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DETERMINATION OF RATIONAL DESIGN VALUES FOR GAS-AIR COOLERS COMPONENTS OF EXHAUST GASES OF MARINE POWER PLANTS

Svitlana Kuznetsova [1]
Valerii Kuznetsov [1 *]
Andrii Voloshyn [2]
[1] Admiral Makarov National University of Shipbuilding, Mykolaiv, Ukraine
[2] State Research Design & Shipbuilding Centre, Mykolaiv, Ukraine

* Corresponding author: *valeriy.kuznetsov@nuos.edu.ua (Valerii Kuznetsov)*

ABSTRACT

Modernisation of marine power plants in the transport vessel fleet to satisfy the requirements of the International Maritime Organization is an urgent scientific and technical problem. Currently, the use of catalytic selective filters, dry and wet scrubber systems and exhaust gas recirculation for marine diesel engines is widely used for this purpose. An analysis of the use of ejection gas-air coolers is presented as an additional method of emission reduction. However, the use of such device does not neutralise the harmful emissions of power plant engines, but only increases the volume concentration of their exhaust gases. But this will help to increase the efficiency of dispersion of harmful emissions, by reducing the concentration of harmful emissions to values not exceeding the maximum permissible concentrations. Its efficiency depends on the load mode of the diesel engine. It is found that the initial concentration of harmful substances in combustion products due to their dilution with fresh air at 100% engine load is reduced by about 50%. The values of the reduction of the concentration and temperature of exhaust gases with the reduction of the engine load to 75% and 50% depending on the louvre angle are obtained. It is proved that ejection gas-air coolers can be an effective additional means for compliance with modern environmental parameters, especially when vessels are in special areas of the world's oceans.

Keywords: vessel, marine power plant, environmental parameters, emissions, gas-air cooler, nozzle.

INTRODUCTION

Today, maritime transportation is one of the most cost-effective ways of transporting goods for different purposes around the world. United Nations data [1] shows that in 2019 there was a 4.1% growth of the world merchant fleet, and that by the beginning of 2020 the total number of merchant vessels was 98,140.

In spite of the fact that the percentage of harmful emissions of marine power plants does not exceed 7–9% of the world total, the International Maritime Organization (IMO) rules are consistently strengthening the requirements to limit the level of harmful emissions into the atmosphere during the operation of the power plants of sea transport vessels. The greatest attention is given to the levels of sulphur oxides and nitrogen oxides, which ship owners are obliged to reduce (Fig. 1). This applies particularly to the 'special' areas of the world's oceans – the Black Sea, Mediterranean Sea, Baltic Sea, North Sea, Red Sea, the Antarctic area, and the Caribbean Sea area, including the Gulf of Mexico [2, 3].

