

СУДОВЫЕ ЭНЕРГЕТИЧЕСКИЕ УСТАНОВКИ, СИСТЕМЫ И УСТРОЙСТВА

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RESEARCH AND DEVELOPMENT OF EFFECTIVE TECHNOLOGY FOR AIR BASIN PROTECTION WHILE SHIP OPERATION

V. Ye. Leonov¹, A. D. Serdyuk²

¹ — Kherson State Maritime Academy, Kherson, Ukraine

² — Kherson sea port, Kherson, Ukraine

Currently, the marine area has two limited areas of special control – SECA and ECA, in which it is permissible to use only low-sulfur fuel, the content of sulfur compounds in which should not exceed 0.1% of the mass, and in the rest of the main part of the sea area it is permissible to use high-sulfur fuel containing no more than 3.5% S-compounds of the mass. The use of low Sulphur fuels is mainly stimulated by environmental concerns – reducing air basin pollution by reducing Sulphur dioxide emissions to the detriment of the economy as the cost of low Sulphur fuels is 2-5 times higher than that of high Sulphur fuels. By the decision of the International Maritime Organization since 01.01.2020 all sea trade and passenger transport are transferred to the low-Sulphur fuel (containing S-compounds no more than 0.5% of the mass.). Exceptions to this are only those vessels that are equipped with exhaust gas purification systems of ship power plants from sulfur compounds, as well as those vessels that conduct research on the development of effective methods of purification from sulfur compounds. The analysis of technical solutions for the treatment of waste gases of ship power plants from sulfur compounds and implemented technologies on some liners are conducted. As an alternative solution for the treatment of exhaust gases of ship power plants from sulfur compounds, a new complex technology is proposed by us, which is fundamentally different from the previously developed. Comparison of two technological schemes is performed by nine main parameters. Recommendations on the introduction of the system of waste gases purification of ship power plants from sulfur compounds on sea vessels when using cheap high-sulfur marine fuel on board vessels are developed. The alternative technology of exhaust gas of ship power plants purification from toxic compounds has undeniable advantages in comparison with the previously developed technology - in depth of purification, heat recovery, the value of prevented damage to the air basin, protection of the marine environment, continuity of the process regardless of the specific situations of the sea crossing, management of the processes of purification and utilization of the heat of exhaust gases of ship power plants – automatic, autonomous from the navigational bridge.

Keywords: marine fuel, sulfur compounds, special control areas, cleaning, ship power plants, exhaust gases, scrubber cleaning, catalytic cleaning, International Maritime Organization, toxic substances, research, degree of conversation.

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ИССЛЕДОВАНИЕ И РАЗРАБОТКА ЭФФЕКТИВНОЙ ТЕХНОЛОГИИ ЗАЩИТЫ ВОЗДУШНОГО БАСЕЙНА ПРИ ЭКСПЛУАТАЦИИ СУДОВ

В. Е. Леонов¹, А. Д. Сердюк²

¹ — Херсонская государственная морская академия, Херсон, Украина

² — Херсонский морской торговый порт, Украина, Херсон

В настоящее время морская акватория имеет две ограниченные по площади зоны особого контроля: SECA и ECA, в которых допустимо использовать только низкосернистое топливо, в котором содержание сернистых соединений не должно превышать 0,1 % масс., а в остальной основной части морской акватории используется высокосернистое топливо, содержащее не более 3,5 % масс. S-соед. Использование низкосернистого топлива стимулировано главным образом экологическими аспектами — снижением ущерба воздушному бассейну за счет уменьшения эмиссии сернистого ангидрида — в ущерб экономическим, поскольку стоимость низкосернистого топлива в 2–5 раз выше стоимости высокосернистого. По решению Международной морской организации с 01.01.2020 г. весь морской торговый и пассажирский транспорт переводится на низкосернистое топливо (не более 0,5 % масс. S-соед.). Исключение из этого составляют только те суда, которые укомплектованы системами очистки отработанных газов судовых энергетических установок от сернистых соединений, а также суда, на которых проводятся исследования по разработке эффективных способов очистки от сернистых соединений. Проведен анализ технических решений по очистке отработанных газов судовых энергетических установок от сернистых соединений и технологий, реализованных на некоторых круизных судах.

