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REDUCING THE HARMFUL EMISSIONS AND POROUS POLLUTIONS WHILE COMBUSTION OF WATER-FUEL EMULSIONS

Abstract: *Based on the experimental and theoretical studies, a scheme of system for complex gas cleaning method of an internal combustion engine was developed. This system reduces the content of NOx in gases by 55%, SO_2 by 50%, and the content of solid particles by 3 times. The use of a complex system ensures that gases are purified from toxic ingredients and heat emissions to the level recommended by IMO.*

Keywords: *water-fuel emulsion, internal combustion engine, harmful emissions.*

Introduction

Receiving additional energy due to deep utilization of heat losses of an Internal Combustion Engine (ICE) saves fuel consumed for the operation of a ship's power plant. This, accordingly, leads to a decrease in emissions of harmful substances into the atmosphere, contributes to the satisfaction of the more stringent standards of the International Maritime Organization (IMO), which regulate the limits of these emissions.

According to the MAN specialists, the IMO requirements (III level from SO_2, NOx emissions) can be fulfilled using the following technologies: Water-Fuel Emulsion combustion (WFE) – WIF (Water in Fuel Emulsion); Scavenge Air Monistening (SAM); Exhaust Gas Recirculation (EGR); Selective Catalytic Reduction (SCR).

The use of a combined SAM & WIF scheme to reduce NOx emissions is promising: water vapor in the combustion chamber increases the heat output and reduces the O_2 content. According to MAN, an increase in thermal power and a reduction of O_2 in the charge air provides a decrease of the combustion temperature, which leads to a decrease in NOx emissions. In addition, it should be noted that with a decrease of the combustion temperature, the soot concentration increases, as well as the amount of CO.

The use of WIF technology leads to an increase of fuel consumption up to 1.2% (if the condensing surfaces of isn't used when gases cooling below the dew point temperature of H_2SO_4 and H_2O vapors), SAM technology – 2.3%, EGR technology – 4.6%, SCR technology – 7.5-15% (taking into account the price of urea). But WIF technology provides a reduction of NOx to 30%, SAM technology – 45%, the existing EGR system – 70%; SCR technology – by 80% (at the required level of IMO requirements (III level) – 80% reduction of NOx). In addition, the SCR system must be accompanied by scrubber technology for the removal of SO_2.

Literature Review

In [1] as consequence of deteriorated fuel quality, soot deposits on the EGB tubes, had increased and, in some cases, had resulted in soot fires. In extreme cases, the soot fire had developed into a high temperature iron fire in which the boiler itself burned. According to data of [2, 3], when water-fuel emulsion (WFE) is combustion, the deposits become loose, or fully absent due to decrease of soot and coke generation. During combustion of WFE drops micro-explosions are observed, which intensify burning process, which is also observed in combustion chambers of combustion engines [4]. However, in these literary sources there is no quantitative data of pollution intensity. In [5] the results of experimental studies on effect of standard diesel fuel (DF) combustion and environmental diesel fuel (EDF), with water content of 12%,…, 31% by mass on indicators of toxicity and smoke of exhaust gases are presented. According to [5], indisputable advantage of using EDF in diesel engine is its effect on exhaust gases smoking, which in maximum load is decreased in 1.3 times,..., 2.7 times. According to the data [5, 6] using of WFE does not require constructive alterations of diesel engine and can significantly improve environmental characteristics of engine.

Majority of the studies reported that soot and particulate matter (PM) were reduced with increase in water concentration [7, 8]. Numerical and experimental study showed reduction in the soot emission of 68% and 75% that when 10% and 15% respectively of water content by volume in the WFE were used [9, 10]. From the various experimental results reported, the majority of the studies confirmed that soot and PM are reduced by using the WFE emulsion fuel [11, 12]. WFE is used as alternative fuel and decreases the emissions of NOx and PM in diesel engines [13]. Based on the obtained results [14], it can be stated that an operation of the engine with diesel fuel and WFE reduces emissions of PM in 2.5 times,..., 3.5 times, that can be explained by the presence of water vapour in combustion chamber as a catalyst that helps burning carbon particles and other components difficult to oxidize. In [15] the influence of parameters of combustion process in existing low capacity boiler plants on the level of formation of nitrogen oxides, carbon monoxide and soot was studied.