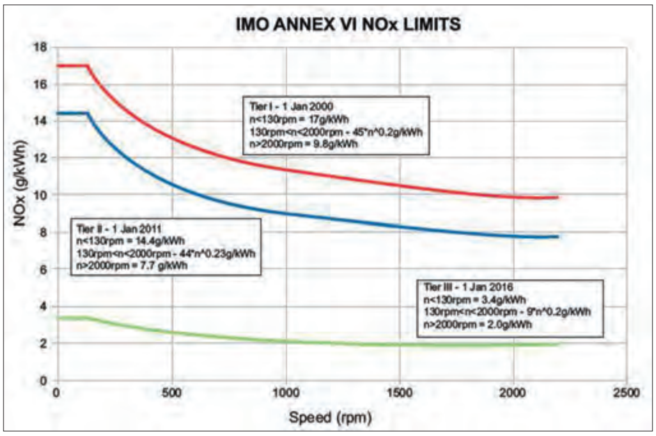

Fig. 1. IMO emission reduction requirements

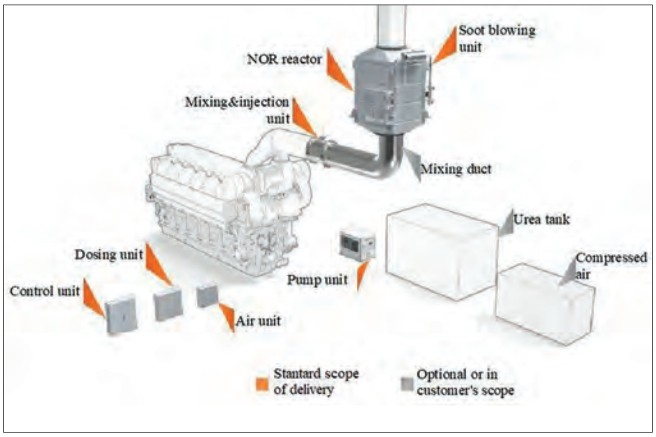

Fig. 2. Wärtsilä NOx Reducer system

In 2010, Annex VI to the International Convention on the Prevention of Air Pollution (MARPOL - 73/78) [4] introduced a requirement to improve the energy efficiency of vessels, which is directly related to the amount of fuel that is used, and the emissions of carbon dioxide – CO_2. Strictly, this gas is not a pollutant but a greenhouse gas, the control of emissions of which is covered by the UN Framework Convention on Climate Change and the Kyoto Protocol. Besides, an indirect cause of the development of the greenhouse effect is thermal pollution of the environment due to the relatively high temperature level and quantity of exhaust gases during the operation of sea transport vessel power plants. Moreover, the operation of vessels in different climatic zones of the world's oceans can cause a decrease in the efficiency of the cooling systems of the main and auxiliary engines, which can additionally increase the level of thermal emissions by up to 3% [5].

So, in today's practice it is considered necessary to ensure environmental efficiency in the operation of power plants of marine transport vessels by reducing their thermal and harmful emissions.

LITERATURE ANALYSIS OF EXISTING BASIC TECHNICAL SOLUTIONS HIGHLIGHTING THE UNRESOLVED PART OF THE PROBLEM

The specific challenge of measures to reduce environmental pollution by marine power plants is the need to implement them in the limited space of the vessel's engine room. This task is relatively easy to solve when designing and building new vessels, but problems can arise when retrofitting the propulsion systems of vessels currently in service.

The manufacturers of equipment for marine power engineering offer several directions for the "greening" of marine power plants – the use of catalytic selective filters, dry and wet scrubber systems, as well as recirculation of exhaust gases of ship diesel engines.

Fig. 2 shows the *Wärtsilä* NO_x *Reducer* (*NOR*) wet system for additional treatment of the exhaust gas flow to comply with IMO Tier III [6].

The final elements of the catalytic reaction in the selective catalytic filter are pure nitrogen and water, i.e., the main constituents of the environment. No liquid or solid by-products are formed. The result is lower NO_x levels, but no significant change in the temperature of the flue gas.

Alfa Laval offers the *Pure* SO_x *Express* system (Fig. 3) [7] to reduce SO_x levels.

Fig. 3. Pure SOx Express system by Alfa Laval

This system allows vessels to continue to use heavy fuel and still meet Tier II and Tier III emission requirements for SO_x levels. In addition, the temperature of the exhaust gases is significantly reduced.

In these systems, simultaneously with the reduction of harmful emissions, the temperature of the exhaust gases is also reduced.

However, the use of these scrubber systems causes problems with the selection of scrubber elements depending on the operating mode [8] and also with the disposal of the scrubber wash water, especially when the vessel is at sea [9].

Dry cleaning can also be used to reduce the amount of SO_x in the exhaust gases.

The company SodaFlexx has developed and implemented a technology for neutralising sulphur components SO_x by injecting sodium bicarbonate $NaHCO_3$ into the exhaust gas stream [10, 11]. Due to the chemical reaction, a highly stable and non-toxic salt – sodium sulphate Na_2SO_4 – is formed. It can be removed into the atmosphere or captured by special cyclone separators.

Solvay and Andritz have proposed the Bicar dry scrubber [12]. This was installed on the ferry "Piana". According to the independent third party CERTAM, about 96% of the SO_x was removed from use. According to [12], the scrubber is certified by DNV GL.

