source in the middle and lower parts of the room, a significant decrease in gas exchange was observed even under the 0.3 MPa mode. At the same time, a decrease in the intensity of combustion was observed, which is explained by the intensive filling of the lower part of the room with an inert (with increased moisture content) gas-vapor-air mixture with JWGE.

2. The JWGE set is an effective means of shielding properties of JWGE in the opening to the adjacent room. Thus, thermal energy shielding for all experiments occurs with a fairly high efficiency of 85–88 %.

3. The JWGE set is an effective means for reducing the temperature of heated gases. Thus, the regression equation, obtained from the results of experimental studies, made it possible to establish the influence of significant factors on the selected criterion of optimality. According to the results, it was established that the decrease in the average volume temperature in the adjacent room occurs already under the 0.3 MPa mode. This is explained by a decrease in the intensity of gas exchange through the open hole in which the JWGE works.

In addition, the assessment of JWGE efficiency after 2 minutes from the moment of its implementation shows that the speed of reaching the required temperature in the adjacent room depends on the ejection coefficient, which determines the capacity of JWGE for heat removal. This gives an understanding that the greater the ejection coefficient, the more intense the heat exchange process.

## Conflicts of interest

The author declares that he has no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study and the results reported in this paper.

## Funding

The study was conducted without financial support.

## Data availability

All data are available in the main text of the manuscript.

## Use of artificial intelligence

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

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