Modern methods can be used for statistical treatment of experimental data [16, 17]. For estimating the efficiency of such greening and fuel saving technologies during the operation in actual climatic conditions various methods of modelling [18, 19] are applied.

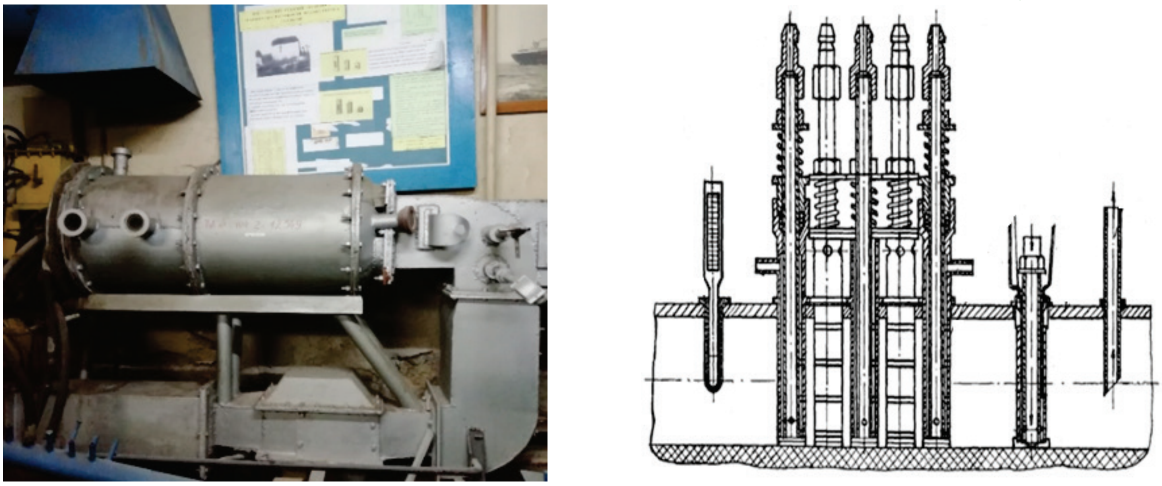
The aim of the research is to develop a system for the integrated purification of ICE exhaust gases. Research tasks: to carry out experimental research of pollution processes of EGB, that influence a heat transfer intensity, and EGB working reliability; to obtain dependences of pollution rate from wall temperature and values of wall temperature range with minimum pollution; to obtain emission rates of toxic ingredients before and after using system for the integrated purification of exhaust gases.

Methodology

Experimental researches of pollution intensity at wall temperature values below dew point temperature of sulfuric acid vapors were carried out in an experimental setup (Fig. 1a) with combustion of fuel oil and WFE based on them.

The experimental installation includes the following elements: combustion chamber, burner, fuel preparation system, gas duct. The form of combustion chamber provides a good filling of torch. The dimensions of the chamber: length – 800 mm, internal diameter – 300 mm. A rotary nozzle is used as a burner [20, 21]. Much attention during development and commissioning of experimental setup was paid to fuel system, which is designed to burn from 1 kg/h to 3 kg/h of fuel. Preparation of WFE for combustion in furnace of experimental setup was carried out in a separate installation. Air is supplied to the burner by a fan through the air heater. The temperature of hot air was 150°C,..., 180°C. The flue gases were removed from the installation by exhaust fan.

There were working areas (Fig. 1b) with sample tubes with an outer diameter of 25 mm provided in installation gas duct to study pollution process. Cooling of samples to study LTHS pollution was carried out with air from a receiver or from four thermostats with water and oil.



(a) (b)

FIGURE 1. *General view of experimental setup (a) and tube-samples of low-temperature condensation economizer (b)*

The assemblies of three tube samples were installed in gas *duct* of experimental setup, where gas velocity was 7 m/s,..., 8 m/s and its temperature about 200°C.

Experiments were carried out measurements of the geometric characteristics of each tube-sample, which made it possible to determine the outer area of the sample *F* to the test. After that we weighed each sample (before the experiment) – mass m_1. At the end of experiment, packs of tube samples were pulled out from gas pipeline. Samples with corrosion products, acid and soot deposits were weighed against by analytical weights (mass of m_2).

