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SUBSTANTIATION OF REGULATION OF THE EMISSION LIMITS OF SULFUR AND NITROGEN OXIDES IN EXHAUST GASES ON SHIP POWER ENGINES

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INTRODUCTION

Presently and on a prospect according with the limited nature resources of hydrocarbon raw material of unrenewable character there is an acute problem of reducing fuel consumption in the technogenic systems. In a marine transport industry 1 billion of fuel is consumed in a year, when combustion of which produces 3.5 billion tons of carbon dioxide – the main initiator of the global «climate crisis» on the planet, i.e. the «greenhouse» effect.

A rate on substituting of traditional hydrocarbon raw material of unrenewable character by «green» energy did not justify itself. So, in a present work the question is raised, how it is possible to bring down the expense of ship diesel fuel, undercharge on him, to decrease the extrass of dioxide carbon during ship's operation.

1. Raising of task

In accordance with Annex of VI of «Rules for the Prevention of Air Pollution from Ships» of International Convention for Prevention Pollution from Ships on 1973, changed by Protocol on 1978[1] (Convention МАРПОЛ – 73/78, more hard requirements are foreseen to maintenance of content of sulfur compounds in a ship fuel in the whole world including zones of ECA «Emission Control Area»):

– 4,50 % the masses till January, 1, 2012;

– 3,50 % the masses from January, 1, 2012;

– 0,50 % the masses from January, 1, 2020 .

The content of sulfur compounds in the fuel used in the districts of ECA must not exceed:

[1] MARPOL Consolidated edition 2011: Articles, Protocols, Annexes and Unified Interpretations of the International Convention for the Prevention of Pollution from Ships, 1973 as modified by the 1978 and 1997 Protocols. London: CPI Group, 2011. 447 p. ISBN 978-92-801-1532-1.

– 1,00 % the masses from June, 1, 2010;

– 0,10 % the masses from January, 1, 2015.

The zone of SECA (Special Emission Control Area) includes Baltic and North Seas,English channel.

From November, 2012 these restrictive measures were accepted at the level of national legislation in the North-American 200-mile zone at the coast of the USA and Canada (zone of the special control of ECA).

From January, 1, 2014 the zone of ECA was joined by the district of the Caribbean Sea, the USA, Puerto Rico and Virgin Islands of USA.

According to new positions, dividing of ship engines is conducted by three levels. The first level complies with the provisions of the Rule 13 current Appendix of VI to Convention of МАРПОЛ – 73/78, two levels are here added. The third level is more strong, and will be used to the existent ships.

By the technical code of NOx is foresee restrictive requirements to content of nitrogen oxides in exhaust gases of ship power engines (special control zone NECA).

The basic sources of atmosphere polution from ships are[2,3]:

– ozone-destroying and toxic substances, transported by LPG-vessel;

– gas emissions of main and auxiliary engines;

– incineration of garbage and wastes in ship's plant;

– low-boiling hydrocarbons of C_1– C_{5+}, penetrating into atmosphere when loading

oil tankers and LPG-vessels

Annex VI of МАРПОЛ Convention – 73/78 entered into force on 19 May, 2005 and presently is obligatory for implementation on all vessels of gross tonnage 400 units and more, performing international voyages, and also for the stationary and floating drilling and production platforms, and extractive platforms, set after a border territorial waters of the off-shore states. For confirmation accordance of these ships and platforms to the requirements of Convention МАРПОЛ – 73/78 on questions of prevention pollution of atmosphere they must get the «International Air Pollution Prevention Certificate».

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[2] Леонов В.Е., Ходаковский В.Ф., Куликова Л.Б. Основы экологии и охрана окружающей среды: монография. / под ред. В. Е. Леонова. Херсон: Видавництво Херсонського державного морського інстітуту, 2010. 352 с.

[3] Леонов В.Е., Соляков О.В., Химич П.Г., Ходаковский В.Ф. Обеспечение экологической безопасности судоходства: монография /под ред. В. Е.Леонова. Херсон – С-Пб : Видавництво Херсонського державного морського інституту, 2014. 188 с.

In Annex VI МАРПОЛ – 73/78 put forward a number of requirements to limit emissions into the atmosphere from ships:

a) ozone-destroying substances:

on ships are prohibited using units that use ozone-destroying substances, namely: halon 1211, halon 1301, halon 2402 (halon 114B2), CFH (chloro-fluoro-hydrocarbons) – 11, CFH – 12, CFH – 113, CFH – 114, CFH – 115, if these units are installed on board after 19.05.2005 year.

Exploitation on ships the units using chloro-fluoro-hydrocarbons mounted before Appendix VI Conventions of МАРПОЛ – 73/78 going into effect allowed until 01.01.2020. After this date, there is a complete ban on the use of ozone– destroying substances on ships:

b) oxides of nitrogen and sulphur:

– the content of sulfur compounds in any liquid fuel used on board the ship should not exceed 3.5% mass, and for SOx emission control areas – SECA, ECA should not exceed 0.1% mass;

– from 01.01.2020г. all world maritime transport has been switched to low-sulfur fuel, in which the content of sulfur compounds should not exceed 0.5% by weight;

– release of sulfur compounds from the ship (main and auxiliary engines) according to the requirements of MARPOL 73/78 should not exceed 6gSO_2/(kW per hour), if this is not provided by the technical characteristics of the ship power plant, then in this case the ship should use a system for cleaning exhaust gases from sulfur compounds. At the same time, it is explained that the «emissions of sulfur compounds from the ship», which are limited by the combustion of sulfur compounds in marine fuel, sulfur dioxide SO_2 is formed;

– the nitrogen oxide (NOx) emission limits mentioned out in Annex VI MARPOL 73/78 apply to diesel engines over 130 kW installed on ships after 1 January 2000.

c) limitation of hydrocarbon vapor emissions from tankers and chemical and gas carriers:

in order to exclude emissions of hydrocarbon vapors from tankers during their loading in the port, the tanker must be equipped with a system for filtering the air displaced from the cargo tanks during their loading. If the tanker does not have such a filtration system, such a system should be available at the oil loading terminal and connected to the cargo tank ventilation system of the tanker being serviced.

The requirements of Annex VI on the prevention of air pollution do not apply:

– to any emissions necessary to ensure the safety of a ship or the safety of life at sea;

– to any emissions resulting from damage to a ship or its equipment, provided that all reasonable precautions are taken after the damage occurs or the emissions are discovered to prevent or minimize that emissions;

– to lifeboat engines or engines used on emergency equipment.

On 15th May, 2015 Committee for the Protection of Marine Environment of International Marine Organization by Resolution MEPC.259(68) renewed Guidance on 2009 year the Exhaust gas cleaning system (EGCS), that was accepted by Resolution of MEPC 184(59). The system EGCS is manned by the devices of the permanent monitoring. As a criterion during realization of monitoring the relation of (χ = SO_2 (million^{-1})/CO_2(% vol) that is accepted depending on the concentration of sulfur compounds in the ship fuel in obedience to Rules 14.1, 14.4 Annex VI Convention of MARPOL 73/78 (table 1).

Table 1

Changing in the criterion of toxicity of EG SPP (χ)
from the concentration of sulfur compounds in ship fuel (SF)

№	A concentration sulfur compounds in SF, % by weight	Retio (χ = SO_2 (million^{-1})/CO_2 (% by vol.) in the EG SPP
1	4,5	195
2	3,5	151,7
3	1,5	65
4	1,0	43,3
5	0,5	21,7
6	0,1	4,3

In exhaust gases engines of transport vehicles, ship main engine (SME) there are more than 250 harmful toxic components that on the class of danger possible to range on four groups[4]. In the general volume of exhaust gases 1% is on toxic components, and 99% – for inert gases and vapors. Negative influence of toxic components of exhaust gases of EG SME is

4 Леонов В.Е., Ходаковский В.Ф., Куликова Л.Б. Основы экологии и охрана окружающей среды: монография. / под ред. В. Е. Леонова. Херсон: Видавництво Херсонського державного морського інституту, 2010. 352 с.

known to an environment, biota and human health[5].[6] Basic influence to air pollution during the operation of ships is made by the following substances and compounds:

*components of «greenhouse» gases, ozone-destroying and toxic substances;

* exhaust gas of main and auxiliary engines;

*incineration of garbage and solid wastes in ship incinerators;

* vapors of hydrocarbons and chemical compounds released into the atmosphere during loading/unloading of oil tankers, chemical gas carriers, during transportation and bunkering of ships;

* mineral and organic dust when transported cargo.

Resolution of the Marine Environment Protection Committee MEPC.282(70) from 1 March 2018, Regulation 5.4.5 of MARPOL Annex VI. which replaced the resolution IMO MEPC.213 (63), requires Administrations to ensure that the Ship Energy Efficiency Management Plan (SEEMP) of ships of 5000GT and above complies with Regulation 22.2 of MARPOL Annex VI.