В качестве альтернативного решения по очистке отработанных газов судовых энергетических установок от сернистых соединений нами предложена новая комплексная технология, принципиально отличающаяся от разработанной ранее. По девяти основным параметрам выполнено сравнение двух технологических схем, разработаны рекомендации по внедрению системы очистки отработанных газов судовых энергетических установок от сернистых соединений на морских судах при использовании на борту судов дешевого высокосернистого судового топлива. Альтернативная технология очистки отработанных газов судовых энергетических установок от токсических соединений имеет неоспоримые преимущества по сравнению с разработанной по глубине очистки, утилизации теплоты, величине предотвращенного ущерба воздушному бассейну, защите морской окружающей среды, непрерывности процесса, независимо от конкретных ситуаций морского перехода, управлению процессами очистки и утилизации теплоты отработанных газов СЭУ — автоматическому и автономному со штурманского мостика.

Ключевые слова: судовое топливо, сернистые соединения, зоны особого контроля, очистка, судовые энергетические установки, отработанные газы, скрубберная очистка, каталитическая очистка, Международная морская организация, токсические вещества, исследования, степень превращения.

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Introduction

International Maritime Organization (IMO) in order to protect the environment, biosphere, and humans requires reducing the content of Sulfur compounds in marine fuel [1]. During the period from 2012 to 2015, the concentration of sulfur compounds in marine fuel in Special control areas – ECA and SECA – decreased by 10 times - from 1.0 to 0.1% of the mass., in the rest of the shipping world area it decreased by 1.0% - from 4.5 to 3.5% of the mass. During the Session of the Subcommittee on Pollution Prevention and Response (PPR), IMO from 05 to 09.02.2018. (the headquarter of the IMO, London) made the decision to prohibit the use of navigation since 01.01.2020 worldwide the fuel with the high content of sulfur compounds. It was decided to transit to low-Sulfur fuel with no more than 0,5 % Sulphur-compounds of mass., i.e. reduction of sulfur compounds concentration by 7 times. The resolution of the Session states that this prohibition does not apply to vessels with special equipment for the purification of exhaust gases of ship power plants (EG SPP). The use of this Exhaust Gas Clean System (EGCS) will allow reducing the concentration of Sulphur compounds and solid particles in EG SPP (**only two toxicants**), as provided in MARPOL 73/78, Annex V, paragraph 4.1. The prohibition will not apply to vessels involved in research and the development of new systems to reduce emissions of harmful substances and compounds in EG SPP. “The adoption of the amendments will help us to preserve the environment and reduce the number of diseases and premature deaths due to air pollution by exhaust gases from ships,” said John Maggs, senior policy adviser, Seas at Risk and president of the International Clean Shipping Coalition (CSC), commenting on the results of the Session [2].

Methods and Materials

Heterogeneous catalytic method was used to neutralize toxic substances and compounds contained in EG SPP. To select the most selective and active catalysts, a flow-type ideal displacement unit was developed and applied, which included the following units:

- 1) preparation of a reaction mixture of a given composition;
- 2) catalytic reactor apparatus;
- 3) gas chromatographic analysis of initial reaction and post-reaction mixture;
- 4) cooling and condensation of the exhaust gas flow;
- 5) calculation of the degree of neutralization of toxic compounds and determining the activity of catalysts.

The experiments were conducted on the two oxide catalysts: ICT-12-8 and AOC-78-56 in Boreskov Institute of Catalysis as part of Siberian Branch of the Russian Academy of Sciences, fraction 1×1 mm (table 1). The study of the activity of the catalyst was carried out in running unit (reactor of ideal displacement) with a fixed catalyst.

The temperature was controlled by thermocouple; the temperature measurement was ranging between 20-450 degrees Celsius. The carbon monoxide content analysis were carried out by using the detector of the gas chromatograph at the inlet in the reactor apparatus and at the output from it. The CO concentration measurements were taken at least three times. The average value was considered as the measurement result.