The pollution speed of metal surface *K* at a certain temperature of the tube wall was determined by formula:

$$K_p = \frac{m_1 - m_2}{F \cdot \tau} \tag{1}$$

where:

K_p – pollution speed of metal surface, g/(m²·h);

m_1 – mass of sample before experiment, g;

m_2 – mass of sample after cleaning of soot deposits and corrosion products, g;

F – average surface of the outer surface of the sample to the experiment, m³;

τ – duration of experiment, h.

Results

Based on the experimental data, the equation of the pollution rate K_p depending on the wall temperature t_w during the fuel oils (W^r = 2%) combustion (1 mode) was obtained by the approximation method. In this case, the polynomial equation was selected:

$$K = 3082.92 - 117.228 \cdot t_w + 1.6613 \cdot t_w^2 - 1.0344 \cdot 10^{-2} \cdot t_w^3 + 2.3881 \cdot 10^{-5} \cdot t_w^4 \tag{2}$$

This equation (regression coefficient R = 98.3859; R^2 = 96.7718 is obtained for the following characteristics of the pollution intensity: t_w = 85°C,..., 130°C, W^r = 2%. Figure 2 shows the calculated (predicted) values for K_p using the fitted model. In addition to the best predictions, the figure shows:

95% prediction intervals for new observations and 95% confidence intervals for the mean of many observations. The prediction and confidence intervals correspond to the inner and outer bounds on the graph of the fitted model.

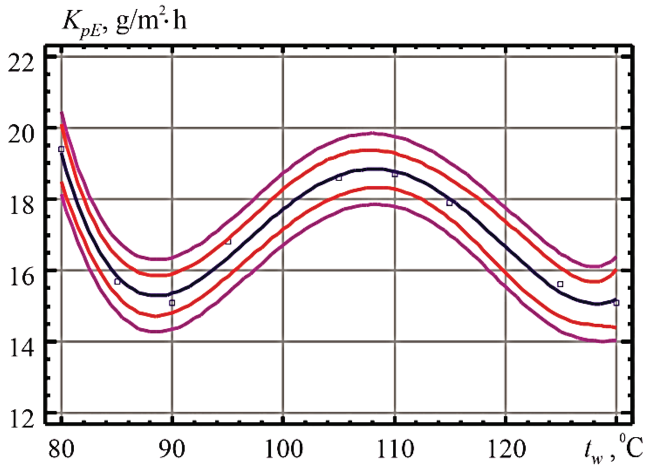


FIGURE 2. *Experimental dependences of pollution rate K_{pE} from wall temperature t_w with confidence and prediction curves during the fuel oils combustion*

Comparison of the calculated values of the pollution rate K_{pC} (equation (2)) from those obtained during the experimental study K_{pE} is δ_K = ±5% (Fig. 3).

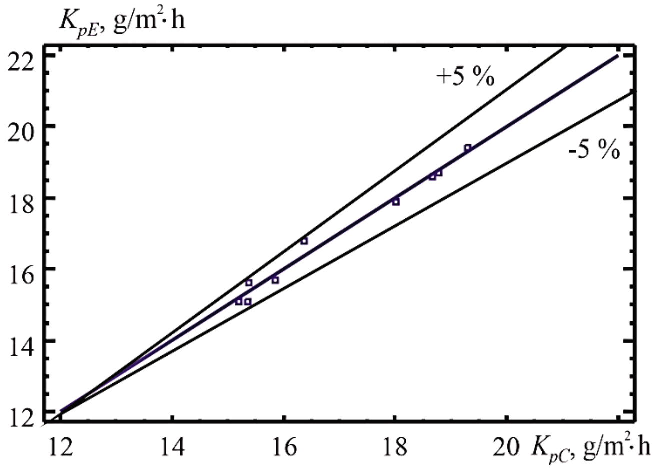


FIGURE 3. *Comparison of calculated pollution rate K_{pC} values with experimental K_{pE} during the fuel oils combustion*

The polynomial equation of the pollution rate K_p depending on the wall temperature t_w during the WFE (W^r = 30%) combustion (2 mode) based on the experimental data, was selected:

$$K = 624.931 - 23.3676 \cdot t_w + 0.3306 \cdot t_w^2 - 2.0583 \cdot 10^{-2} \cdot t_w^3 + 4.7526 \cdot 10^{-6} \cdot t_w^4 \quad (3)$$

This equation (regression coefficient R = 99.6865; R^2 = 99.373) is obtained for the following characteristics of the pollution intensity: t_w = 80°C,..., 130°C, W^r = 30%. Figure 4 shows the calculated (predicted) values for K_p with prediction and confidence intervals.

