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**Malakhov O.,
Kolegaev M.,
Malakhova D.,
Maslov I.,
Brazhnik I.,
Gudilko R.**

# IMPROVEMENT OF WORKING PARAMETERS OF SHIPS WITH THE USE OF WATER-FUEL EMULSIONS

*Об'єктом дослідження є процес підготовки і спалювання обводнених видів палива на морських суднах. Одним з найбільш проблемних місць в використанні таких палив є складність процесу підготовки водо-паливної емульсії і відсутність даних, які однозначно вказують на гранично допустимі значення концентрації води в судновому дизелі. В результаті досліджень встановлено, що присутність води в паливі при певних умовах роботи морського судна може приводити до поліпшення процесу горіння. В цьому випадку скорочуються шкідливі викиди, знижується температура відхідних газів і скорочуються витрати на паливо.*

*В ході дослідження використовувалась нова технологія суднової обробки водо-паливних емульсій. Запропонований метод змішування води з паливом забезпечував структурні зміни молекулярного складу емульсії в порівнянні з початковою структурою вуглеводнів і забезпечував підвищену дисперсність при її розпорошуванні в факелі горіння. Основою для створення технології підготовки водо-паливних емульсій були два процеси – кавітація і механічне змішання води і палива на високих швидкостях.*

*Отримано, що поліпшення основних експлуатаційних показників морських суден на різних режимах навантаження головного двигуна може досягатися при концентрації води в паливі до 15 %. Це пов'язано з тим, що підвищується якість горіння палива за рахунок зниження показників нагару і відкладень на внутрішніх поверхнях робочих циліндрів. Процес використання водо-паливних емульсій на судах має ряд особливостей, які визначаються обладнанням, що використовується. Дуже важливим питанням є питання стійкості факела горіння, який створюється форсунками суднового головного двигуна. Завдяки якісній підготовці водо-паливної емульсії спостерігалося зниження сумарної витрати палива при збереженні робочих характеристик судна на постійному рівні. У порівнянні з аналогічними суднами, які працюють на стандартному паливі, зниження теплової напруженості головного двигуна судна було досягнуто за рахунок зниження температури димових газів, що викидаються в атмосферу.*

**Ключові слова:** *водно-паливна емульсія, концентрація води, температура димових газів, факел горіння, головний двигун, витрата палива.*

## 1. Introduction

At present, it can be stated that all ships of water transport use in the operation of ship power plants not pure diesel fuel, but fuel emulsions with the presence of a water component.

According to the manufacturer's requirements, distilled marine diesel fuel must be supplied for burning in the ship's main engine or the inert gas generator. In practice, this requirement is almost never maintained. Very often, in order to save, lower-quality fuels are used, which are characterized by the presence of water, solid inclusions or highly viscous hydrocarbon compounds in the form of bitumens, asphaltenes, resins, etc.

The presence of water in the fuel in most cases can't be avoided. Natural processes of moisture condensation from the environment, technical malfunctions in the sealing units and seals of fuel and ballast tanks lead to the ingress of the water component into the fuel.

The solution to the problem of using water-fuel emulsions is relevant, since all ships, without exception, in their design contain a fuel preparation circuit. Its execution may vary depending on the design of the ship, but at the same time it always has the main basic elements – hydraulic lines, pressure equipment, filtration systems, separation, etc. [1].

## 2. The object of research and its technological audit

*The object of research* is the process of preparing and burning watered fuels on ships. One of the most problematic places in the use of such fuels is the complexity of the process of preparing a water-in-fuel emulsion and the lack of data that unequivocally indicate the maximum allowable values of water concentration in a marine diesel engine.

Without exception, all sea ships in their design contain a fuel preparation circuit. Its execution may differ depending on the design of the ship, but at the same time there always exist basic elements – hydraulic lines, pressure equipment, filtration systems, separation, etc. [2].

The general flow chart of the fuel preparation circuit is as follows: when bunkering a ship in a port, fuel is initially pumped into ship storage tanks. As required, fuel from tanks is supplied to the ship's main engine or to the combustion chamber of an inert gas system. Intermediate elements in this case are usually the heaters and fuel separators.

The characteristic flaws of a ship's fuel loop system usually manifest themselves only during its operation. During fuel injection into the ship, mechanical suspensions and various liquid impurities usually move along with the main stream. They mainly include: condensates of moisture from the environment, various types of liquid fuels and lubricants, particles of rust, scale, and solid components of petroleum products, for example, asphaltenes or bitumens. All these impurities significantly reduce the quality of burning fuel, reduce all the operating characteristics of the ship, reduce the efficiency of the ship's main engine and lead to an accelerated failure of the main components and elements of the fuel equipment.

## 3. The aim and objectives of research

*The aim of research* is a scientific solution to the problem of increasing the technical and economic indicators of the work of the navy ships through the implementation of a new technology for the preparation and combustion of water-fuel emulsions.