Table 1

ICT-12-8 and AOC-78-56 catalyst characteristics

The catalyst	Chemical composition, mass %	Specific surface area, m ² /g
ICT-12-8 in the granules form	CuO – 10 Cr ₂ O ₃ – 10 Al ₂ O ₃ – 80	170
AOC-78-56 in the granules form	Co ₂ O ₃ – 11 Cr ₂ O ₃ – 6 Cr(+VI) no more than 0,05 SiO ₂ – 82,95	110

Results

The EG SPP are consisted of more than 200 harmful toxic components (for simplification we will consider 200 toxic compounds) which are carcinogenic, mutagenic, irritating and poisonous by their nature, relate to the 1-4 classes of dangerous impact on human's health. Furthermore, besides chemical pollution and toxicant conversion which lead to the range of ecological problems, for example, "greenhouse effect", "acid" rains, oxygen deficiency, the EG SPP possess high enthalpy. The temperature of EG SPP in the exhaust path is within 350-500 degrees Celsius, depending on the operating mode of the SPP, which in turn leads to the thermal pollution of the air basin. In connection with the factors mentioned above, from the standpoint of environmental safety, cleaning of EG SPP and reduction its temperature is an urgent problem [3].

The company Wartsila to reduce the emission of Sulphur dioxide from EG SPP offers the following technological directions – the transfer of maritime transport to the low-Sulfur fuel, the use of liquefied natural gas, scrubber cleaning [4]. In the directions mentioned above, Wartsila gives preference to the scrubber cleaning from Sulphur dioxide. In work [5] researches on scrubber cleaning from sulphurous anhydride are carried out and it is defined that the maximum degree of cleaning from SO_x makes 95 %, and from solid particles (soot) — 60 %. It remains unclear under what conditions the above results have been achieved, with or without circulation of the reactive absorbent, whether the degree of purification obtained is sufficient for the safe release of purified gases into the atmosphere.

In work [6] the analysis and generalization of use of catalysts for neutralization of toxic substances and connections is conducted.

In work [7] computational studies on the emission reduction components of “greenhouse” gases in the operation of the courts are conducted. Carbon dioxide, methane, nitrous oxide are the key components of “greenhouse” gases. The calculation was carried out on the condition that the average air temperature should not exceed 2 degrees Celsius in accordance with the Protocol of the Climate Summit (2015, Paris, France). The method of calculation of emission components of “greenhouse” gases released during combustion of marine fuel in the conditions of the regular route and port handling.

In work [8] as a result of survey of shipping companies and ship owners the most effective technologies which will allow to optimize Operational Coefficient of Energy Efficiency of Ships (OCEES) and to reduce considerably emission of carbon dioxide were revealed. The analysis of the possible use of alternative marine fuel, which will reduce carbon dioxide emissions and increase the OCEES.

However, it should be noted that the transfer of ships to alternative fuels will require significant modernization of SPP and large investments, considerable time for modernization.

In works [9] – [10] for the first time studies have been conducted to minimize operating OCEES when changing the main parameters of a real sea crossing – the distance of the transition, the mass of the load, speed of the vessel. On the basis of the developed mathematical model in these works the basic conditions for minimization of OCEES were formulated and, accordingly, recommendations on reduction of carbon dioxide emission – the main component of “greenhouse” gases were developed.

The cruise company “Carnival Corporation” [11] – [12] 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). EGCS technology works during sea crossings, 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 [2].

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

The main stages of EGCS [13]:

1. Cooling the EG SPP with the disposal of excess heat of the EG SPP.
2. Wet scrubber cleaning (absorption process) EG SPP from SO_x 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 SO_x compounds, alkali, solid particles in the marine environment.
5. The release of cleaned EG SPP from SO_x and solid particles into the atmosphere.

In our opinion, the basis of EGCS technology is the wet scrubber cleaning (stage 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, in 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 is discharged into the marine environment.

The flow diagram of EGCS technology is shown in figure 1.