Comparison of the calculated values of the pollution rate K_{pC} (equation (2)) from those obtained during the experimental study K_{pE} is δ_K = ±5% (Fig. 5).

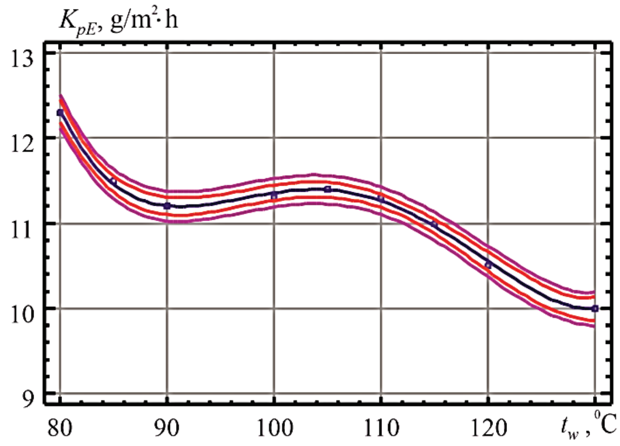


FIGURE 4. *Experimental dependences of pollution rate K_{pE} from wall temperature t_w with confidence and prediction curves during the WFE combustion*

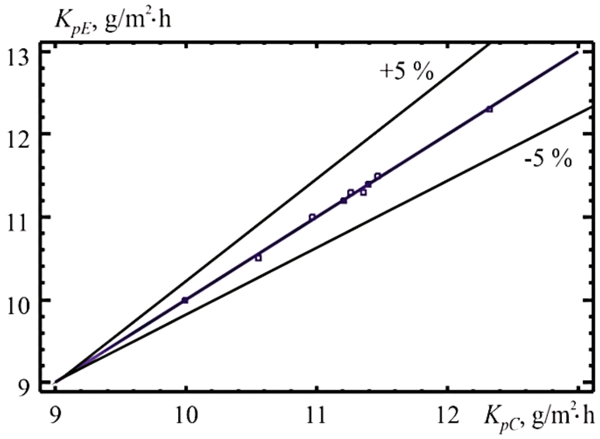


FIGURE 5. *Comparison of calculated pollution rate K_{pC} values with experimental K_{pE} during the WFE combustion*

System for complex gas cleaning method

Based on the experimental and theoretical studies (Fig. 1), a scheme of system for complex gas cleaning method of an ICE was developed (Fig. 6).

Possibility of solving complex problems in proposed technology is ensured by combustion of WFE with specifically recommended value of water content (W^r = 30%). Such WFE composition substantially affects not only running of thermal and physicochemical processes along the entire path of fuel combustion aggregates (starting from combustion zone and to cut of flue), but also directs them in the required direction. For performing tasks in technology of proposed method, providing solutions to problems of improving economic efficiency, improvement of environmental indicators and reliability, it is envisaged 4 stages of technological process:

1. WFE preparation with a water content of about 30%.
2. WFE combustion with a water content of about W^r = 30% leads to formation of equimolar ratio NO_2: NO in exhaust gases at outlet of combustion zone (as confirmed by patent and providing low-temperature corrosion (LTC) reduction), as well as reducing NOx, SO_2, PM emissions.
3. Installation of condensing surfaces, on which conditions are created for passivation of metal and a sharp decrease LTC intensity, as well as conditions from side of gases and in condensate to intensify NOx, SO_2, PM absorption.
4. Continuation of absorption intensification on condensing surfaces of gas flues (providing conditions for reliable operation of their metal) or maintaining temperature of metal of these gas flues above the dew point temperature of sulfuric acid vapour H_2SO_4 without NOx, SO_2 absorption, but ensuring reliability of work (at low LTC level).