To achieve this aim it is necessary to perform the following objectives:

1. To develop a new universal technology for the preparation of water-fuel emulsions with the possibility of integrating it into the ship's circuit for preparing fuel.
2. To determine the main indicators of the working process of the developed technology for preparing a water-fuel emulsion and show how they can be used in the practice of operating ships.
3. To determine the boundaries of the numerical ranges of the stability zone of combustion torch, depending on the temperature of the torch and the concentration of the water component in the starting emulsion for combustion.

## 4. Research of existing solutions of the problem

The influence of water in fuel on its combustion processes in internal combustion engines was first considered in 1880 [1]. A large amount of research in this area has been carried out by the authors of [3, 4].

Analytical review of the known results of theoretical and experimental studies does not allow to unequivocally argue about the negative effect of water in the fuel on the performance of the combustion process [5, 6]. It is known that during the combustion of fuel due to the appearance of such intermediate chemical compounds as alcohols, small additives of water lead to an improvement in the quality of the combustion process [7, 8]. In this case, the torch dispersion increases and the degree of concentration of harmful components (soot, toxic nitrogen and sulfur oxides, etc.) in exhaust gases, temperature of flue gases, etc., may decrease [9, 10].

According to the classification of works [11, 12], moisture in diesel fuel can be divided into two types: internal and external. Internal, colloidal moisture is always present in the fuel and is evenly distributed per unit volume [13, 14]. Its quantity is determined by the natural composition of the fuel and the relative humidity of the atmospheric air. In the tropics, compared with the northern areas, this figure will always be higher. Hydrated moisture refers to colloidal moisture – a part of water that is chemically bound to mineral fuel impurities [15]. Usually they include calcium sulphate and aluminosilicate [16]. The indicator of hydrated moisture is the ash content of the fuel. The higher it is the more hydrated moisture is contained in the initial volume of fuel.

External moisture in marine fuel is always variable, since it is caused by various reasons. The main sources of its occurrence on the ship can be divided into: atmospheric, man-made and technical.

Atmospheric moisture enters the ship's fuel tank through the vent bilge valve. In the tropics, the relative humidity of air is 96–98 %. The temperature difference inside and outside the tank usually reaches 10 °C. For these reasons, the amount of precipitation can be quite substantial and go up to 0.3 % of the total volume of the fuel tank [2]. Man-made and technical sources of external moisture are usually: emergency breaks at the joints or corrosion of pipelines passing through fuel tanks; places of interfacing tanks containing water and fuel.

To remove moisture from the fuel on ships, two types of cleaning are used – preliminary and main. Pre-flotation is based on the separation of water and fuel through the power of Archimedes. During the actual operation of the ship, natural flotation is practically not used in fuel storage tanks. The reason is the absence in tanks of the necessary elements of flotation plants – technological holes and drainage lines for sludge removal [17]. The main stage of cleaning is the use of filters and separation equipment [18]. Thus, it can be stated that regardless of the type of technology used, water in the fuel is always present on ships.

From a scientific point of view, many of the issues related to the theory of burning ship watered fuels remain unexplored and require their own thorough research [3, 5]. There are no specific studies that would reflect the experimental studies of the processes of hydrodynamic interaction of two immiscible liquids under the influence of high speeds of movement or large dynamic loads [6, 9]. Also, the issues of mechanical mixing of two liquids at high speeds of movement [19] are not fully considered. Known scientific results describing the motion of a heterogeneous stream of a jet disintegrating into droplets under the influence of high temperatures are scattered [20, 21]. Sometimes they are contradictory [22, 23] and require their own systematization with simultaneous comparison with the results of independent experiments.

At present, there are no data available that may indicate clear numerical ranges of permissible moisture concentrations in the fuel [24]. There are also no theoretical or experimental studies showing the stability of the flame of combustion, depending on the temperature of the flame and the concentration of the water component in the initial emulsion that is fed to the combustion.

Obtaining of theoretical and experimental results on the description of the combustion process of watered fuel in the working conditions of the ship has a particular interest. Ultimately, such studies are supposed to formulate basic indicators and a method for estimating the degree of influence of water concentration in the fuel on the working processes in the ship power plant or in the ship inert gas production system.

Based on the analysis of technical problems associated with the operation of ships, it can be stated that its solution requires an important scientific and technical challenge, which is development of a method that will increase the efficiency of operation of ships. The basis of this method should be the use of new technology for the preparation of water-fuel emulsions with their subsequent combustion in the working conditions of the ship.

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## 5. Methods of research

During the studies, marine diesel fuel of the following brands was used: Marine diesel oil, Diesel euro 2M, Gas Oil, Marine Gas Oil, ENEOS Diesel Gas Oil.