Exhaust gas (pos. 16) after SPP (pos. 17) is supplied to the economizer (pos. 15), in which the EG temperature decreases below 50 degrees Celsius, 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 al-

774

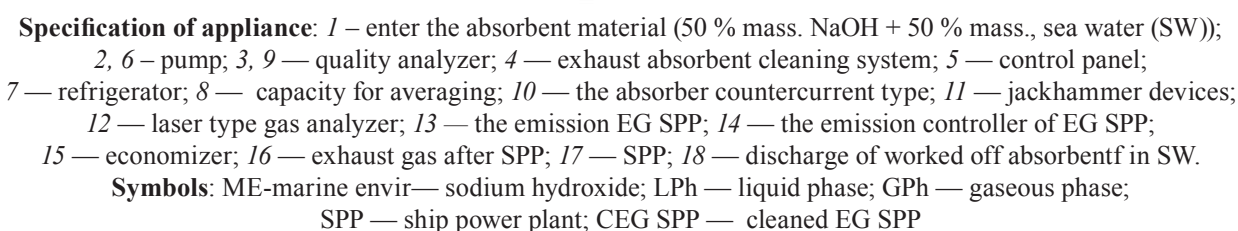


Fig. 1. The diagram of the EG SPP purification by «Carnival Corporation» company [11] – [13]

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

IMO aims to create a highly efficient, environmentally safe, trouble-free ship that meets the high level of Constructional CEES (CCEES) in the 2020-2025 years [14] – [16].

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 [3]:

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 degrees Celsius.
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 OCEES.

There is a brief description of the process below (fig. 2):

EG SPP from the main marine engine (1) at a temperature of 400 degrees Celsius 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 degrees Celsius enter the refrigerator-condenser (19), in which the temperature decreases to 25 degrees Celsius, into the scrubber (17), where sulfuric acid is formed, the latter is collected in a container (18).

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1. The contour of the condensate from the container (12) at a temperature of 25 – 45 degrees Celsius, is pumped (6) the condensate in the primary heat exchange circuit is heated to 100 degrees Celsius and is supplied to the main distribution tank (9), which is automatically displayed in the secondary circuit of the economizer (7), which is produced by the vapor pressure of 14 kgf/cm², is used to drive the steam turbine (16) and/or the production of electricity by a generator (15) or steam is supplied to steam turbine installation (11), where it is used as extra power for propulsive system of the vessel. After energy is transferred to the turbine (16 or 11), the exhaust steam is returned as condensate to the tank (12).

2. The air circuit-passes through the delivery part of the twin turbine, the heat exchanger for cooling the engine and fuel-air enters the marine engine.

For cooling the processed EG SPP to 15–25 degrees Celsius in the refrigerator condenser (19) and receiving additional economy of energy it is offered to use ship diesel fuel as the cooling agent.

In order to ensure the operation of the second stage of the process-catalytic neutralization of toxic components of EG SPP, studies have been carried out on a flow type unit for the selection of the most active and selective catalyst. In work [17] we have for the first time established that for a class of catalytic oxidation of toxic connections instead of the big nomenclature of harmful substances and connections it is possible to simplify the researches on the catalyst choice considerably, using as initial raw materials only carbon monoxide in mixture with air.