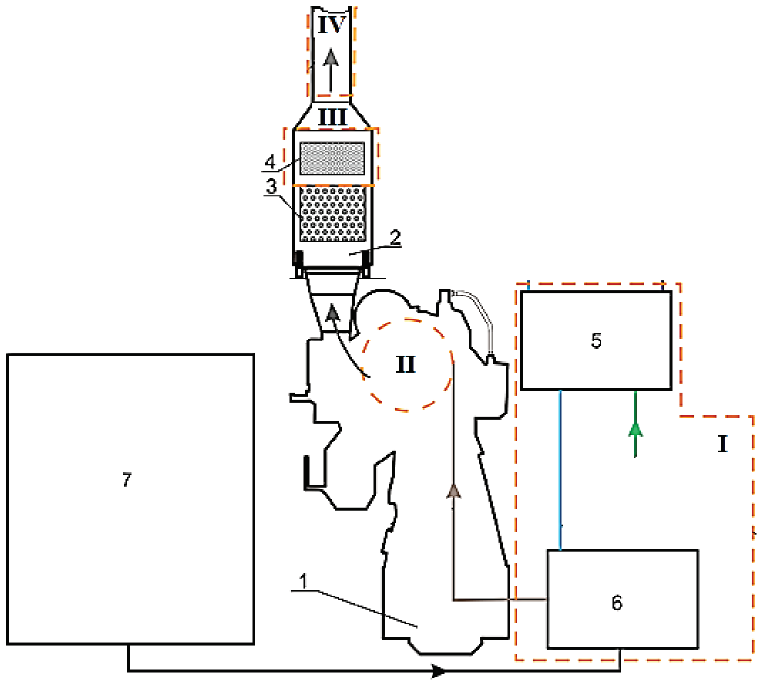


FIGURE 6. The scheme of system for complex gas cleaning method and stages of cleaning, where: I – WFE preparation with a water content of about 30%; II – reducing concentration of toxic substances and solids in gases when WFE is burnt with water content 30%; III – adsorption processes occurring on condensing surfaces of exhaust gas boilers; IV – processes occurring on condensing surfaces of gas flues; 1 – ICE: 2 – EGB; 3 – dry convective surface; 4 – condensing heating surface; 5 – water preparation unit; 6 – Water-Fuel Emulsion preparation unit; 7 – fuel tank

The main elements of the power plant, which provides for the combustion of specially prepared WFE with a water content of 30%, are the ICE and the EGB. A dry convective surface and a condensing surface must be installed. In the EGB to perform tasks. It is also mandatory to install a water treatment unit and WFE (the first stage of gas purification). Specially prepared WFE is supplied to the ICE injectors.

As a result of the combustion of activated WFE at the engine outlet we obtain exhaust gases of the corresponding composition with a reduced amount of toxic ingredients up to 35% or more, and most importantly, the equimolar ratio of NO_2 : NO in NOx (which is confirmed by our experimental and literature data). This is the second stage of exhaust gas cleaning, which allows to reduce, for example, the concentration of NOx by 30-50%.

Further, the exhaust gases enter to the EGB, in which a dry convective surface is installed at the inlet (superheater, vapor-generating surface), and a condensing convective surface in the form of an economizer and (or) a hot water supply section with a metal temperature of 70-130°C at the outlet, which leads to condensation of sulfuric acid vapors in the exhaust gases of ICE.

In the acid condensate under the indicated conditions, an average concentration of about 57% is established. The result is a sharp increase of SO_2 and NOx absorption. The presence in them of an equimolar ratio of NO_2 : NO provides passivation of the condensing surface made of carbon steel. This provides a sharp decrease of the LTC intensity, an increase of the operation reliability of these condensing surfaces and the possibility of a sharp increase of the depth of exhaust gases utilization to ~ 80-90°C instead of 160°C (when standard fuels combustion). Thus, the third stage of gas cleaning is carried out.

Further, the gases after the EGB enter to the gas duct. With such a low gas temperature and ensuring the temperature of the gas duct metal after the ICE at a level of 70-80°C, that is, in the presence of sulfuric acid condensate on the inner surface of the gas ducts, the process of absorption of toxic substances will continue with reliable operation of the gas duct metal, and the intensity of the mass flow will additionally decrease H_2SO_4 and LTC (this is the fourth stage of gas purification).

This is due to the fact that in gases there is an equimolar ratio of NO_2 : NO, which means that the passivation of the metal surface and a decrease of the LTC will be ensured with a minimum temperature difference between the gases and the metal of the gas ducts.

Thus, the implementation of these stages of gas purification provides a decrease of the content of toxic ingredients in gases by almost 50% (compared to existing technologies, which provide a decrease of the exhaust gas temperature of the EGB to 160°C) and partial removal of solid particles, contained in gases (when WFE combustion, solid and soot particles are 80% less than standard fuels combustion) (Fig. 7).