To neutralise harmful components in the exhaust gases, it is possible to use the Dry Exhaust Gas Scrubber manufactured by Crystec Technology Trading GmbH [13]. However, its use is possible with an exhaust gas flow rate of up to 72 m³/h, which limits its use by diesel generators

Another direction of the reduction of the NO_x level in exhaust gases of diesel engines is gas recirculation, the principle of which is illustrated in the diagram in Fig. 4 [14, 15], and it is shown that recirculation is economically justified in partial engine operation modes and at a recirculation rate of 12–20%.

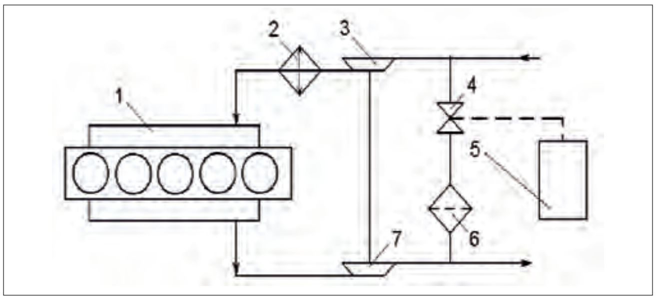

Fig. 4. Schematic diagram of gas recirculation: 1 - diesel engine; 2 - cooler; 3 - compressor; 4 - valve; 5 - control unit; 6 - filter; 7 - turbine

But at the same time, it has been shown in [15, 16] that such degrees of recirculation can increase the exhaust gas temperature by 4.5–9.1%. So, it can increase the thermal load on the environment (Fig. 5).

The ecological parameters of marine power plants depend on many factors and can deteriorate during their operation. One effective way to control them is vibroacoustic diagnostics and monitoring of the working process of diesel engines [17, 18, 19, 20]. However, this method requires the installation of additional equipment on the main and auxiliary engines of the power plant.

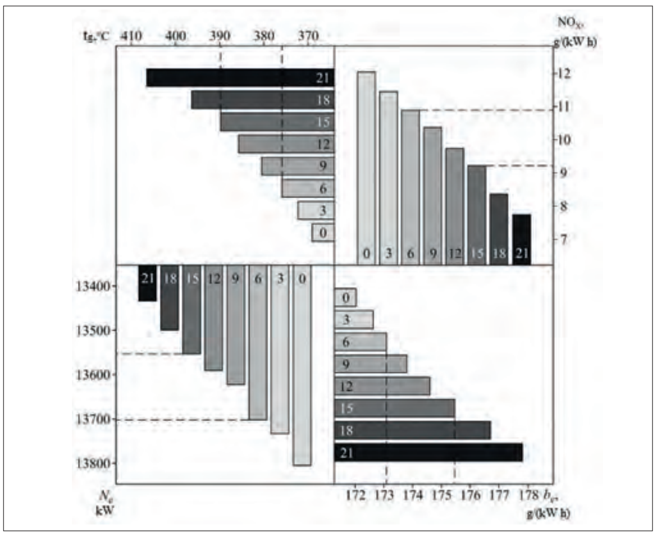

Fig. 5. Variation of exhaust gases NO_x emissions, specific effective fuel consumption be, effective power Ne, exhaust gas temperature tg at 100% load of 7S60MC Kawasaki MAN-B&W diesel engine at various EGR

Wang and Yao [21] presented the results of their research on the effect of dimethyl ether on methyl decanoate HCCI on the emission characteristics of a low-speed diesel engine. However, in our opinion, it is still necessary to conduct more detailed research on the direct effect of these additives on the structural elements of a diesel engine – injectors, cylinder walls, exhaust valve, etc. In addition, the fuel preparation system before feeding into the engine is significantly complicated, which will accordingly increase the cost of operating such systems.

In [22], Korczewski proposes to determine the parameters of chemical emissions in the exhaust gases of marine diesel engines on the basis of the emission calculation model that he developed. He presented the results of a comparison of the computational model with the results of the operation of a four-stroke marine diesel engine, which showed good convergence. However, he noted that it is advisable to use the proposed method at a steady state of engine operation. He does not specify measures to reduce emissions if they exceed the values of the maximum permissible norms.