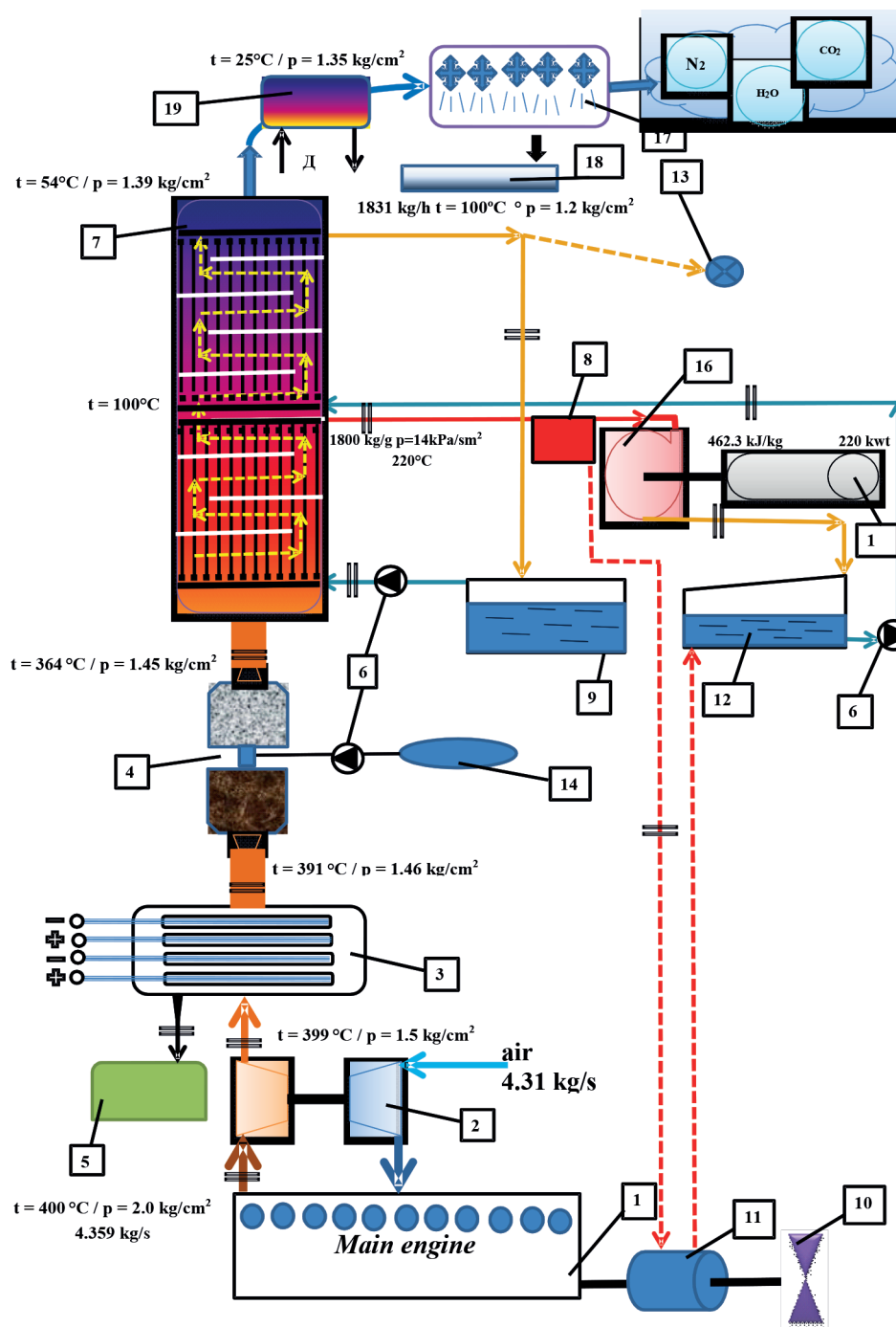


Fig. 2. Scheme of purification from toxic compounds of the EG SPP and utilization of heat of the EG SPP for a «OXL SAMURAI» ship [3]

The mass of catalyst which was loaded in the reactor ICT-12-8 was 90 mg. The degree of carbon monoxide conversion was changed from 28 % to 82 % (table 2, 3).

Table 2

Results of research on ICT-12-8 at the 11 cm³/s gas mixture flow

№	T, °C	Cco (input), mg/m³	Cco (output), mg/m³	Xco, %	K*, mm³/s × g	LnK
1	160	123	89	28	33,76	3,56
2	160	123	90	26	31,78	3,46
3	210	123	60	51	74,83	4,32
4	260	123	34	72	132,88	4,89

Table 3

Results of research on AOC-78-56 at the 11 cm³/s gas mixture flow

№	T, °C	Cco (input), mg/m ³	Cco (output), mg/m ³	Xco, %	K*, mm ³ /s × g	LnK
1	150	123	73,60	40,28	2,83	1,04
2	150	123	73,60	40,28	2,83	1,04
3	200	123	34,23	72,22	7,03	1,95
4	250	123	22,25	81,94	9,40	2,24

Note:

1. X_{co} is the degree of conversion of carbon monoxide, %.
2. K* is the rate constant of the chemical oxidation reaction of CO, mm³/s×g.

According to the study of the carbon monoxide oxidation on ICT-12-8 and AOC-78-56 catalysts following points should be mentioned:

1. The oxidation rate of carbon monoxide on ICT-12-8 and AOC-78-56 catalyst increases with an increase in temperature.

2. The ICT-12-8 catalyst is the most active one, because at equal temperatures the rate constant of a chemical reaction on ICT-12-8 catalyst is much more, than on the AOC-78-56 catalyst.