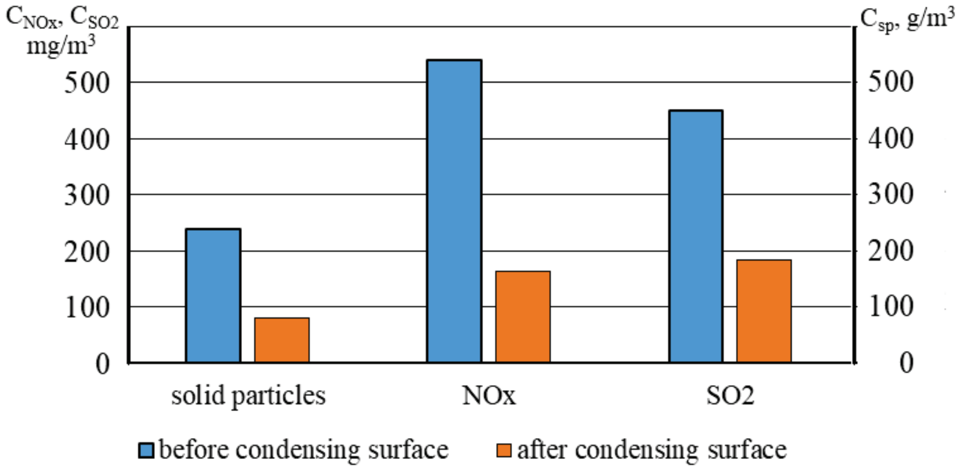


FIGURE 7. *Emission rates of toxic ingredients*

Conclusions

The best burning out of fuel combustible components due to applying a WFE provides decreasing a concentration of solids and soot in the exhaust gases and hence their toxicity.

The kinetics of low-temperature pollution on EGB condensation surfaces with WFE combustion are investigated to obtain approximation equations for predicting processes development.

When WFE combustion with a water content of 30%, the LTC intensity decreases, which makes it possible to install condensing heating surfaces in the EGB. The installation of a condensing heating surface in the EGB reduces the content of NOx in gases by 55%, SO_2 by 50%, and the content of solid particles by 3 times.

The use of a complex system ensures that gases are purified from toxic ingredients and heat emissions to the level recommended by IMO.

Conflicts of Interest: The author declares no conflict of interest.

References

[1] Soot deposits and fires in exhaust gas boilers, MAN Diesel & Turbo, September 2014.

[2] Wojs M.K., Orliński P., Kamela W., Kruczyński P., *Research on the influence of ozone dissolved in the fuel-water emulsion on the parameters of the CI engine* [in:] *IOP Conference Series: Materials Science and Engineering*, 2016, Vol. 148, pp. 1-8.

[3] Baskar P., Senthil Kumar A., *Experimental investigation on performance characteristics of a diesel engine using diesel-water emulsion with oxygen enriched air*, Alexandria Engineering Journal, Vol. 56, Issue 1, 2017, pp. 137-146.

[4] Miao Y.C., Yu C.L., Wang B.H., Chen K., *The applied research of emulsified heavy fuel oil used for the marine diesel engine*, Advanced Materials Research, 2013, Vol. 779, pp. 469-476.

[5] Parsadanov I.V., Solodovnikov V.V., *Application of water fuel emulsion in autotractor diesel. Ecological efficiency (part 1)*, Internal Combustion Engines, 2011, Vol. 2, pp. 118-120.

[6] Zang T., Okada H., Tsukamoto T., Ohe K., *Experimental study on water particles in the combustion of marine four-stoke diesel engine operated with emulsified fuels*, Paper 193, CIMAK, Vienna 2007.

[7] Vellaiyan S., Amirthagadeswaran K.S., *The role of water-in-diesel emulsion and its additives on diesel engine performance and emission levels: A retrospective review*, Alexandria Engineering Journal, 2016, Vol. 55, pp. 2463-2472.

[8] Kornienko V., Radchenko M., Radchenko R., Konovalov D., Andreev, A., Pyrysunko M., *Improving the efficiency of heat recovery circuits of cogeneration plants with combustion of water-fuel emulsions*, Thermal Science, Vol. 25, Issue 1, Part B, 2021, pp. 791-800.

[9] Gupta R.K., Sankeerth K.A., Sharma T.K., Rao G., Murthy K.M., *Effects of water-diesel emulsion on the emission characteristics of single cylinder direct injection diesel engine – A review*, Applied Mechanics and Materials, 2014, Vol. 592, pp. 1526-1533.