For water-fuel emulsions based on diesel engine diesel brand Diesel euro 2M (Greece) numerical data on changes in flash point, the concentration of the main components of the outgoing flue gases, developed power and fuel consumption on the ship's main engines are developed. The range of volume concentration of water in the fuel corresponds to the range from 0 to 15 %.

The preparation of a water-fuel emulsion is carried out due to the work of a structurally modified single-stage centrifugal pump brand DESMI NSA series (Denmark). Its capacity is 10 $m^3$/h, and the maximum pressure is 10 m $H_2O$.

When using the cavitation process during the processing of a water-fuel emulsion, a multi-channel digital vacuum gauge ACM 2000 (Netherlands) was used to measure the pressure inside the working chamber.

Measurements of the composition and temperature of the flue gases on the ship were carried out using a universal digital flue gas analyzer 717R Flue Gas Analyzer (USA). Its absolute error in measuring the temperature did not exceed 0.3 %, and when measuring the concentration of the components of the flue gases did not exceed 5 %.

When conducting research, the following methods were used:

– analytical method – to conduct a comparative assessment of the characteristics of water-fuel emulsions;
– jet theory – when studying the characteristics of the burning torch;
– diffusion theory of combustion with the scheme of the reduced film – to simulate the combustion process of a water-fuel emulsion;
– theory of statistics – for processing experimental data on the combustion of water-fuel emulsions;
– probability theory – to assess the stability of emulsions to breakdown;
– dimension theory – to obtain the main criterial dependencies of the combustion process of watered fuel;
– numerical approximation methods – to build temperature characteristics;
– experiment planning method – to study the main indicators of the process of burning water-fuel emulsions.

## 6. Research results

When conducting experiments using the cavitation process, working on the principle of rotation of a two-phase flow of water and fuel, an estimate of the degree of flow swirling degree is used. It is calculated as a dimensionless complex:

$$\Gamma_w = \frac{Q}{\Gamma R} = \frac{Q}{(2\pi w R)R}, \qquad (1)$$

where $Q$ – fuel consumption, $m^3$/s; $\Gamma$ – circulation of the fuel flow; $R$ – pipe radius, m; $w$ – circumferential flow rate of fuel on the pipe wall, m/s.

All experiments were conducted in the range of variation of the $\Gamma_w$ value from 0.02 to 0.8. This range corresponds to a change in the volume flow rate of the fuel-water emulsion from 0.01 to 0.117 $m^3$/s and the feed rates of the main fuel flow at the entrance to the treatment unit from 15 to 30 m/s.

During the experiments, it was found that when the flow was turned up, the radius of the cavitation zone became close to the pipeline radius, and its length was from 0.1 to 5.17 pipe diameters. The results of these experiments are shown in Fig. 1.

Experimentally, an estimate is obtained of the influence of the cavitation zone length on the total hydraulic pressure loss $\Delta P$ inside the working chamber. The results are shown in Fig. 2.

The use of cavitation suggests that improving the quality of the fuel-in-water emulsion will lead to an increase in the main operational parameters of the ship. Using the example of an inert gas production system on a tanker, it is found that the total consumption of consumed fuel as a result of using the cavitation treatment process is reduced. These results are shown in Fig. 3. Fig. 3 shows the change in fuel consumption in two modes of operation of the ship – the normal operation of the inert gas system and the installation of a cavitation fuel treatment unit. Fig. 1–3 correspond to the actual operating conditions of the tanker. They show the results of measurements that correspond to the first six hours of operation of the inert gas generation system. Curves 2, 3 in Fig. 3 correspond to the operation of an inert gas system using a cavitation process for treating fuel and constructed during various experiments. They are received at intervals of 34 days between tanker flights.

In the course of the experiments, the flash point was determined for various concentrations of the mixture of the ship diesel engine Diesel euro 2M with water. Results in Fig. 4 relate to two methods of preparing a water-fuel emulsion. In Fig. 4 curve 1 corresponds to the mechanical method of mixing, when two initial components of the emulsion (water and diesel) were fed to a centrifugal pump with an impeller, which was perforated in the areas of inter-blade channels. Curve 2 in Fig. 4 corresponds to the preparation of a water-fuel emulsion using a cavitation process.