3. The work on the ICT-12-8 catalyst allows to save catalyst mass which is loaded in the reactor, meanwhile operations under the same conditions on the AOC-78-56 catalyst require the 15 times more catalyst mass loaded in than the used on the ICT-12-8 catalyst. It indicates the predominant activity of the ICT-12-8 catalyst.

Therefore, for catalytic neutralization of toxic components of EG SPP (second stage), the ICT-12-8 catalyst, equipped in reactors, is recommended (fig. 3, 4).

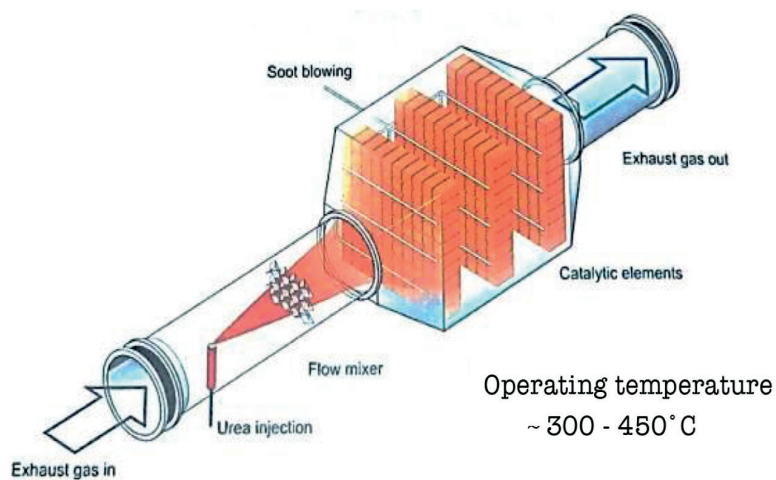
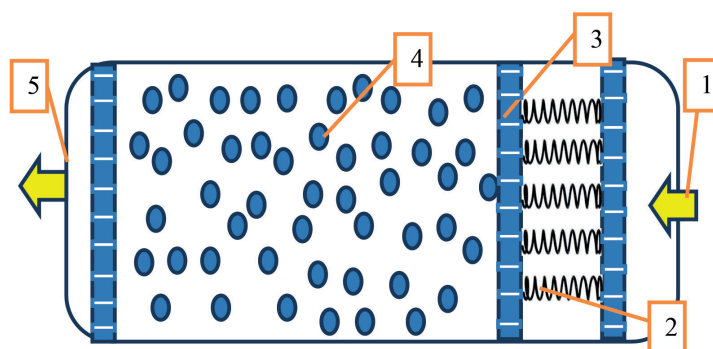


Fig. 3. Reactor apparatus with NO_x reduction catalyst of the block type



1 — input collector of the original EG SPP, 2 — compensation devices,
3 — movable plate under the effect of the compensation devices, 4 — catalyst granules,
5 — output collector of the cleaned EG SPP

Fig. 4. Reactor apparatus with a oxidation catalyst [3]

The structure of distribution of the EG SPP recovered heat is presented in figure 5.