Research on the features of the cold start of the main engine of the vessel is the subject of work by Adamkiewicz et al. [23]. Typical damage to the structural elements of a diesel engine is presented. Recommendations are made to reduce the harmful effects of transient processes on these elements. However, there are no data on the changes in the level of emissions of harmful substances during the cold start of the engine.

The analysis of current methods for neutralising harmful emissions showed that, in order to achieve the required efficiency, it is necessary to install a large amount of additional equipment and measuring instruments in the limited volume of the engine room and directly on the engines. These methods do not provide complete emission control of the exhaust gases and are costly to install and operate on a ship in service. Selection of these methods depends on the ship type and operation mode [24], which can considerably limit their application. In addition, the literature data on the efficiency of such systems in the transient modes of operation of the marine power plant – entry and exit from the port, loading and unloading operations – are very limited. This necessitates the development of additional ways to comply with the environmental standards of ship power plants.

In [25], in order to reduce the exhaust gas temperature and concentration of harmful emissions, the use of gas-air coolers of power plant exhaust gases is proposed (Fig. 6). It is explained that the use of such coolers will not require a significant modernisation of the gas exhaust system of power plant engines and the vessel's funnel.

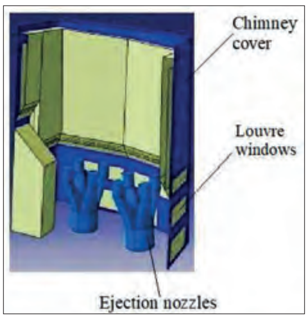

Fig. 6. Injection gas-air cooler

A positive effect of their operation will be a reduction in the volumetric concentration of the emission level by diluting the exhaust gases with ejected cold air, which will also reduce the exhaust gas temperature. This can be an effective additional means of improving the environmental parameters of vessels, especially when operating in "special" areas of the world's oceans.

At the same time, the proposed gas-air coolers are designed with the same 45° angle as the air supply louvre windows. When operating in "special" areas, it is typical to change the engine load of both the main and auxiliary marine power plant. This will change the flow rate and consequently the velocity of the flue gases as an ejection flow of gases, which in turn will change the efficiency of the unit, which can be corrected by changing the angle of opening of the louvre windows. So, it is advisable to consider the dependences of the pollutant concentration at the outlet and the exhaust gas temperature on the angle of the louvre windows and the temperature of outside ejected air under different operating modes of the diesel engine.

INVESTIGATION METHOD

The modern method for studying the processes of heat transfer and mixing in the elements of power plants is CFD – the computer fluid dynamics method. The mathematical model that describes these processes includes the continuity, momentum and energy conservation equations. These are presented in the following form [26]:

Continuity equation

$$\frac{\partial \rho}{\partial t} + \nabla\,(\rho \vec{V}\,) = 0, \quad (1)$$

where ρ is the mass flow density, and $\vec{V}$ is the vector of the local fluid velocity;

Momentum equation

$$\frac{\partial(\rho\vec{V})}{\partial t} + \nabla(\rho\vec{V}\vec{V}) = \nabla p + \nabla\tau + \rho\vec{g} + \vec{F}, \quad (2)$$

where p is the static pressure, $\rho\vec{g}$ is the gravitational force per unit mass, $\vec{F}$ are the external forces acting on the flow, and τ is the pressure tensor;

Equation of energy conservation

$$\frac{\partial(\rho E)}{\partial t} + \nabla\big(\vec{V}(\rho E + p)\big) = \nabla\big(-\vec{J}_q + (\tau_{eff}\vec{V})\big), \quad (3)$$

where $\vec{J}_q$ is the heat flow density, $E = h - \frac{p}{\rho} + \frac{V^2}{2}$ is the total energy of the working fluid, h is the working fluid enthalpy, and the expression $\tau_{eff}\vec{V}$ represents viscous heating.

The closure of the system of equations is performed by adding semi-empirical equations for the pressure tensor, the heat flux, the equation of state for ideal gases, and the differential equations of the turbulence model.