There are two parts to a SEEMP:

Part 1 provides a possible approach for monitoring ship and fleet efficiency performance over time and some options to be considered when seeking to optimize the performance of the ship.

Part 2 provides the methodologies ships of 5000GT and above should use to collect the data required pursuant to Regulation 22.2 of MARPOL Annex VI and processes that the ship should use to report the data to the ship's Administration or any organization duly authorised by it.

SEEMP involves the development of recommendations to improve the energy efficiency of maritime transportation with the unconditional fulfillment of the requirements for the protection of the crew, ship, cargo, marine and environment.

Efficiency the SEEMP depends on use by ship of the accumulated scientific and practical experience in part of economy of fuel, decline of time of cargo operations, diminishing of emission of harmful toxic components with exhaust gases of ship power plants.

[5] Леонов В.Е., Ходаковский А.В. Экология и охрана окружающей среды :учебное пособие./ под ред. В.Е. Леонова. Херсон: Видавництво Херсонської державної морської академії , 2016. 352 с.: ISBN 978-966-2245-34-9

[6] Леонов В.Е., Дмитриев В.И. Пути повышения эффективности морских грузоперевозок : монография. Москва : МОРКНИГА. 2019. 299 с. http://www.morkniga.ru/p828682. ISBN 978-5-902080-40-4.

2. Research results

In accordance with the Resolution of the International Maritime Organization No. 218 dated 01/17/2017 from 01/01/2020 ships sailing in all sea (oceanic) shipping areas are switched to low-sulfur marine fuel, except for the special control zones of SECA, ECA. The only exceptions are ships equipped with Exhaust gas cleaning system (EGCS) from sulfur compounds, as well as ships on which research work is carried out to study the process of purification of ME exhaust gases from sulfur compounds.

As a basic lack of using low-sulphur marine fuel, one should highlight its high cost – 2-5 times higher than the cost of high-sulphur fuel. At the same time, the advantage of using low-sulfur fuel in comparison with high-sulphur fuel is very doubtful, since this reduces the emission of only one substance – sulfur dioxide, and the emission of the remaining more than 249 toxic substances and compounds contained in the exhaust gases of the ship ME remains practically unchanged.

In support of this premise, it should be pointed out that for the first time in the work[7,8,9,10] we found that the prevented damage to the air basin in the case of the transfer of SPP from high-sulphur fuel to low-sulphur fuel does not cover the total costs for the difference in the cost of low-sulphur and high-sulphur fuel. This convincingly indicates that the transition of the world's maritime transport from high-sulphur to low-sulphur fuels has a negative economic result and does not solve the problem of protecting the air basin during the operation of ships.

As a result of incineration of hydrocarbon fuel exhaust gases, that contain different toxic substances and connections, basic from that oxide of carbon, hydrocarbons, soot, connections of heavy metals, oxides of sulphur and nitrogen, hydrocarboxylic acids, aldehydes, cetones, dioxide of carbon, appear in ship power plants. In the future, hydrogen, methanol, hydrogen sulfide, ammonia, bottom solid gas-crystal hydrates, C_1– C_{5+} aliphatic alcohols, carbon dioxide, and water will be used as fuel for SPP.

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[7] MEPC 65/INF.17 IMO Model Course on Energy Efficient Operation of Ships. London: World Maritime University.2013. 61 p.

[8] Пивоваров Л.А. Разработка плана управления энергетической эффективности судна (ПУЭЭС) для танкеров. Материалы V Международной научно-практической конференции MINTT – 2013, Херсон. 2013. С. 73–77.

[9] IMO поддержала запрет на высокосернистое топливо. Одесса: газета Работник моря. 2018. № 4(140). с. 14

[10] Zhrnur V. N., Leonov V.Ye. The squat-effect and environmental problems at reduction ship's speed in shallow water and harmful emissions. *Вестник Государственного Университета Морского и Речного Флота имени адмирала С. О. Макарова*. С-ПБ. 2014. Выпуск 4(26) . С. 176–184.

Computational studies were carried out according to the methodology discribed in the work[11].

The absolute damage caused to the air pool by the exhaust gases of the SPP, Y, UAH / year, is determined by the formula:

$$Y = \gamma \times \sigma \times f \times M \quad (1)$$

where – γ is a constant depending on the hazard class of hazardous substances emitted with the waste gases of the SPP,

UAH / standard tons; σ – is an indicator of the relative danger of atmospheric air pollution in different territories (in the work, $\sigma = 4$ is taken); f – is a correction that takes into account the nature of the dispersion of the mass of emitted substances in the atmosphere and is determined by the formula:

$$f = [100/(100 + \varphi \times h)] \times [4/(1 + \upsilon)], \quad (2)$$

where h – is the geometric height of the exhaust pipe from the outlet of the power plant to the mouth of the exhaust, m; υ – average annual value of the wind speed module at the level of the weather vane, is taken equal to 3 m/s; φ – is a dimensionless correction for the thermal rise of the emission plume in the atmosphere, is determined by the formula:

$$\varphi = 1 + \Delta T/75, \quad (3)$$

where ΔT is the average annual temperature difference at the exit from the mouth of the exhaust pipe and in the atmosphere,°C, is determined by the formula:

$$\Delta T = T - t, \quad (4)$$

where t – is the maximum air temperature at 13^{00} of the hottest month of the year for the selected region, °C; T – is the temperature of the exhaust gases of the SPP at the outlet of the SPP,°C. M – is the reduced mass of the annual emission of harmful components of the exhaust gases of the SPP entering the atmospheric basin, cond. t/year, is determined by the formula:

$$M = \sum Ai \times mi \quad (5)$$

where Ai is an indicator of the relative danger of the harmful component of the i-th type, conv.t /mt; N is the number of components

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[11] Лєонов В. Є., Пустова С. М. Методичні рекомендації для проведення практичних занять з дисципліни: «Екологія та охорона навколишнього середовища». Херсон : ВЦ ХДМА. 2018. 104 с.

of the exhaust gas of the SPP; mi is the mass of the emission of the harmful component of the i-th type, mt/year.

Prevented damage, P, UAH/year, resulting from the transition to less toxic fuel is determined by the formula:

$$P = Y_{DF1} – Y_{DF2}, \quad (6)$$

where Y_{DF1},Y_{DF2} – is the absolute damage, UAH/year, caused to the air basin when operating on different types of fuels (DF_1, DF_2).

Specific prevented damage, UAH/t, is determined by the formula:

$$P_{SD} = P/Q, \quad (7)$$

where Q is the mass of fuel used, mt/year.

The reduced mass of pollutant emissions, standard tons/year, during the operation of the SPP on diesel fuel is determined by the formula:

$$M_{DF1} = Q(C_{CO}^{DF1} \times A_{CO} + C_{NOx}^{DF1} \times A_{NOx} + C_{SO2}^{DF1} \times A_{SO2} + C_{CHx}^{DF1} \times A_{CHx} + C_{SOOT}^{DF1} \times A_{SOOT}). \quad (8)$$

Absolute damage, UAH/year, during the operation of the ship power plant on DF_1 is determined by the formula:

$$Y_{DF1} = \gamma \times \sigma \times f \times M_{DF1} \quad (9)$$

The reduced mass of pollutant emissions, t/year, when the SPP operates on DF_2 fuel is determined by the formula:

$$M_{DF2} = Q(C_{CO}^{DF2} \times A_{CO} + C_{NOx}^{DF2} \times A_{NOx} + C_{SO2}^{DF2} \times A_{SO2} + C_{CHx}^{DF2} \times A_{CHx} + C_{SOOT}^{DF2} \times A_{SOOT}). \quad (10)$$

Absolute damage, UAH/year, during the operation of the ship power plant on DF_2 is determined by the formula:

$$Y_{DF2} = \gamma \times \sigma \times f \times M_{DF2}. \quad (11)$$

The amount of prevented damage, UAH/year, is determined by the formula:

$$P = Y_{DF1} – Y_{DF2}. \quad (12)$$

The value of specific prevented damage, UAH/mt, is determined by the formula:

$$P_{SP}= P/Q, \quad (13)$$

Initial data for carrying out computational studies:

1. Marine fuel consumption: Q = 40000 mt/year.

2. The concentration of sulfur compounds (in terms of methylmercaptan-MC) in marine fuel changed, % wt. – 0.1; 1.0; 3.5; 4.5.

3. Air temperature: t = 35°C.

4. Exhaust gas temperature after SPP: t = 500°C

5. $\sigma = 4$.

6. γ = 48 UAH/conv.t.

7. The height of the funnel of SPP is h = 20 m.

8. The speed of air mass movement in the area of the mouth of the exhaust funnel is υ = 3 m/s.

The research results are shown in Fig. 1 and in table 2.