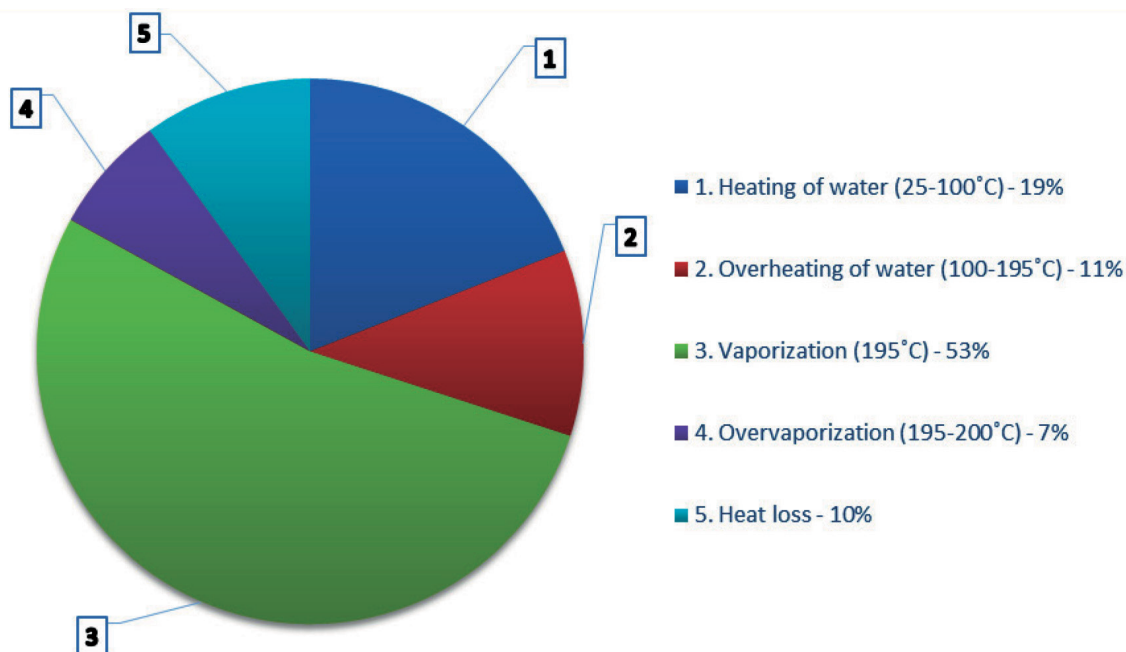


Fig. 5. The degree of EG SPP heat usage (%)

Most of the recuperated heat (60 %) is converted into process steam of high parameters, 30 % – for water heating, heat losses are comprised 10 %.

On the basis of the carried out researches and calculations layout decisions on placement of complex installation “cleaning – utilization of heat – cleaning” EG SPP in machine-boiler room office in relation to the real motor ship “OXL SAMURAI” are developed.

The developed technology is designed to be implemented directly on board the vessel and allows, in comparison with known proposals, to solve the following main issues of navigation in the framework of improving the energy efficiency and environmental safety of the vessel/voyage, minimizing OCEES:

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 utilization 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.

Discussion

The analysis and generalization of technical solutions for purification of the EG SPP of Carnival Corporation company (EGCS) and suggested by our group of specialists is conducted (table 4).

Table 4

Comparison of the purification and heat utilization systems of EG SPP

№	Indicators	Carnival Corporation	Variation		New technological solution	Variation	
			+	-		+	-
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		✓	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 environment	P	
5	Heat utilization of EG SPP	Economizer is used	✓		Two-circuit heat recovery system is used	✓	
6	Payback period of the installation	Three years	✓		Less than three years	✓	
7	Operating mode of the installation	In ports, when maneuvering and sea crossings	✓		In ports, when maneuvering and sea crossings	✓	
8*	Prevented damage to the air basin, \$/year	2 000 000		✓	10 000 000	✓	
9	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	✓	
	TOTAL		Three (+) Six (-)			Nine (+)	

Note. Calculations on item 8 are made for mv "OXL SAMURAI".

As a result of technical and economic analysis of two technological schemes of the 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 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 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 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 Carnival Corporation.

Conclusion

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 (fig. 1). 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. (fig. 2) is suggested. A comparison of the two processing schemes is done according to nine 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.

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ИНФОРМАЦИЯ ОБ АВТОРАХ

Леонов Валерий Евгеньевич —

доктор технических наук, профессор
Херсонская государственная морская академия
73000, Украина, Херсон, проспект Ушакова, 20
e-mail: leonov_v_e@i.ua

Сердюк Александр Дмитриевич —

второй помощник капитана теплохода
m/v “Maria-1”
Херсонский морской торговый порт
73000, Украина, Херсон, ул. Потемкинская, 3
e-mail: alexanderserdyuk@ukr.net

INFORMATION ABOUT THE AUTHORS

Leonov, Valeriy Ye. —

Dr. of Technical Sciences, professor
Kherson State Maritime Academy
20 Ushakova Avenue, Kherson, 73000, Ukraine
e-mail: leonov_v_e@i.ua

Serdyuk, Alexander D. —

Second officer, m/v “Maria-1”
Kherson sea port
3 Potemkinskaya Str., 73000,
Kherson, Ukraine
e-mail: alexanderserdyuk@ukr.net

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