Newton's law equation: by neglecting the bulk viscosity, the stress tensor can be represented as

$$\tau = \mu\left[\nabla\vec{V} + (\nabla\vec{V})^T - \frac{2}{3}\nabla(\vec{V}I)\right], \quad (4)$$

where μ is the coefficient of molecular viscosity, and I is the unit vector.

Fourier's law equation: The heat flow is determined by the expression

$$\vec{J}_q = -\lambda_{eff}\nabla T, \quad (5)$$

where $\lambda_{eff} = \lambda + \lambda_t$ is the coefficient of effective conductivity.

Mendeleev–Clapeyron's law equation is presented in the form

$$p = R \cdot \rho \cdot T, \quad (6)$$

where R is the individual gas constant for the working fluid.

To calculate the processes of mixing flows the species transport equation was used. It is presented in the form

$$\frac{\partial}{\partial t}(\rho Y_i) + \nabla \cdot (\rho\vec{v}\,Y_i) = -\,\nabla \cdot \vec{J}_i + R_i + S_i, \quad (7)$$

where R_i is the net rate of production of species I and S_i is the rate of creation by addition from the dispersed phase plus any user-defined sources. An equation of this form will be solved for N-1 species, where N is the total number of fluid phase chemical species present in the system. The mass fraction of the species must sum to unity. To minimise numerical error, the N^{th} species should be selected as that species with the overall largest mass fraction, such as N_2 when the oxidiser is air.

On the basis of the recommendations given in [27, 28], the *RSM* turbulence model was used to close the system of equations (1)–(7). To solve the resulting system, the *RANS* approach was implemented using the *Code-Saturne* software package with a free license [29] and the *SimScale* cloud service [30].

The mathematical model with the adopted turbulence model was verified by comparing the results of numerical modelling with experimental data from a full-scale bench test of a model of a ship's gas-air cooler. The discrepancy between the results did not exceed 5% [31].

DETERMINATION OF THE EFFICIENCY OF THE GAS-AIR COOLER

Modelling of gas-air cooler operation was carried out for the following conditions: exhaust gas temperature at the cooler inlet t_{gas} = 375°C, G_{gas} = 1.25 kg/s, which corresponds to the characteristics of the engine 7L16/24 of MAN B&W company, used as a drive engine of marine diesel generators [32], ambient air temperature 17°C, with diesel oil as fuel. The fuel currently used in marine power plants, both liquid and gaseous, has a rather diverse chemical composition. Therefore, in order to summarise the results obtained, the change in the total

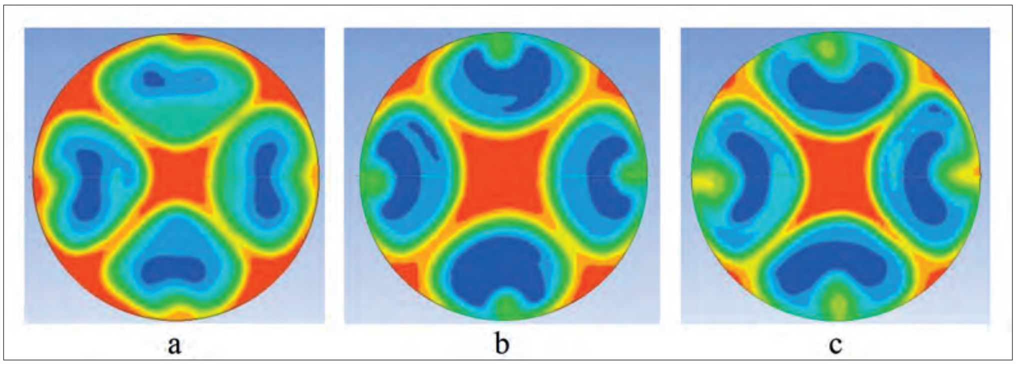

Fig. 7. Variation of output concentration at 45° louvre opening angle as a function of engine load: a - 100%; b - 75%; c - 50%

concentration of the CO_2+NO_x components of diesel fuel combustion products at the outlet of the gas-air cooler was researched.

Changes in the combustion product yield for the 45° louvre opening angle at 100%, 75% and 50% engine load are shown in Fig. 7.