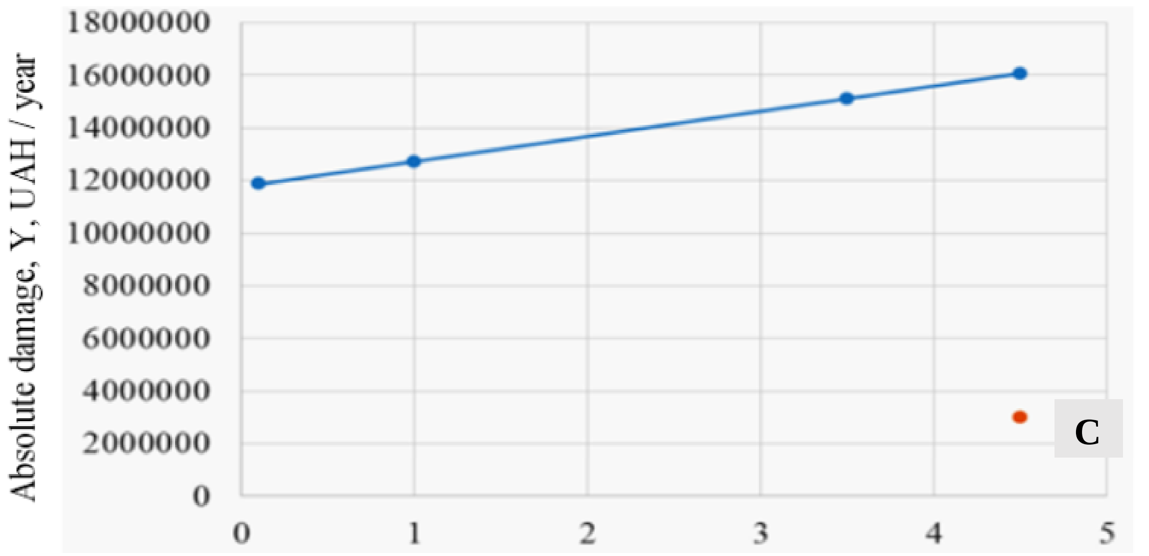

Fig. 1. Dependence of the absolute damage caused to the air basin from the exhaust gases of the power plant, on the content of sulfur compounds in marine fuel

MC, % wt.	0,1	1	3,5	4,5
Y, hrn./year	11868091,17	12729603,38	15123170	16 080 165,89
$Y_{4,5\ k}$				3000428,544

3. Evaluation of the environmental and economic feasibility of switching from high-sulphur to low-sulfur marine diesel fuel

On the website: «Ship and bunker. Com prices» provides data on the cost of marine fuel in various regions of the world.

Table 2

Calculation of absolute damage to the air basin and material costs for marine fuel

1. Data	1. 16.03.2019
2. Port	2. Port «New York»)
3. Fuel price: 3.5% wt and DF 0.1%wt	3. $DF_{3,5\%}$ = 495\$/mt; $DF_{0,1\%}$ = 970\$/ mt
4. Maximum air temperature in 13^{00} of the hottest month of the year in the occupied port	4. 35°C
5. The values of absolute damages (Yi) are determined by the formulas (9.11)	5. $Y_{3,5\%}$=48·4·0,41·192113,44 =15.123.170 UAH/year. $Y_{0,1}$=48·4·0,41·150763,36=11.868.091,17 UAH/year
6. Prevented damage when replacing high-sulphur fuel with low-sulphur fuel	6. P=15123170-11868091,17 = 3.255.078,83 hrn./year
7. The difference in the cost of marine fuel	7. P_{DF}= 970 – 495 =475\$/mt 1\$ = 26,9 UAH at the rate of the National Bank of Ukraune P_{DF}=475*26,9=127.775 UAH/mt
8. Determine the material costs for fuel consumption	8.E_C=40.000*127.775=511.100.000 UAH/year (E_C – exploatation consumption)
9. We calculate the value of the economic efficiency indicator η	9. η = E_C/P = 511.100.000 UAH/year / /3255078,83 UAH/year = 157 times

Summary. According to theoretically substantiated data, it can be stated that from the point of view of the economy of the voyage and the damage to the air pool, the transition from high-sulphur fuel to low-sulphur fuel is inexpedient. Namely: on 157 times the cost of low-sulphur fuel is higher than the prevented damage to the air pool resulting from the replacement of high-sulphur fuel (3 .5 wt % S-compounds) for low sulfur fuel (0.1 wt % S-compounds) (Annex VI of MARPOL 73/78).

Even if we imagine the complete absence of sulfur compounds in marine fuel, for which we extend the straight line (Fig. 1) to the intersection with the y-axis (the concentration of sulfur compounds in marine fuel is zero), then even in this ideal case, the absolute damage to the air basin will exceed 11,000,000 UAH in year. At the same time, when using high-sulphur fuel containing 4.5% wt. sulfur compounds, but in combination with the catalytic purification of exhaust gases of the SPP (index C in Fig. 1), other things being equal, the absolute damage to the air pool will be only 3,000,428 UAH. per year, which is of 5.4 times lower than when using the same high-sulphur marine fuel 4.5% wt. sulfur compounds, but without the use of a catalyst, and 3.7 times lower than the absolute damage obtained with absolutely desulfurized marine fuel.

Thus, based on our research work, it follows that the transition of maritime transport to low-sulfur marine fuel is not justified, both from the standpoint of the economic indicators of the sea crossing, and in terms of protecting the marine environment.

4. Research on the purification of exhaust gases from SPP from sulfur oxides

The analysis, generalization and comparison of technical solutions for the purification of exhaust gases of the SPP of the Wartsilla, Carnival Corporation (EGCS)[12],[13],[14],[15],[16],[17],[18] and those developed by specialists of the Kherson State Maritime Academy[19],[20],[21] were carried out. The cruise company Carnival Corporation has developed its own technology for

[12] Tran T.A. Research of the Scrubber Systems to Clean Marine Diesel Engine Exhaust Gases on Ships. Journal of Marine Science: Research & Development.2017. 243 p. DOI: 10.4172/2155-9910.1000243.

[13] Anders B. Laursen. Availability of elements for heterogeneous catalysis: Predicting the industrial viability of novel catalysts. Chinese Journal of Catalysis. 2018. p. 16–26. DOI: 10.1016/S1872-2067(17)62979-6.

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[17] Carnival Corporation & PLC. Sustainability. 2018. URL: http://www.carnivalcorp.com/phoenix.zhtml?c=140690&p=irol-sustainability.

[18] Carnival Corporation’s Exhaust Gas Cleaning Technology installed on 60 percent of fleet. 2018. URL: https://www.prnewswire.com/news-releases/carnival-corporations-exhaust-gas-cleaning-technology-installed-on-60-percent-of-fleet-300413964.html

[19] Леонов В.Е., Чепок М.В., Дробитко Р.А. Пути повышения энергетической эффективности и экологической безопасности морского флота. In proc. of the XI International conference «Strategy of quality in industry and education». Bulgaria, Varna: Technical University. 2015. Vol. 2, pp. 87–93.

[20] Леонов В.Е., Сыс В.Б, Чернявский В.В., Сыс В.В. Современные технологии автоматизации безопасного управления судами , энергосбережения, защиты морской и окружающей среды: монография/ под ред. В.Е. Леонова. Херсон: Видавництво Херсонської державної морської академії. 2019. 556 с. ISBN 978-966-2245-66-0.

[21] Леонов В.Е., Чернявский В.В. Современные методы исследований и обработки экспериментальных данных: монография / под ред. В.Е. Леонова. Херсон: Видавництво Херсонської державної морської академії. 2020. 520 с. ISBN 978-966-2245-60-8.

cleaning EG SPP, which allows to reduce to a minimum the content of Sulfur compounds and solid particles (EGCS technology)

EGCS technology works during sea sailings, and during stops of the vessel or when maneuvering in port. «Our system is a state-of-the-art, environmentally-friendly technology, and its application attests to the willingness of Carnival Corporation to comply with international norms and regulations,» said M. Kachmarek, Vice President of Carnival Corporation . The cruise company Carnival Corporation has developed its own technology for cleaning EG SPP, which allows to reduce to a minimum the content of Sulfur compounds and solid particles (EGCS technology). The cruise company Carnival Corporation has developed its own technology for cleaning EG SPP, which allows to reduce to a minimum the content of Sulfur compounds and solid particles (EGCS) technology.

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EGCS technology allows to clean EG SPP only from two pollutants: SOx and solid particles (soot).

The main stages of EGCS:

1. Cooling the EG SPP with the disposal of excess heat of the EG SPP.
2. Wet scrubber cleaning (absorption process) EG SPP from SOx and solid particles with an absorbent of 50% NaOH solution mixed with sea water.
3. Cleaning of worked off liquid absorbent from solid particles.
4. Reset the worked off absorbent with SOx compounds, alkali, solid particles in the marine environment.
5. The release of cleaned EG SPP from SOx and solid particles into the atmosphere.