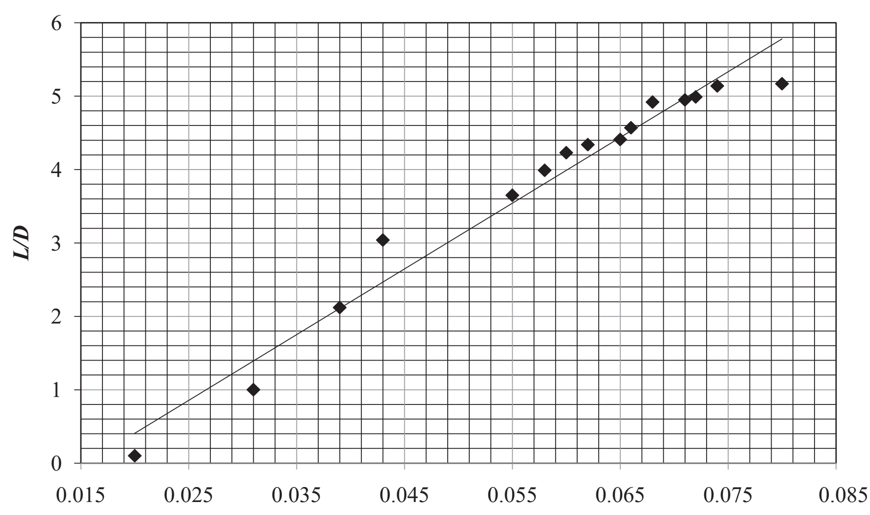


**Fig. 1.** The influence of the flow swirling degree on the length of the cavitation zone

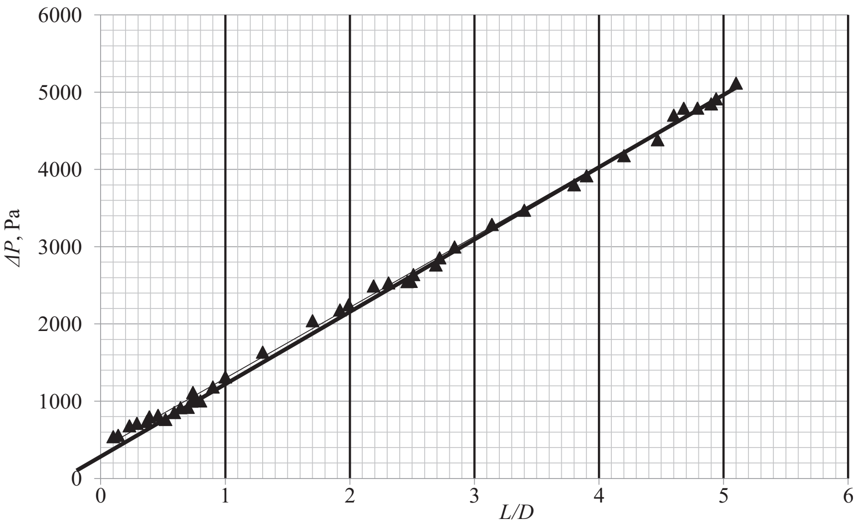


**Fig. 2.** Effect of cavity length on hydraulic losses along the channel length

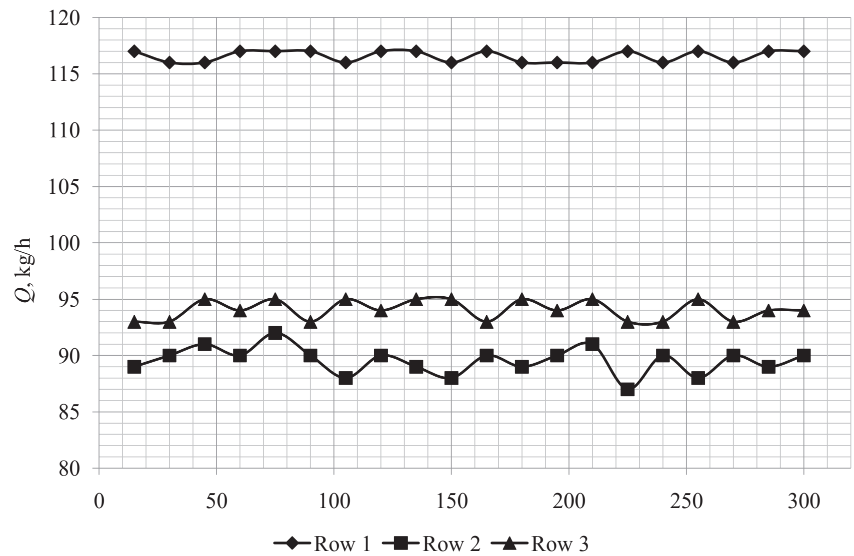


**Fig. 3.** Change in fuel consumption when using the cavitation process. Gas production on the tanker: Row 1 – in normal mode; Row 2, 3 – with fuel processing