The processing of similar results in the form of dependences *n_out* = *f*(*v_rel*), where *n_out* is the diesel fuel vapour output concentration, *v_rel* is the relative engine load, %, for different louvre opening angles is shown in Fig. 8a–11. Fig. 8b shows the results of calculations of the output concentrations and the exhaust gas temperature as a function of the external air temperature. Their values are defined as the average integral in the outlet section.

Analysis of the results shows the following.

Changes in the outdoor temperature have an insignificant effect on the investigated performance of the device. The changes in output concentration and temperature do not exceed 3% (Fig. 8b). Much stronger influence is exerted by the change of engine load and the louvre windows opening angle (Fig. 8a–11).

Thus, for the louvre opening angle of 45° (Fig. 8a), the temperature drop with a change in motor load from 100% to 75% and 50% is 12.5% and 19.5%, respectively. At the same time, the corresponding reductions in concentration are 13.8% and 22.7%.

At an opening angle of 60° (Fig. 9), there is a slightly smaller temperature drop of 11.2% and 14.3%, but a larger concentration drop of 14.4% and 19.7%, respectively.

At an opening angle of 30° (Fig. 10), the reduction in temperature and concentration when the load is reduced from 100% to 75% is 10.1% and 12.6%, respectively. At the same time, the largest reductions in temperature and concentration of up to 50% are observed at 22.8% and 27.7%, respectively.

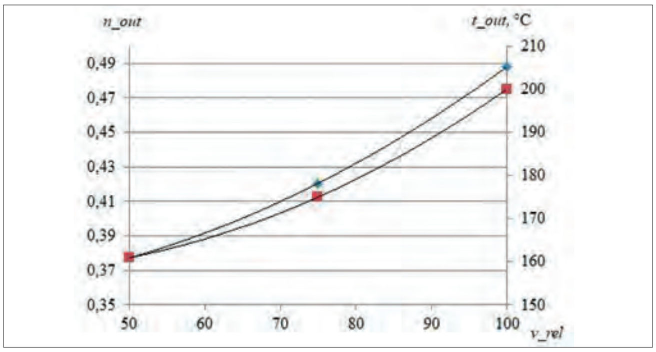

Fig. 8a. Effectiveness of the gas-air cooler operation at 45° louvre opening angle as a function of engine load: ▪ – temperature change; ♦ - concentration change

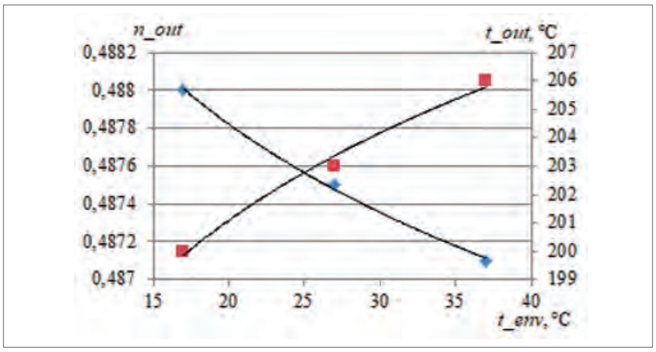

Fig. 8b. Effectiveness of the gas-air cooler operation at 45° louvre opening angle as a function of environmental temperature: ▪ – temperature change; ♦ - concentration change

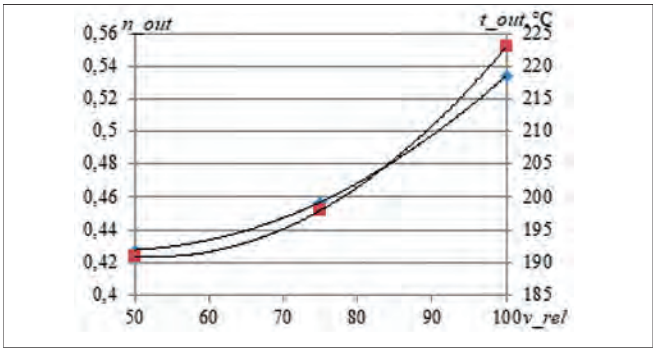

Fig. 9 Effectiveness of the gas-air cooler operation at 60° louvre opening angle as a function of engine load: ▪ – temperature change; ♦ - concentration change