In our opinion, the basis of EGCS technology is the wet scrubber cleaning (point 2) EG SPP of sulfur compounds with the help of absorbent-50% NaOH solution mixed with seawater, at a pressure of 10 bar, with the help of special spray devices that convert the absorbent into a fine mist phase. As a result, the interaction of SO_2 and SO_3 contained in EG SPP with sodium hydroxide, respectively, formed sulfite and sodium sulfate. At the same time, the degree of purification from SO_2 and SO_3 in EG SPP is at 98% level. In the process of wet scrubber cleaning, by the opinion of the authors of the project, solid particles from EG SPP are absorbed by the absorbent. This is questionable because the solids are hydrophobic and therefore must be released to the atmosphere.

A rather complex technological task is a stage 3 of purification of the worked off absorbent from solid particles. After this stage, the spent absorbent containing sulfite, sulfate, sodium hydroxide, solid particles are discharged into the marine environment.

The flow diagram of EGCS technology is shown in articles.

Exhaust gas, shown in Fig.2, (pos. 16) after SPP (pos. 17) is supplied to the economizer (pos. 15), in which the EG temperature decreases below 50°C, then enters

the lower part of the absorber (pos. 10), where is the counter flow in a spray form, a mist is supplied as the absorbent, containing 50% by weight. of sodium hydroxide (lye) mixed with sea water. As a result of the interaction of sulfur oxides with alkali sulfites and sodium sulfates are formed, dissolving in the absorbent, in the opinion of the authors, solid particles (soot) are transferred. In general, quite complex in composition and aggressive worked-off absorbent after the absorber (pos. 10) sequentially moves to the container (pos. 8) for averaging, particle cleaning system (pos. 4), the quality analyzer (pos. 3) and further discharged into the marine environment (pos. 18). The scheme provides recycling of spent absorbent after the tank (pos. 8) part of the spent absorbent pump (pos.6) through the condenser (pos. 7), the quality analyzer (pos. 9) fed to the upper part of the absorber (pos. 10). The purified EG SPP (pos. 13) is thrown out into atmosphere.

It is of scientific and practical interest to consider an alternative technical solution for cleaning EG SPP from toxic components developed by us (Fig. 3).

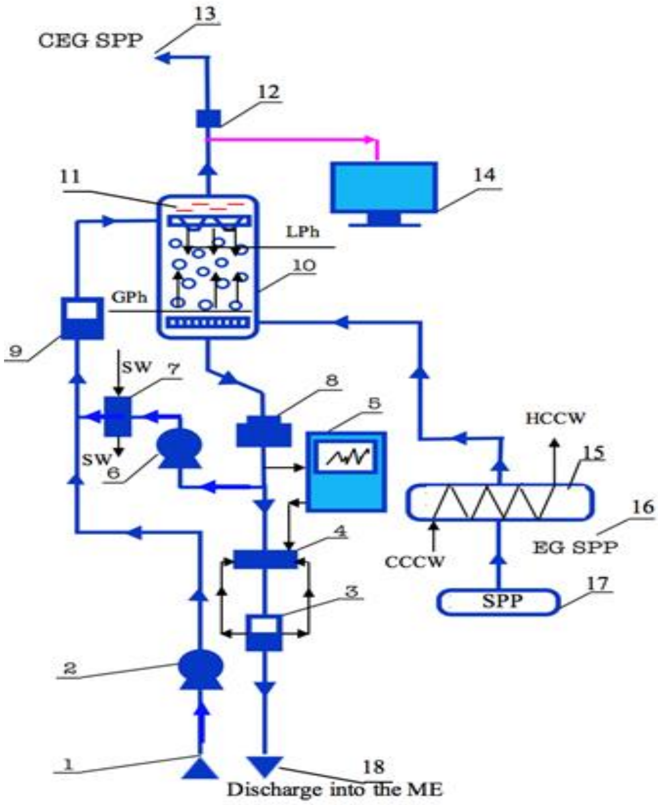

Fig. 2. The flow diagram of EGCS technology

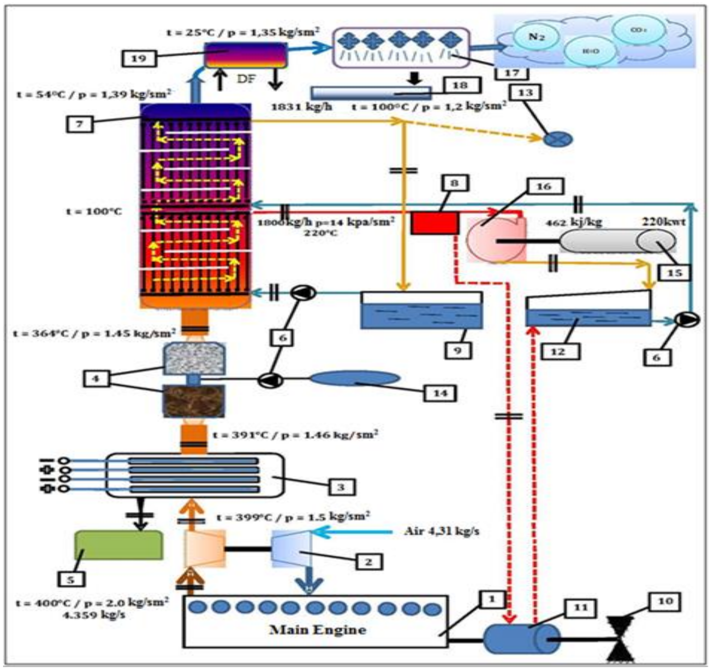

Fig. 3. A comprehensive scheme for the purification from toxic compounds and utilization of heat of the EG of SPP for the vessel «OXL SAMURAI»

IMO aims to create a highly efficient, environmentally safe, trouble-free ship that meets the high level of Energy efficiency constructional design index (EEDI) in the 2020-2025 years[22],[23],[24],[25]. To implement this general direction, the complete solution of technological tasks for purifying EG SPP, and heat utilization shall be offered.

The main stages of the complex process are:

1. Quantitative high-temperature purification of EG SPP from soot.
2. Catalytic purification, neutralization of toxic substances and compounds contained in the EG SPP.

2.1. By means of catalytic oxidation.

2.2. Method of catalytic reduction.

3. Dual circuit technology for utilization of excess heat of the EG SPP.
4. Cooling the EG SPP to the temperature of 20-30°C.
5. Absorption of sulfuric anhydride condensate to produce sulfuric acid.

The technology of heat recovery of the EG SPP provides:

1) the continuity of the utilizing process of the EG SPP;

2) the increase in the efficiency of SPP, voyage, minimizing the EEOI.

There is a brief description of the process below:

EG SPP from the main marine engine (1) at a temperature of 400°C enter the turbine (2) and then go into the electro filter (diffusional filter) (3), catalytic reactor unit (4), which is equipped with oxidation and reduction catalysts. At a temperature of 363.6 degrees Celsius, the EG SPP enter the economizer (7), where heat is exchanged with water circuits, then at a temperature of 54°C enter the refrigerator-condenser (19), in which the temperature decreases to 25°C, into the scrubber (17), where sulfuric acid is formed , the latter is collected in a container (18). It should be noted that the technical solutions proposed and implemented on cruise ships by Wartsilla and Carnival Corporation are not original and new.

It should be noted that the technical solutions proposed and implemented on cruise ships by Wartsilla and Carnival Corporation are not

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[22] Guidelines for voluntary use of the ship energy efficiency Operational indicator (EEOI). London: IMO. 2009. 45 p.

[23] Leonov V.Ye., Serdyuk A. D. Research and Development of Effective Technology for Air Basin Protection While Ship Operation. Вестник Государственного университета морского и речного флота имени адмирала С. О. Макарова. С-Пб. 2018. Т. 10. № 4. с. 770–782 . DOI:10.21821/2309-5180-2018-10-4-770-782.

[24] Leonov Valeriy. Solution of the Two-vector Problem of Resource Saving on Board of the Ship. American Journal of Traffic and Transportation Engineering. 2021. Vol. 6, № 6 . p. 147–155. doi: 10.11648/j.ajtte.20210606.11.

[25] Раевский П. Снижение уровня эмиссии оксидов серы на судах морского флота. Спб: Журнал «Двигателестроение». 2007. № 1 (227). С. 43–49.

original and new. As early as fourteen years ago, in the work of Raevskiy[26], various industrial technologies for desulphurization of exhaust gases from a power plant were considered.