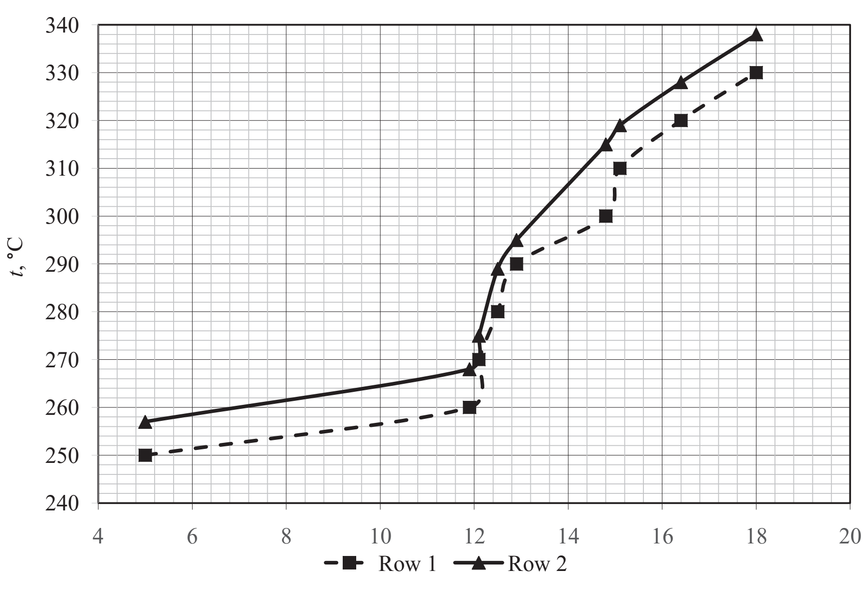


**Fig. 4.** The effect of water concentration on the flash point of the water-fuel emulsion: Row 1 – mechanical preparation; Row 2 – cavitation preparation

In the course of the experimental studies, it was established how the presence of water in diesel fuel influences two main operational parameters of the ship – fuel consumption and the temperature of exhaust flue gases. Flow measurements were made during the transition of the ship, when the three operating modes of the load of the ship's main engine at a constant number of revolutions were respectively: 80 %, 50 % and 30 %. The change in temperature and composition of the exhaust flue gases, depending on the moisture content of the fuel, was experimentally investigated using the load mode of the ship's main engine, which is 80 %. The measurement results are shown in Fig. 5, 6.

When using a water-fuel emulsion during the ship operation, the concentrations of the main components of the outgoing flue gases were measured.

These include: carbon monoxide CO, oxygen $O_2$ and carbon dioxide $CO_2$. The values of the last two components, depending on the concentration of water in the fuel, are shown in Fig. 7. Both curves are built in the operating conditions of the ship at a load of the ship's main engine, amounting to 80 %.

Measuring the current capacity of the ship's main engine in the mode of its current operation is directly related to the calorific value of the water-fuel emulsion used. In this case, it should be borne in mind that it is necessary to supply water-fuel emulsions for combustion in the ship's propulsion mode. During this mode, the load on the ship's main engine is almost constant, and the number of revolutions of the engine shaft varies within small limits.

The characteristic dependence of the change in the current power of the ship's main engine with increasing water concentration in the water-fuel emulsion is shown in Fig. 8.

When conducting experiments in the conditions of the ship, part of the measured data did not coincide with each other. An example of such a discrepancy in reproducing the measurement results is the fuel consumption values. They are shown in curves 2 and 3 in Fig. 3.

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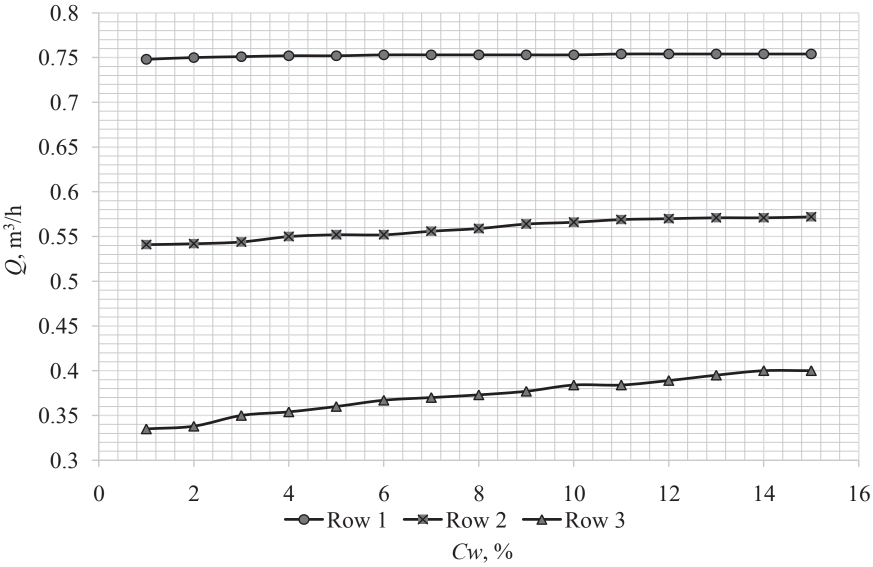


