MACHINE BUILDING

Original article
UDC 621.313.12-883:629.12.037.4-83
https://doi.org/10.23947/2541-9129-2022-4-51-60

On the Prospects for the Development of Marine Propulsion Systems for Their Compliance with the Environmental Standards of the International Convention

Aleksandr N. Rak
Kamchatka State Technical University (Petropavlovsk-Kamchatsky, Russian Federation)
lion15ua@rambler.ru

Abstract
Introduction. The shipping industry pays great attention to the safety of man-made and natural systems. At the same time, increased requirements are imposed not only on the quality of the fuel composition, but also on exhaust emissions. Currently, Annex VI of the MARPOL-73/78 Convention has been ratified by many of its signatories. The compliance with this document requires that engine emissions comply with the specified NO_x level limits. Until recently, such rules were mainly applied in the Baltic and North Seas, but over time, the compliance with environmental standards will affect other areas of navigation.

The work objective is to show through the study of modern technical solutions that we need an integrated approach to solve practical environmental problems, which will allow developing rational schemes of modern marine propulsion systems, taking into account their compliance with the safety requirements of technogenic and natural systems.

Materials and Methods. The methods and recommendations given in open sources and corresponding to the requirements of the International Maritime Organization (IMO) were used in the work. The experience of leading foreign firms and domestic enterprises in terms of modern design solutions that will reduce ship emissions to acceptable limits is analyzed and summarized.

Research Results. The issues related to the study of factors influencing the development of rational schemes of ship propulsion systems, taking into account their current level of development, pricing policy and the compliance with the environmental requirements, are considered. It is shown that one of the effective ways to reduce NO_x emissions is the installation of a selective catalytic reducer (SCR) on the main engine, and the use of efficient and innovative power generation technologies to reduce technogenic emissions. In the medium term, the transition to gaseous fuels is predicted, and in the long term – to hydrogen technologies.

Discussion and Conclusion. Possible technical solutions to reduce emissions of nitrogen oxides by installing selective catalytic reducers on the main marine engines are presented. It is established that one of the promising areas of development are diesel-electric propulsion systems. It is shown that in the medium term, due to stricter environmental requirements, there will be a transition to gaseous fuels, which will allow us with minor structural changes to increase the power of the existing main engines and to reduce emissions of nitrogen oxides and greenhouse gases. In the long term, the transition to hydrogen fuel cells with continuous improvement of the technological level of production, storage and development of the corresponding infrastructure can be considered as a real alternative to hydrocarbon fuels in marine transport.

Keywords: main engines, selective catalytic reducer, electric propulsion system, solid-state generator, battery system, combined system, fuel.

For citation. Rak A. N. On the Prospects for the Development of Marine Propulsion Systems for Their Compliance with the Environmental Standards of the International Convention MARPOL-73/78. Safety of Technogenic and Natural Systems, 2022, no. 4, pp. 51–60. https://doi.org/10.23947/2541-9129-2022-4-51-60

Introduction. Safety requirements of technogenic and natural systems in marine transport attract attention to exhaust emissions. Currently, Annex VI of the MARPOL-73/78 Convention [1–3] has been ratified by many of its signatories, and, consequently, all engines currently in operation must meet the required NO_x emission levels. For example, in the Baltic and North Sea regions, a reduction in port fees is used as an incentive to use low-sulfur fuels. The use of modern technologies should ensure the required permissible level of emissions and further improvement and development in order to adapt to such restrictions [1–3].

Emission limits may require the development of new technologies, but then the chosen solution will not necessarily be optimal. The systems operating on the built vessels will be used on average for at least 25 years, which corresponds to the service life of the vessel. Such methods of reducing exhaust emissions as selective catalytic reduction and water emulsification are already used on two-cycle engines of some well-known manufacturers, for example, MAN B&W.

Until recently, NO_x and SO_x were the main focus of environmental services, but now more attention is paid to exhaust gas components such as HC, particulate matter, CO and CO_2.