This article[27] was initiated by a number of regulations and amendments adopted by the International Maritime Organization and the European Union at that time, namely Regulation No. 5 of Annex VI to MARPOL 73/78 and EU Directive 2005/30 / EC introduced severe restrictions on the content sulfur compounds in fuel (no more than 1.5%, and since 2010 – no more than 0.1% by weight). The use of fuels with a higher sulfur content was allowed only with equipment for cleaning exhaust gases from SOx. A technology based on the process of absorption of sulfur compounds by sea water has been proposed to clean the exhaust gases of the power plant from sulfur compounds[28].

In[29] it is indicated that technical solutions for the purification of exhaust gases from sulfur oxides using the process of absorption by sea water on ships equipped with ship power plants with a capacity of 1200 to 5000 kW allow achieving the maximum efficiency of gas purification from SOx at the level of 80 %. The question arises whether this degree of purification of exhaust gases is sufficient in comparison with the emissions of exhaust gases from the ESP when using low-sulfur marine fuel (no more than 0.1% by weight).

The technology[30] provides for the purification of waste seawater waste after the absorber from suspensions (?) and oil products (?).

The work[31] presents the results of using wet scrubbers on various ships with seawater spraying of gases by analogy, as currently offered by the companies Wartsila, Carnival corporation. The only difference is that the companies Wartsila, Carnival Corporation add sodium hydroxide (NaOH-50% wt.) to the seawater used as an absorbent

This raises questions (???), what is the novelty of technical solutions offered by Wartsila, Carnival Corporation.

The developed technology is designed to be implemented directly on board the vessel and allows, in comparison with known proposals, to solve

[26] Раевский П. Снижение уровня эмиссии оксидов серы на судах морского флота. Санкт-Петербург : Журнал «Двигателестроение». 2007. № 1 (227). С. 43–49.

[27] Там само

[28] Раевский П. Снижение уровня эмиссии оксидов серы на судах морского флота. Санкт-Петербург : Журнал «Двигателестроение». 2007. № 1 (227). С. 43–49.

[29] Там само

[30] Там само

[31] Там само

the following main issues of navigation in the framework of improving the energy efficiency and environmental safety of the vessel/voyage, minimizing EEOI:

1) use on board the vessel cheap high-sulfur heavy fuel IFO 380 (3,5% sulphur compounds by mass.);

2) improve the economic performance of the ship, the voyage through the utilization of the heat of the EG SPP and obtaining target products;

3) to ensure the environmental safety of the marine environment in the operation of ships, regardless of their design, type, cargo and route.

Thus, the following ecological and economic problems of shipping are solved as a result of the performed complex innovative technology of purification and utilization of heat of the EG SPP:

1. Application on board of the vessel at sea cargo transportation of cheap high-sulfur diesel fuel in areas of special control SECA, ECA, and from 01.01. 2020. – around the world.

2. Sanitary cleaning of the EG SPP to a safe level is provided for all toxic components and, in particular, for sulphur compounds and solid particles.

3. Deep regeneration of the heat of the EG SPP and their purification is carried out.

4. EG SPP after sequential processing directly on board of the ship turn the target commodity products.

5. Increases the economic efficiency of shipping, efficiency of voyage, ensures the protection of the marine environment.

6. The payback period of the integrated process unit does not exceed three years.

The analysis and generalization of technical solutions for purification of the EG SPP of Wartsilla, Carnival Corporation Company (EGCS technology) and suggested by author is conducted in Table 3.

Table 3

The analysis and generalization of technical solutions for purification of the EG SPP of Carnival Corporation Company and suggested by authors[32,33,34,35].

№	Indicators	Carnival Corporation	Variation		Suggested by authors	Variation	
1	2	3	4		5	6	
1	Cleaning method of EG SPP	Scrubber cleaning – absorption		–	Electrodiffusion cleaning from soot, catalytic neutralization of EG SPP toxic compounds	+	
2	Materials	50% mass NaOH with seawater, chemically cleaned water		–	Catalysts, chemically cleaned water	+	
3	Purification of EG SPP	Cleans from SO_x compounds and solid particles (soot)		–	Cleans from all EG SPP toxic compounds	+	
4	Repeated pollution of the environment	Marine environment is polluted by sulfite, sulfate, sodium hydroxide, soot		–	No repeated pollution of the marine environment	+	
5	Heat utilization of EG SPP	Cooling EG SPP chemically cleaned water without heat recovery		П –	Two-circuit heat recovery system is used	+	
6	Power usage	Requires increased power consumption, main and standby generators are used		–	Energy sources are generated – the first circuit is steam (14 atm), the second circuit is heated water 40-85 ° C	+	
7	Metal consumption of the installation	High		–	Low – five times lower compared to technology campaigns «Carnival Corporation», «Wartsilla»	+	
8	Payback period of the installation	Three years	+		Less than three years	+	

[32] Леонов В.Е., Чернявский В.В. Современные методы исследований и обработки экспериментальных данных: монография / под ред. В.Е. Леонова. Херсон: Видавництво Херсонської державної морської академії. 2020. 520 с. ISBN 978-966-2245-60-8.

[33] Guidelines for voluntary use of the ship energy efficiency Operational indicator (EEOI). London: IMO. 2009.-45 p.

[34] Leonov V.Ye., Serdyuk A. D. Research and Development of Effective Technology for Air Basin Protection While Ship Operation. *Вестник Государственного университета морского и речного флота имени адмирала С. О. Макарова*. С-Пб. 2018. Т. 10. № 4. с.770–782 . DOI:10.21821/2309-5180-2018-10-4-770-782.

[35] Leonov Valeriy. Solution of the Two-vector Problem of Resource Saving on Board of the Ship. American Journal of Traffic and Transportation Engineering. 2021. Vol. 6, № 6 . p. 147-155. doi: 10.11648/j.ajtte.20210606.11.

Continuation of table 3

9	Operating mode of the installation	In ports, when maneuvering and sea crossings	+		In ports, when maneuvering and sea crossings	+	
10	Prevented damage to the air basin, $/year	2 000 000		–	10 000 000	+	
11	Ecological compatibility of new technical solutions	Transfer of toxicants from the gas phase (EG SPP) to the marine environment		–	Transfer of toxicants(EG SPP) to the neutral compounds and target products, deep utilization of waste gas heat	+	
	TOTAL		Two (+) Nine (-)			Eleven (+)	

**Note: Calculations on item 10* made for M/V «OXL SAMURAI».*

As a result of technical and economic analysis of two technological schemes of the Wartsilla, Carnival Corporation Company and technology developed by our group of specialists, our team should conclude that we have developed technological scheme which has undeniable advantages in comparison with the Wartsilla, Carnival Corporation Company, which is a consequence of the following scheme parameters:

1) efficiency due to the cleaning and neutralization of all toxic compounds contained in the EG SPP, in comparison with only two toxicants by Wartsilla, Carnival Corporation Company;

2) ecological safety, due to the combined effect of neutralizing the toxic compounds contained in the EG SPP, and convert the final target in production while the technology by Wartsilla, Carnival Corporation company is organized to transfer pollutants from the gas phase of the EG SPP into the liquid marine environment;

3) the value of the prevented damage to the air basin under similar conditions is five times greater in comparison with the technological scheme of Wartsilla, Carnival Corporation.

The decision of the Session of the Marine Environment Protection Committee of the International Maritime Organization requires to use the low-sulphur fuel containing no more than 0.5% Sulphur-compounds of the mass on ships from 01.01.2020 worldwide. This IMO requirement does not affect vessels equipped with exhaust gas cleaning systems of SPP, as well as those vessels that conduct research on the development of effective methods of purification from sulfur compounds

The analysis of well-known technical solutions for EG SPP purification are performed, among which there are such companies as «Carnival

Corporation», «Wartsilla», which have developed a scrubber cleaning method of EG SPP from sulfur compounds. The technology of the EG SPP purification from toxic compounds developed by a group of specialists of Kherson State Maritime Academy under the guidance of Professor Leonov V. Ye. is suggested. A comparison of the two processing schemes is done according to eleven parameters. As a result, the undeniable advantage of second technology is determined.

We consider it appropriate to conduct a feasibility study of the two technologies under the auspices of the Committee for the Protection of the Marine Environment of the International Maritime Organization with the objective to choose the technology for purifying EG SPP for implementation on maritime transport.

5. Discussion

The developed technology is intended directly for functioning on board of the vessel and allows, in comparison with the known technical proposals, to solve the following main topical issues of shipping:

1. Use cheap heavy fuel on board IFO 180.-380 (3,5% weight «S»).

2. To increase the economic indicators of the vessel, voyage due to the utilization of the heat of the exhaust gas of the ship power plant and the receipt of target products.

3. Ensure the ecological safety of the sea environment during the operation of ships, regardless of its project, type, cargo and route.

Thus, as a result of the developed technology for the purification and utilization of the heat of the exhaust gases of the SPP, the following environmental and economic problems of navigation are solved:

1. The use of cheap high-sulfur diesel fuel on board a vessel for sea cargo transportation in the areas of special control of SECA, ECA, and from 01.01.2020 – all over the world.