**Fig. 5.** The effect of water concentration on the consumption of water-fuel emulsion. Load mode of the ship's main engine: Row 1 – 80 %; Row 2 – 50 %; Row 3 – 30 %

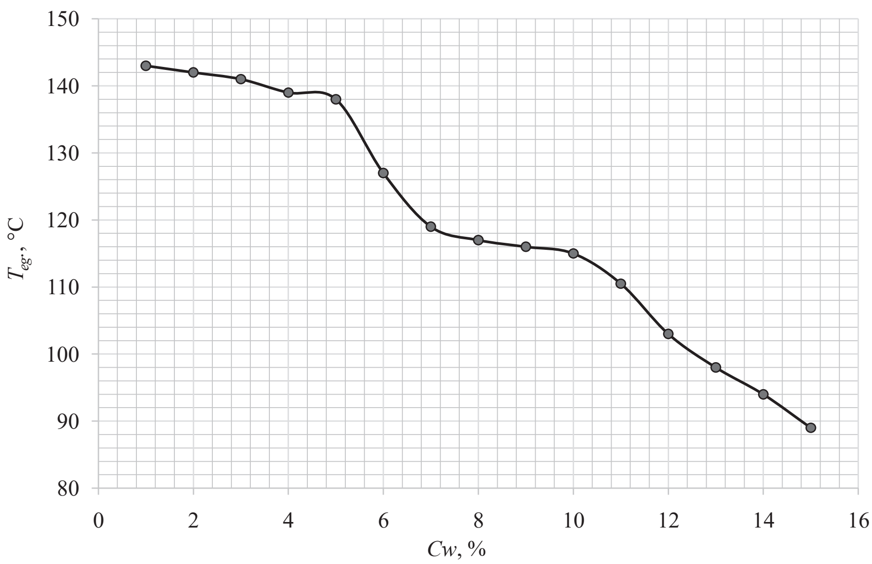


**Fig. 6.** Influence of water concentration on exhaust flue gas temperature

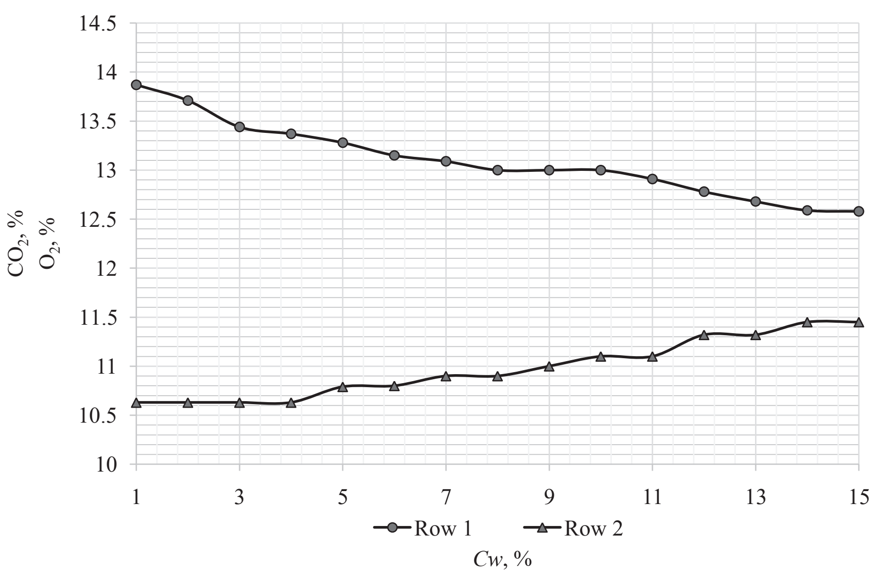


**Fig. 7.** The effect of water concentration in the emulsion on the concentration in the flue gases: Row 1 – carbon dioxide $CO_2$; Row 2 – Oxygen $O_2$

Differences in these numerical values can be explained by the following reasons:

– the climatic conditions in which the ship operated changed, which led to: a change in temperature and moisture content of the burning air; changes in the temperature of the seawater going to the treatment and cooling of the inert gas system;

– during storage of fuel in fuel tanks during the transfer of the ship, its physical performance, in particular, the amount of deposited sediment, has changed, which ultimately led to a different quality of its processing.

When analyzing the results, it is concluded that the use of cavitational dispersion of fuel leads to a significant improvement in the quality of the inert gas system. In this case, while maintaining the volume flow rate of inert gases produced by the system, the total consumption of fuel consumed is reduced. In the first case (comparison of curves 1 and 2 in Fig. 3), the average consumption of fuel is reduced from 116.55 kg/h to 89.55 kg/h. This is a percentage of 23.1 %. In the second case (comparison of curves 1 and 3 in Fig. 3), the average consumption of fuel is reduced from 116.55 kg/h to 94.05 kg/h. This is a percentage of 19.3 %.