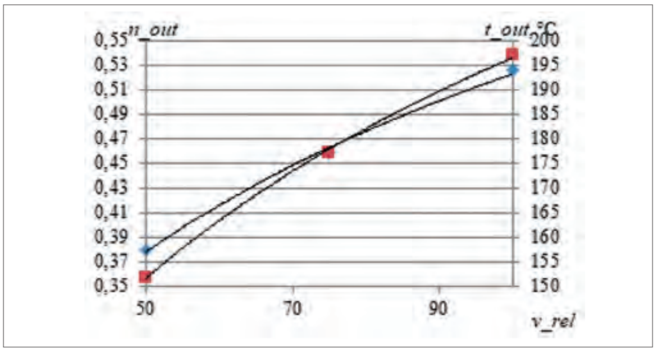

Fig. 10. Effectiveness of the gas-air cooler operation at 30° louvre opening angle as a function of engine load: ▪ – temperature change; ♦ - concentration change

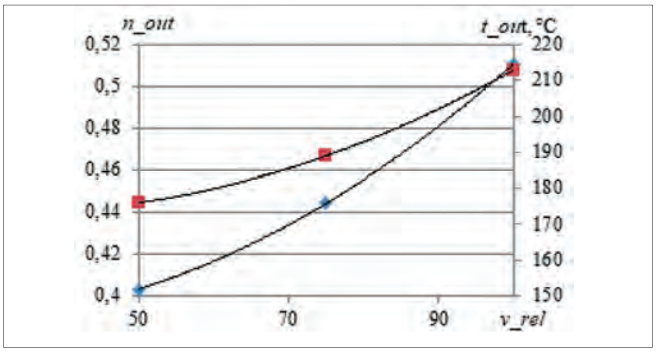

Fig. 11. Effectiveness of the gas-air cooler operation at 45° and 60° louver opening angles as the function of engine load: ▪ – temperature change; ◆ - concentration change

The expected effect of the combined louvre opening of 45° and 60° was not significant (Fig. 11). The reductions in temperature and concentration from 100% to 75% and 50% are 11.3% and 17.3%, 13.1% and 21.06%, respectively.

DISCUSSION OF THE RESULTS

The modernisation of shipboard propulsion systems in operation to comply with IMO Tier III is a current scientific and technical issue. The results show that gas-air coolers for diesel engine exhaust gases can be an effective additional means of reducing concentration and temperature.

Running at 100% engine load, the concentration reduction efficiency is around 50%. With a standard louvred window opening of 45° and a reduction in engine load from 100% to 75%, it is reasonable to increase the opening angle to 60°, and with a further reduction to 50% to reduce the angle to 30°.

The proposed technical solution of the gas-air exhaust gas cooler does not neutralise the harmful emissions of power plant engines, but only increases the volume concentration of exhaust gases. However, at the same time, this will help *to increase the efficiency of dispersion* of harmful emissions, by reducing the concentration of harmful emissions to values not exceeding the maximum permissible concentrations. This will enable the use of gas-air coolers as an effective additional means of ensuring the environmental friendliness of power plants, especially in transient modes of operation. More detailed results can be obtained by analysing the operation of a particular ship power plant, taking into account the load schedule and the location of the vessel.

Further research can be aimed at studying the efficiency of the device depending on specific ship operating conditions in various areas of the world's oceans, as well as determining the total efficiency of the gas-air cooler when low-speed and medium-speed diesel engines work together.

FINAL CONCLUSIONS

The effectiveness of the ejection gas-air cooler for the diesel engine exhaust gases of the marine power plant as an additional means of improving its environmental performance is shown.

It is demonstrated that, in order to ensure effective operation of the device at varying engine loads, the louvre windows opening angle should be 30–60°.

The explanation of the mathematical model and the open-source software implementing it make it possible to correctly estimate the decrease in the level of harmful emissions depending on the loading of the engines, selecting separate components of fuel for specification.

It is expedient to further investigate the effectiveness of the device in the case of joint operation of low-speed and medium-speed engines and considering the availability of their load schedule.

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