2. Ensuring the sanitary cleaning of the EG of SPP to a safe level for all toxic components and, in particular, for sulfur compounds and solid particles (soot deposits).

3. Implementation of a comprehensive deep utilization of the heat of exhaust gases from the ship power plant and their cleaning.

4. Obtaining target marketable products and heat from the exhaust gases of the SPP after their sequential processing directly on board the ship.

5. To increase the economic efficiency of sea cargo transportation, the efficiency of the vessel / voyage, to ensure the protection of the marine environment.

6. The payback period of a complex resource-saving technological unit does not exceed three years.

7. The analysis, generalization of technical solutions for the purification of exhaust gases were conducted, as a result of the technical and economic analysis of the technological scheme, it should be concluded that the developed technological scheme has undeniable advantages in comparison with the systems of exhaust gas of SPP heat recovery implemented in practice.

In our opinion, the implementation of the developed project for the comprehensive heat recovery of waste gases from ship power plants is possible in one of the two directions presented below:

1. On existing ships, regardless of their type, purpose and gross tonnage.

2. On newly created ships, regardless of their type, purpose and gross tonnage.

Regardless of the direction adopted, the implementation process should be preceded by the following main stages:

1) development of a feasibility study of the proposed technology;

2) development of a business plan for the proposed technology;

3) development of the section «Environmental Impact Assessment» of the proposed technology;

4) development of a one-stage working project with the development of new equipment, and preferably the use of already mastered and manufactured equipment in industry;

5) start-up and pilot industrial tests of a new technology on a ship in a sea passage.

In all of the above stages 1-5, the author of this article and his collaborators are ready to take direct part in agreement with a specific Customer.

Conclusions. Sea transport, despite its obvious economic advantages over other modes of transport, has disadvantages, which are manifested in the high consumption of marine diesel fuel, significant emissions of material and energy waste and, as a consequence, damage to the air basin from the exhaust gases of ship power plants. Existing and mastered in maritime practice, the systems for utilizing the heat of exhaust gas from the SPP do not allow solving the above problems. In this scientific work, the goal is to solve two problems at the same time – economic and environmental. This is achieved through the following measures:

* comprehensive purification of EG SPP from harmful toxic components;

* utilization of the excess heat of the exhaust gas of the power plant with the production of steam, converted into the energy of the ship's motion and / or electricity;

* the continuity of the process, both in the conditions of the sea passage, and in the conditions of the port;

* production of targeted useful products from the harmful substances contained in the EG SPP. The solution of these complex tasks will make it possible to refuse from low-sulfur, expensive and scarce marine fuel and use high-sulfur, cheap marine fuel.

As a result of the feasibility study of two technological schemes – the company Wartsilla, Carnival Corporation and a group of specialists led by Professor Leonov V.Ye. – it should be concluded that the technological scheme developed by us has undeniable advantages in comparison with the process of the company Wartsilla, Carnival Corporation, which results from the following:

1) efficiency, which is due to the purification and neutralization of all toxic compounds contained in the exhaust gas of the SPP, in comparison with only two substances in the technology of the company «Carnival Corporation»;

2) environmental safety, which is due to the cumulative effect of neutralizing toxic compounds contained in the SPP exhaust gas and converting the latter into target products, while the Carnival Corporation technology provides an organized transfer of pollutants from the gas phase of the SPP exhaust gas to the liquid marine environment;

3) the amount of prevented damage to the air basin under similar conditions is five times greater in comparison with the technological scheme of the Carnival Corporation, Wartsilla.

Rationale for limiting the concentration of sulfur compounds in marine fuel. If the emission of sulfur oxides exceeds 6 g/kWh in the exhaust gases of the SPP, the International Maritime Organization recommends that the exhaust gases of the SPP be cleaned from sulfur compounds on board the vessel.

Two main questions arise from this recommendation:

1) it is not quite clear which system for cleaning the exhaust gases of the power plant from sulfur compounds should be used, by whom and when the recommended cleaning system was legalized, what methodology, methodology is incorporated in the cleaning method, where this cleaning system has been worked out, what results have been obtained, the availability of project documentation for the cleaning system, are there test reports and environmental impact assessment?

2) on the basis of what data the SO_2 emission limit of 6g/(kW•hour) was adopted.

The answer to the first question sounds like a good wish, from which it is not clear to the navigator, the mechanic, what should be done in the current situation in terms of if the SO_2 emission limit is exceeded – 6g / (kW•hour)?

To answer the second question, a more detailed evidence-based analysis is needed.

Sulfur compounds contained in marine fuel are a complex composition, including mercaptans, sulfides, ethers, alcohols, acids. During the combustion (oxidation) of sulfur compounds in the cylinders of engines of ship power plants, sulfur compounds are converted quantitatively into sulfur dioxide. To simplify the research, we will assume that all sulfur compounds contained in marine fuel are methyl mercaptan. The accepted simplification will in no way affect the qualitative and quantitative characteristics of the results obtained.

The process of oxidation of methyl mercaptan (CH3SH) in the cylinders of the SPP is described by the following stoichiometric equation:

$$CH_3SH + 3O_2 = SO_2 + 2H_2O + CO_2 + Q_R \quad (14)$$

where Q_R is the amount of released heat of a chemical exothermic reaction, kcal/mol.

Below we give an example of the calculation of sulfur dioxide emissions depending on the concentration of methyl mercaptan in marine fuel.

Based on practical data, we will take the specific consumption of marine fuel (on average) 0.175 kg/kWh, and in each specific case, it is required to accept the specific consumption of marine fuel according to the passport characteristics of the main power plant.

With a concentration of methyl mercaptan (CH_3SH) in marine fuel – 3% wt., the mass of methyl mercaptan (CH_3SH) in marine fuel will be equal to 0.175•3/100=0.00525 kg/kWh. Then, according to the stoichiometric equation (1), carried out by the material balance calculations, the emission of sulfur dioxide with the exhaust gases of the SPP will be: 0.00525•1.33 = 0.00698 kg SO2/kWh. Similar calculations of sulphurous anhydride emissions from the exhaust gases of the SPP were carried out at the concentrations of methyl mercaptan, wt %, in marine fuel: 0.1; 0.5; 1.0; 2.0; 3.0; 3.5; 4.0.

On the basis of the performed calculations, Figure 4 was constructed for the dependence of sulfur dioxide emissions on the content of methyl mercaptan in marine fuel.

6. Practical results

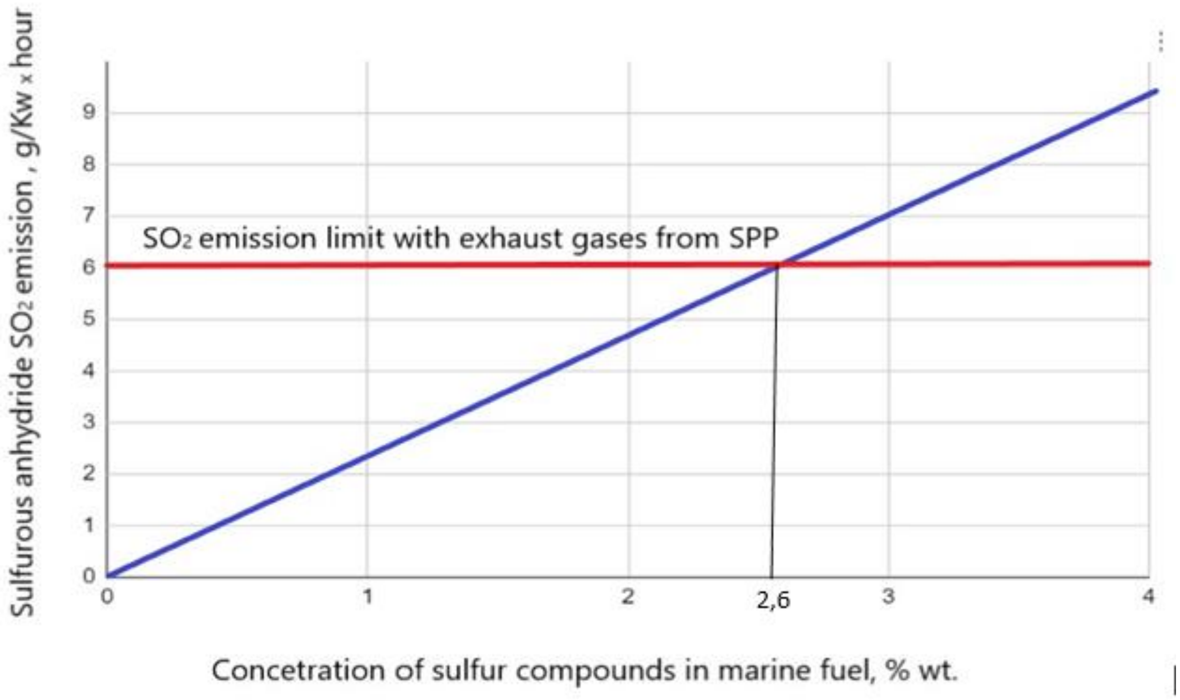

Fig. 4. Dependence of sulfurous anhydride emissions from the exhaust gas from the SPP on the concentration of methyl mercaptan in marine fuel