According to the Fig. 5, the measurement results show that an increase in the concentration of water in the water-in-fuel emulsion leads to a change in the consumption of fuel consumed in a larger direction. It should be noted that this change can't be characterized as permanent. The worst option corresponds to the modes of the ship with a small load on the ship's main engine. In this case, the addition of the water component does not lead to fuel savings. With a maximum value of water concentration equal to 15 %, fuel consumption readings increased by 16.5 %. On the other hand, on the average run, when the load on the ship's main engine is 50 % with a water concentration of 15 %, the increase in consumption is only 4.7 %.

The best effect in fuel economy when using a water-fuel emulsion is achieved with a load on the ship's main engine of 80 %. In this case, when the moisture content of the fuel is 15 %, the change in fuel consumption, compared to a humidity of 1 %, is only 1.57 %. In other words, with the ship running at a load of the main engine equal to 80 %, it is possible to obtain fuel savings of 13.42 % or in real units of measurement 0.102 $m^3$/h.

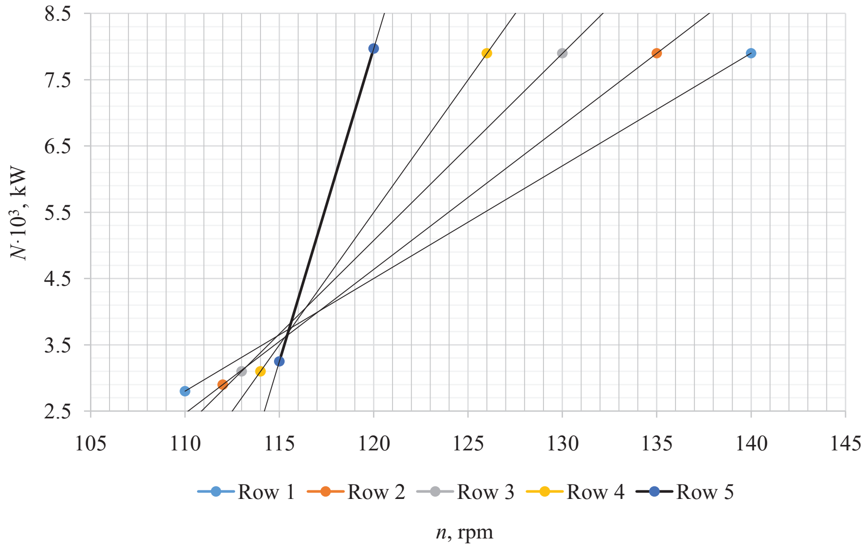


**Fig. 8.** The effect of water concentration on the power of the ship's main engine. Water concentration: Row 1 – 1 %; Row 2 – 3 %; Row 3 – 5 %; Row 4 – 10 %; Row 5 – 15 %

As seen in Fig. 6, the amount of water in the water-fuel emulsion directly reduces the temperature of the ship's flue gases. The temperature drop is mainly due to the additional cost of thermal energy for the dissociation of the water component of the emulsion in the torch. It is these energy costs that lead to a total reduction in total heat losses at the exit from the ship's main engine. By analogy with the economic effect of reducing the level of fuel consumption in the course of the ship with a constant load of the ship's main engine of 80 %, a positive effect is achieved in the temperature balance. The change in humidity in the original water-fuel emulsion from 1 to 15 % resulted in a negative gradient in the temperature difference at the exit of the chimney equal to 52.7 °C. This indicator is very high and shows the prospects of further use of water-fuel emulsions in the working conditions of the ships.

Analysis of the results on the effect of water concentration in the emulsion on the quantitative composition of the components in the exhaust flue gases also indicates a positive effect from the presence of water in diesel fuel. As seen on curves 1 and 2 of Fig. 7, the concentration of carbon dioxide $CO_2$ decreases with a simultaneous increase in the amount of free oxygen in the flue gases. Such a change with the growth of moisture content in the water-fuel emulsion indicates a better burnout of diesel fuel [25], and, consequently, an increase in the total efficiency of the ship's power plant.

In the graphs shown in Fig. 8, it can be seen that an increase in the concentration of water in the fuel changes the power of the ship's main engine according to a linear law. The value of the width of the engine speed range with increasing power decreases with increasing water concentration in the fuel.

On the basis of the presented research materials, it can be argued that the obtained results allow to conclude that the developed new shipboard technology for preparing a water-fuel emulsion is characterized by a high quality of water dispersion and marine diesel fuel. It allows to improve the technical characteristics of the operation of the ship's power plant.

## 7. SWOT analysis of research results

*Strengths.* In comparison with the work of the ship on standard diesel fuel, the use of the developed technology for the preparation of water-fuel emulsions leads to an improvement in the operating performance of the ship. Improving the combustion process and reducing the consumption of consumed fuel leads to a reduction in the economic costs of its use. Reducing the carbon deposits on the walls of the working cylinders of the ship's main engine and reducing the flue gas temperature lead to an increase in the energy and overall efficiency of the ship.