[10] Radchenko R., Pyrysunko M., Kornienko V., Scurtu I.-C., Patyk R., *Improving the ecological and energy efficiency of internal combustion engines by ejector chiller using recirculation gas heat* [in:] Nechyporuk M. et al. (eds.), *Integrated Computer Technologies in Mechanical Engineering. Advances in Intelligent Systems and Computing*, 2021, Vol. 188, Springer, Cham, pp. 531-541.

[11] Patel K.R., Dhiman V., *Research study of water – diesel emulsion as alternative fuel in diesel engine – An overview*, International Journal of Latest Engineering Research and Applications 2017, Vol. 2, Issue 9, pp. 37-41.

[12] Radchenko R., Pyrysunko M., Radchenko A., Andreev A., Kornienko V., *Ship engine intake air cooling by ejector chiller using recirculation gas heat* [in:] Tonkonogyi V. et al. (eds.), *Advanced Manufacturing Processes*, InterPartner-2020, Lecture Notes in Mechanical Engineering, Springer, Cham 2021, pp. 734-743.

[13] Patel N., Modi M., Patel T., *Investigation of diesel engine with water emulsifier – A review*, International Research Journal of Engineering and Technology, 2017, Vol. 4, Issue 2, pp. 879-883.

[14] Kruczyński P., Orliński P., Kamela W., Ślęzak M., *Analysis of selected toxic components in the exhaust gases of a CI engine supplied with water-fuel emulsion*, Polish Journal of Environmental Studies, 2018, Vol. 27, Issue 1, pp. 129-136.

[15] Katin V., Kosygin V., Akhtiamov M., Vol'khin I., *Mathematical models of the output of major pollutants in the process of burning water fuel oil emulsions in boiler plants* [in:] *19th International scientific conference Energy Management of Municipal Transportation Facilities and Transport*, EMMFT, Vol. 692, 2018, pp. 987-997.

[16] Radchenko A., Mikielewicz D., Forduy S., Radchenko M., Zubarev A., *Monitoring the fuel efficiency of gas engine in integrated energy system* [in:] Nechyporuk M. et al. (eds.), *Integrated Computer Technologies in Mechanical Engineering*, Advances in Intelligent Systems and Computing, Springer, Cham 2020, Vol. 1113, pp. 361-370.

[17] Trushliakov E., Radchenko A., Forduy S., Zubarev A., Hrych A., *Increasing the operation efficiency of air conditioning system for integrated power plant on the base of its monitoring* [in:] Nechyporuk M. et al. (eds.), *Integrated Computer Technologies in Mechanical Engineering (ICTM 2019)*, Advances in Intelligent Systems and Computing, Springer, Cham 2020, Vol. 1113, pp. 351-360.

[18] Radchenko M., Radchenko R., Tkachenko V., Kantor S., Smolyanoy E., *Increasing the operation efficiency of railway air conditioning system on the base of its simulation along the route line* [in:] Nechyporuk M. et al. (eds.), *Integrated Computer Technologies in Mechanical Engineering (ICTM 2019)*, Advances in Intelligent Systems and Computing, Springer, Cham 2020, Vol. 1113, pp. 461-467.

[19] Radchenko A., Trushliakov E., Kosowski K., Mikielewicz D., Radchenko M., *Innovative turbine intake air cooling systems and their rational designing*, Energies, 2020, Vol. 13, Issue 23, No. 6201, doi:10.3390/en13236201.

[20] Kornienko V., Radchenko R., Konovalov D., Andreev A., Pyrysunko M., *Characteristics of the rotary cup atomizer used as afterburning installation in exhaust gas boiler flue* [in:] Ivanov V. et al. (eds.), *Advances in Design, Simulation and Manufacturing III (DSMIE 2020)*, Lecture Notes in Mechanical Engineering, Springer, Cham 2020, pp. 302-311.

[21] Kornienko V., Radchenko R., Mikielewicz D., Pyrysunko M., Andreev A., *Improvement of characteristics of water-fuel rotary cup atomizer in a boiler* [in:] Tonkonogyi V. et al. (eds.), *Advanced Manufacturing Processes*, InterPartner-2020, Lecture Notes in Mechanical Engineering, Springer, Cham 2021, pp. 664-674.