Based on the calculated and experimental data obtained (Fig. 4), we will analyze how justified the requirement was to limit the content of sulfur compounds in marine fuel to no more than 0.1% of the mass. in SECA, ECA zones (until 01/01/2020), no more than 0.5% wt. from 01.01.2020 worldwide. At a concentration of sulfur compounds in marine fuel of 0.1% wt. the emission of sulfur dioxide from the exhaust gas of the power plant is less than the permissible limit (6 g / (kW•hour)) by 26.08 times, and with a concentration of sulfur compounds in marine fuel of 0.5% wt. the emission of sulfur dioxide from the EG of the SPP is less than the permissible limit (6g/(kW•hour)) by 5.17 times. Thus, in both cases (0.1% wt. and 0.5% wt. sulfur compounds in marine fuel) there is a significant margin from the prescribed limit for sulfur dioxide emissions. This raises a reasonable question, is it worth it to underestimate the concentration of sulfur compounds in marine fuel, because the process of desulfurization of marine fuel requires significant material and energy costs, which inevitably leads to an increase in the cost of marine fuel and, as a result, leads to a decrease in the economic efficiency of maritime transportation.

What can be offered?

1) the lines in Figure 4 intersect at a point corresponding to a concentration of sulfur compounds in marine fuel of 2.6 wt%. at the same time, the established limit on emissions of sulfur dioxide from the exhaust gas SPP-6g/(kW• h) will not be exceeded;

2) without damage to the air basin, the concentration of sulfur compounds in marine fuel can be increased from 0.5% wt. up to 2.6% wt., i.e. more than five times, which will significantly reduce the cost of marine diesel fuel;

3) at a concentration of sulfur compounds in marine fuel of 3.5% wt. (without additional purification of marine diesel fuel) emissions of sulfur dioxide will exceed the established limit by 1.36 times, which will require the purification of the exhaust gas of the power plant from excess emissions of sulfur dioxide to the established limit, but this in aggregate is the low price of marine fuel containing 3.5% of the mass . sulphurous compounds, and additional purification of the exhaust gas of the power plant from sulfurous anhydride, will improve the efficiency of sea freight transportation.

It should be noted that with a decrease in the concentration of sulfur compounds in marine fuel, the cost of marine fuel increases significantly (Fig. 5-9). Therefore, a reasoned approach is required when determining the maximum allowable content of sulfur compounds in marine fuel.

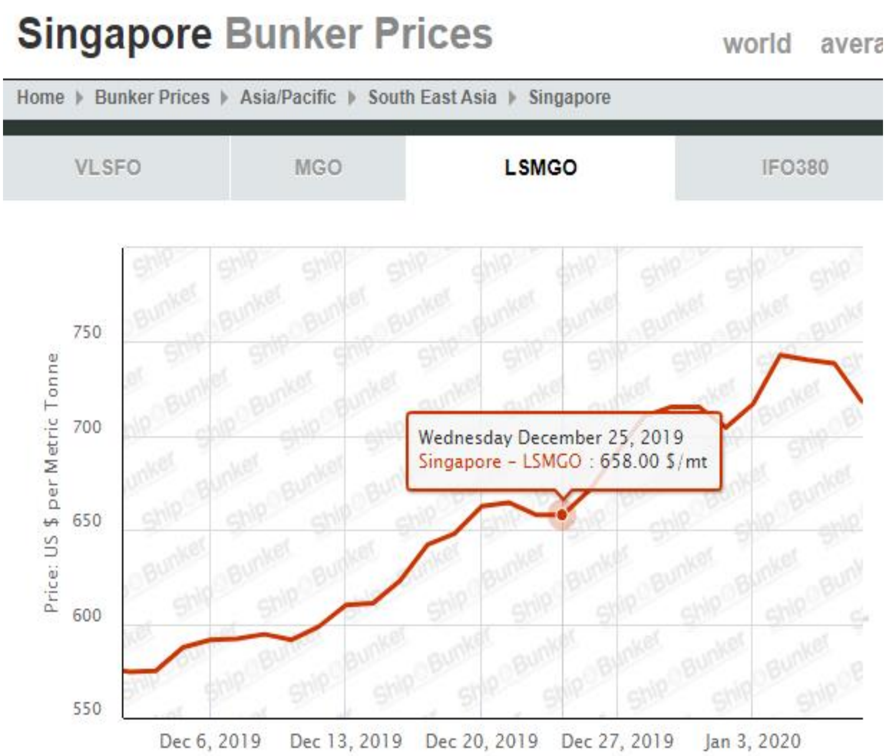

Fig. 5. Cost of marine fuel LS MGO containing 0.1% wt. sulfur compounds, in the port of Singapore (December 25, 2019)

Fig. 6. The cost of marine fuel IFO 380 containing 3.5% of the mass. sulfur compounds, in the port of Singapore (December 25, 2019)

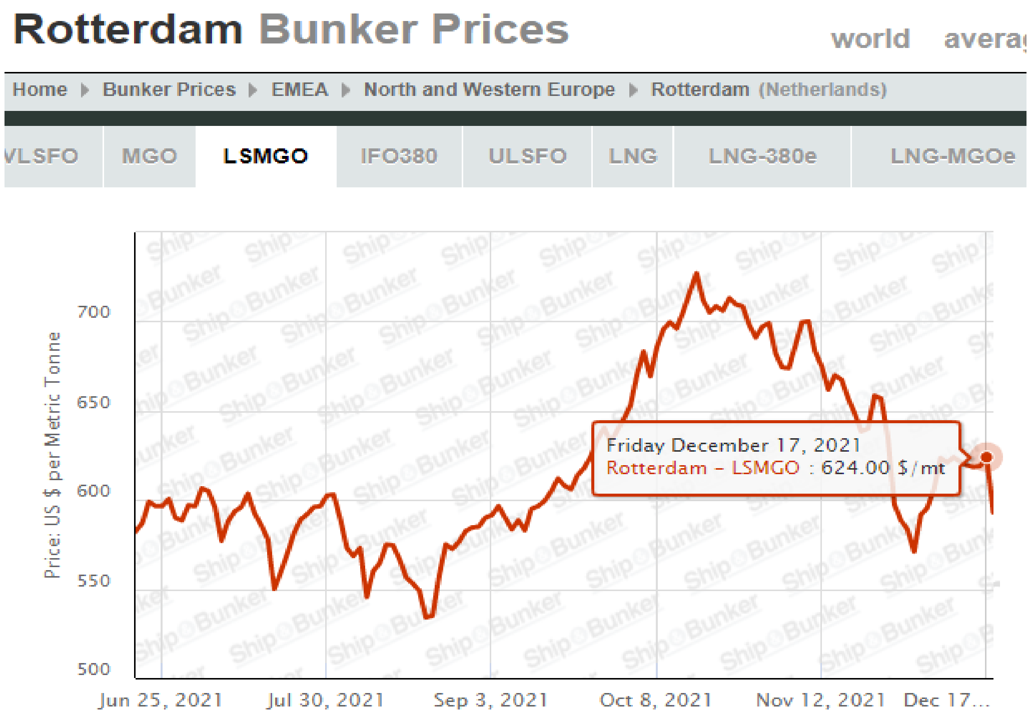

Fig. 7. The cost of marine fuel LS MGO containing 0.1% of the mass. sulfur compounds, in the port of Rotterdam (December 17, 2021)