From an environmental point of view, a reduction in the numerical values of the concentration of the harmful components of the flue gases is a very positive result. The use of the developed technology on ships can lead to a significant reduction in the total number of harmful emissions into the atmosphere.

*Weaknesses.* The weaknesses of the developed technology for the preparation of water-fuel emulsions include the dependence of the quality of the obtained mixture on the initial characteristics of the fuel and the need to continuously monitor the critical value of the concentration of the water component. At certain modes of operation of the ship, the degree of influence of the initial fuel cleaning indicators, its temperature and, as a result, the physicochemical properties can be decisive. The use of high viscosity fuels may result in a low degree of dispersion with water and will not improve the performance of the ship. During ship maneuvers in the port water area, the use of poorly prepared water-fuel emulsion can lead to a decrease in the power of the main engine and the deterioration of its controllability.

*Opportunities.* The most promising in further research are two directions. The first direction is related to obtaining dependencies that describe the influence of the physicochemical properties of the original fuel on the quality of the produced water-fuel emulsion. The second direction is related to studies of the economic performance of the ship when using water-fuel emulsions. It is very important to establish the boundaries of the modes of ship operation, on which the least amount of costs will be achieved without loss of power of the ship's main engine.

*Threats.* There are two main external factors that can have a negative impact on the use of water-fuel emulsions on ships. The first is the poor quality fuel equipment of the ship. Its installation on the ship is usually carried

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out by various manufacturers. In order to save very often inexpensive equipment is installed. It is characterized by low rates of resistance to mechanical wear of fuel channels, resistance to temperature and chemical corrosion, etc.

The second negative factor is the presence on the ships of man-made sources of water ingress into an emulsion already prepared for use. In most cases, these are places where fuel and water tanks mate and various hatch openings for crew access to the tanks. Their presence is due to the design features of the execution of ships.

## 8. Conclusions

1. As a result of research, a method has been developed that improves the operational efficiency of ships through the use of new technology for preparing water-fuel emulsions and their subsequent combustion in the main engine of the ship.

2. It has been established that the maximum fuel economy when using a water-fuel emulsion is achieved with a working load on the ship's main engine equal to 80 %. In this case, when the moisture content of the fuel is 15 %, the increase in fuel consumption compared to a humidity of 1 % is only 1.57 %. This shows that with a ship running at a load of the main engine equal to 80 %, it is possible to obtain fuel savings of 13.42 % or in real units of measurement 0.102 $m^3$/h.

3. Studies of the degree of influence of water in the fuel on the operation of the ship's main engine have shown that:

– steady torch of burning water-fuel emulsion is limited by the value of water concentration equal to 15 %. The temperature range of ignition of the water-fuel emulsion is also determined by the concentration of the water component. Its range is from 250 to 330 °C when the water concentration in the fuel is from 5 to 18 %;

– changing the water concentration in the fuel from 1 to 15 % gives a decrease in the concentration of carbon monoxide CO by 3.635 mg/$m^3$, and carbon dioxide $CO_2$ by 1.3 %.

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***Malakhov Oleksiy,*** *Doctor of Physical and Mathematical Sciences, Professor, Department of Vessel's Thermal Energy, National University «Odessa Maritime Academy», Ukraine, ORCID: http://orcid.org/0000-0002-5003-8715, e-mail: a_malahov@yahoo.com*

***Kolegaev Mikhail,*** *PhD, Professor of the Department of Life Safety, National University «Odessa Maritime Academy», Ukraine, ORCID: http://orcid.org/0000-0002-9328-182X, e-mail: smf@onma.edu.ua*

***Malakhova Diana,*** *Postgraduate Student, Department of Oil-Gas and Chemical Engineering, Odessa National Polytechnic University, Ukraine, ORCID: http://orcid.org/0000-0003-4833-1485, e-mail: diana.dizzy.ds@gmail.com*

***Maslov Igor,*** *PhD, Associate Professor, Department of Ship Power Plants and Systems, Danube Institute of National University «Odessa Maritime Academy», Izmail, Odessa region, Ukraine, ORCID: http://orcid.org/0000-0003-1759-6077, e-mail: igormslv@ukr.net*

***Brazhnik Igor,*** *Postgraduate Student, Department of Life Safety, National University «Odessa Maritime Academy», Ukraine, ORCID: http://orcid.org/0000-0001-9961-9759, e-mail: ig.brazhnik@gmail.com*

***Gudilko Roman,*** *Odessa, Ukraine, ORCID: http://orcid.org/0000-0001-6519-9258, e-mail: romangudilko1973@gmail.com*