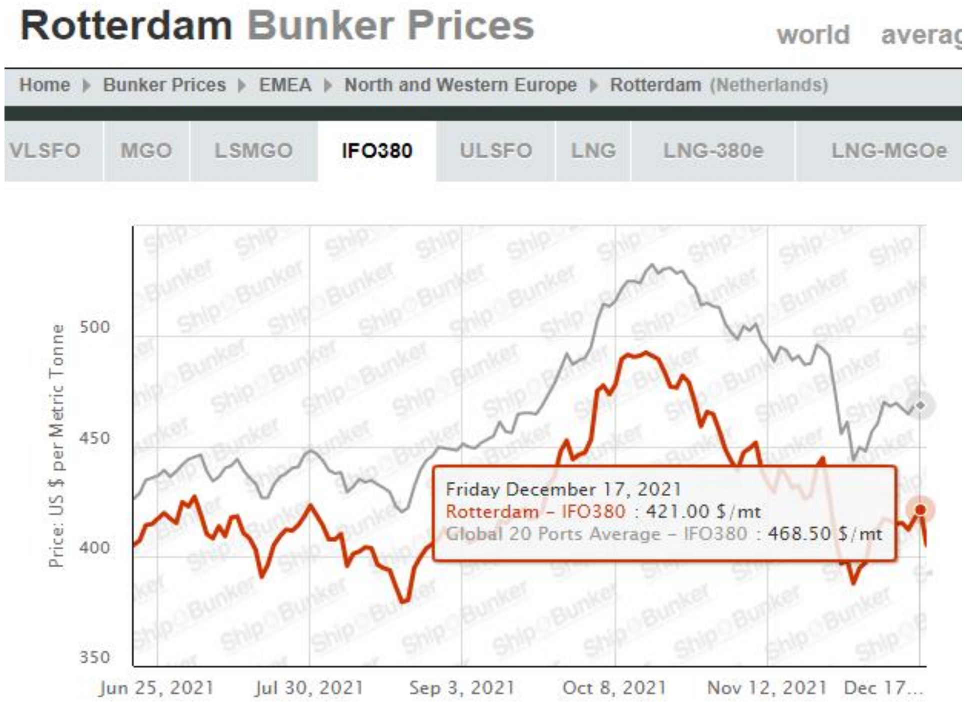

Fig. 8. The cost of marine fuel IFO 380 containing 3.5% of the mass. sulfur compounds, in the port of Rotterdam (December 17, 2021)

Fig. 9. Cost of VL SFO marine fuel containing 0.5 wt. sulfur compounds, in the port of Rotterdam (December 17, 2021)

Figure 10 shows the results of computational studies to determine the minimum price for marine low-sulphur fuel. Calculation studies were carried out on the basis of real prices for marine fuel of three grades – LSMGO (no more than 0.1 wt.% sulfur compounds), VLSFO (no more than 0.5 wt.% sulfur compounds), IFO 380 (no more than 3.5 % wt. sulfur compounds), for three ports of the world – Singapore, Rotterdam, New York, for two time periods – December 2019 (before the transition of the entire fleet to low sulfur fuel), December 2021 (after the transition of the entire fleet to low sulfur fuel).

Based on the analysis of the data shown in Figure 4, it follows that it is possible to provide an acceptable emission of sulfur dioxide with the exhaust gases of the power plant at the level of 6g/(kW•hour), even if the concentration of sulfur compounds in marine fuel is -2.6% wt. To determine the minimum cost of marine fuel according to Figure 8, we restore the perpendicular from the abscissa axis with a concentration of 2.6% of the mass. before the intersection with the intersection point of lines 1,2,3 and through the intersection point we draw a straight line parallel to the abscissa axis until the intersection with the ordinate axis, on the ordinate axis we determine the minimum cost of marine low-sulphur fuel in the amount of 438 USD/mt. As a result of the computational studies, it was found that the cost of low-sulfur marine fuel can be reduced by 1.55 times or by 242 US dollars/mt, without violating the requirements of the International Maritime Organization to limit sulfur dioxide emissions from the exhaust gases of SPP – no more than 6 g SO_2 /(kW•hour).

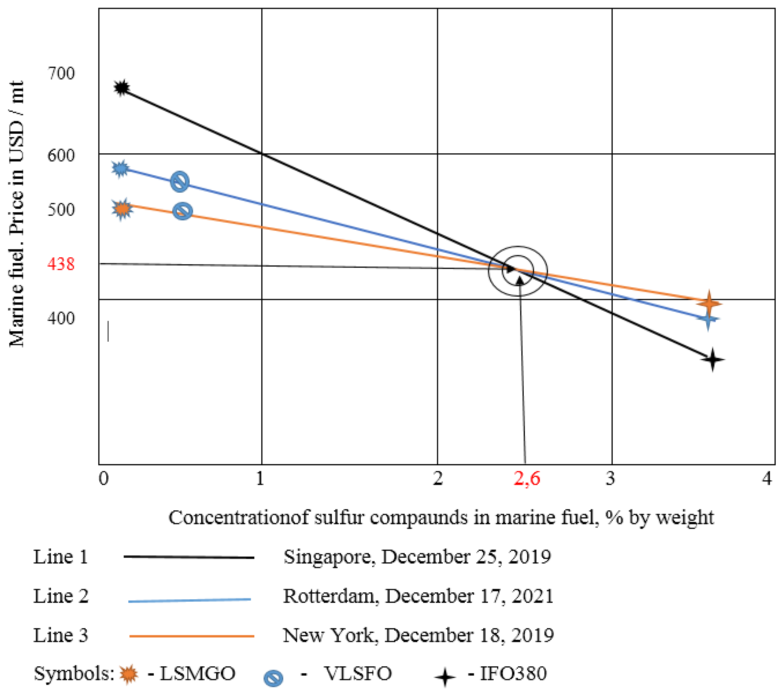

Fig. 10. Study of the influence of the minimum allowable concentration of sulfur compounds in marine fuel depending on the price of marine fuel

Limitation of emissions of nitrogen oxides from waste gases of ship power plants. The requirements for nitrogen oxide emission limits are set out in Annex VI of MARPOL – 73/78 and apply to the main ship power plant with a power of more than 130 kW. The area of special control over emissions of nitrogen oxides from ships was named NECA (the area of the Baltic, North Sea, the English Channel).

In accordance with these rules, the operation of a ship power plant is prohibited if the nitrogen oxide emissions, calculated as total weighted NOx emissions, exceed the following values:

$$17 g/(kW \bullet hour) \text{ at } n < 130 \text{ rpm} \tag{15}$$

$$45 \bullet n^{-0.2} g/(kW \bullet hour) \text{ at } n > 130 \text{ rpm, but } n < 2000 \text{ rpm} \tag{16}$$

$$9.8 g/(kW \bullet hour) \text{ at } n > 2000 \text{ rpm} \tag{17}$$

where n is the rated speed of the engine crankshaft, rpm.

Nitrogen oxides are formed from the air entering the combustion chamber of the SPP, according to the following reaction:

$$N_2 + 2O_2 = 2\ NO_2 – Q_R \tag{18}$$

The process of formation of nitrogen oxides proceeds at high temperatures (1500-1800°C) and pressure (2.5-3.5 MPa), reaction (18) is endothermic. Since reaction (18) is endothermic, the yield of nitrogen oxides should increase with increasing temperature according to the Le Chatelier principle.

Let us analyze the emission of nitrogen oxides according to the criteria given above.

Emissions of nitrogen oxides were calculated depending on the number of revolutions (n) on the crankshaft of the SPP. The following results are obtained:

1) at n = 100 rpm, the output of nitrogen oxides is 17g/(kW•hour);
2) at n = 1000 rpm, the output of nitrogen oxides is 11.3 g/(kW•hour);
3) at n = 2100 rpm, the output of nitrogen oxides is 9.8 g/(kW•hour).

According to practical and theoretical results, it is known that with an increase in the number of revolutions on the crankshaft, the average mass temperature in the SPP cylinder increases and, accordingly, the yield of nitrogen oxides should increase. According to our calculations according to the above equations (15-17), it follows that with an increase in the number of revolutions per unit time, the output of nitrogen oxides, on the contrary, decreases in the series: 17→11.3→9.8 g / (kW•hour).

What is the contradiction, how these criteria (15-17) were obtained and where they were tested??? Unclear??? Another question is what should ship mechanics do if nitrogen oxide emissions exceed the limits set by criteria (15-17)???

According to theoretical developments, with an increase in the number of revolutions on the crankshaft, the power of the SPP increases, with an increase in the power of the SPP, the weighted average temperature in the engine cylinder increases. According to well-known authoritative publications and the theory of oxidation, the yield of oxides with increasing temperature, other things being equal, should only increase, and according to the calculated criteria (15–17), the yield of nitrogen oxides, on the contrary, decreases, which contradicts the known theoretical concepts on the yield of nitrogen oxides depending on temperature.

CONCLUSIONS

As a result of the conducted research, a complex technology for heat recovery and purification of waste gases from the SPP has been developed. The proposed technological development allows us to solve a two-vector problem – to increase the economic performance of maritime cargo transportation and to increase the environmental performance of the sea crossing.

On the basis of research and design developments, it has been proved that by meeting the requirements of the International Maritime Organization for the maximum emission of sulfur oxides during the operation of ships of no more than 6 g/kW•hour, it is possible to increase the allowable limit for the content of sulfur compounds in marine fuel from 0.5% wt. to 2.8% wt. (increase by 5.6 times), while the cost of marine fuel will be reduced by 1.55 times, or by $242/mt.

In this case, the economic efficiency of maritime transportation will be increased.

SUMMARY

The operation of maritime transport leads to a number of environmental problems. Practical recommendations are proposed to reduce the emission of sulfur oxides, nitrogen oxides, carbon oxides released during the operation of ships, to reduce the cost of marine fuel.

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