The work objective is to show through the study of modern technical solutions that an integrated approach is needed to solve practical environmental problems, which will allow developing rational schemes of modern ship propulsion systems to meet the safety requirements of technogenic and natural systems.

Materials and Methods. In this work, the calculated ratios given in open sources and corresponding to IMO requirements [1–3] were used. The author's research and observations on reducing the amount of greenhouse gas (GHG) emissions, taking into account the operating modes of generating plants, are given in [4]. The experience and recommendations of leading foreign firms and domestic manufacturers of marine mechanical and electromechanical equipment, their latest and promising developments in terms of layout arrangement and the development of individual elements were taken into account [5, 6].

Results. To assess the prospects for the possible development of marine propulsion systems, let us consider its generalized scheme (Fig. 1).

In general, the ship's propulsion system has a main engine (ME), diesel generators (DG) and a shaft generator/engine (SG/E). As an electric propulsion installation (EPI), rudder propellers (RP) and "Azipod" systems are used; reduction gearing (RG); solar panels (SP); batteries (B); fuel cells (Fc) (hydrogen or ammonia according to the hydrogen principle of operation); central switchboard (CS); thruster (T); frequency converter (FC) and fuel tanks (FT).

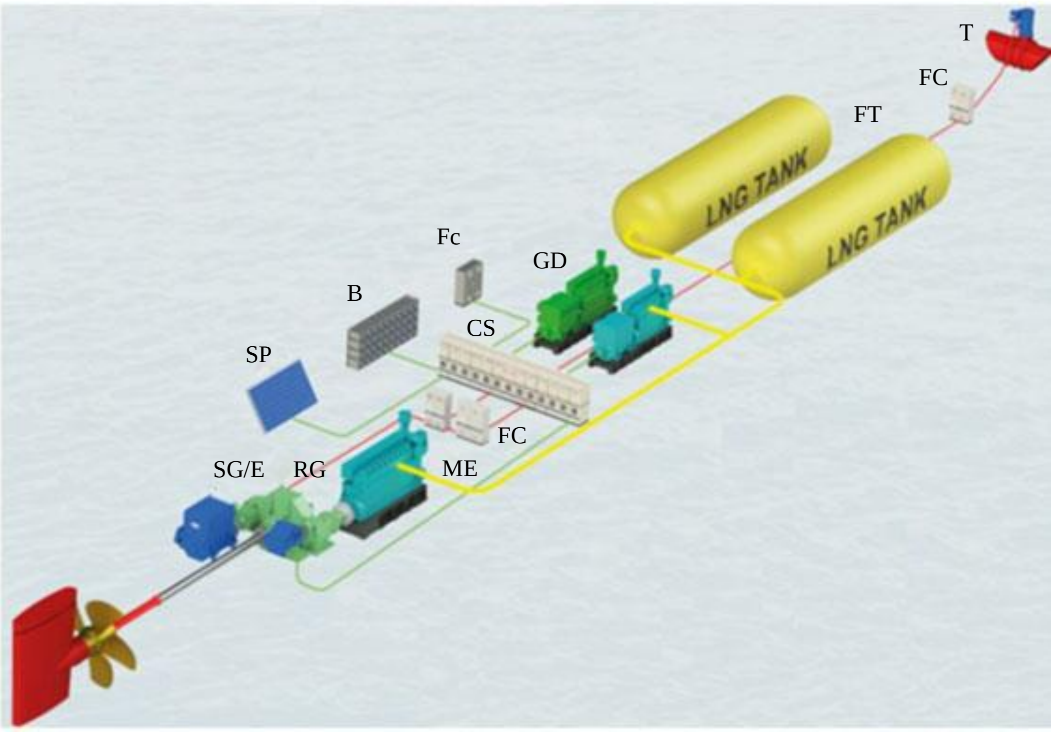

Fig. 1. Generalized ship propulsion system

To carry out research, it is necessary to determine the prime movers. Figure 2 provides typical efficiency and fields of application of prime movers in accordance with ISO 3046

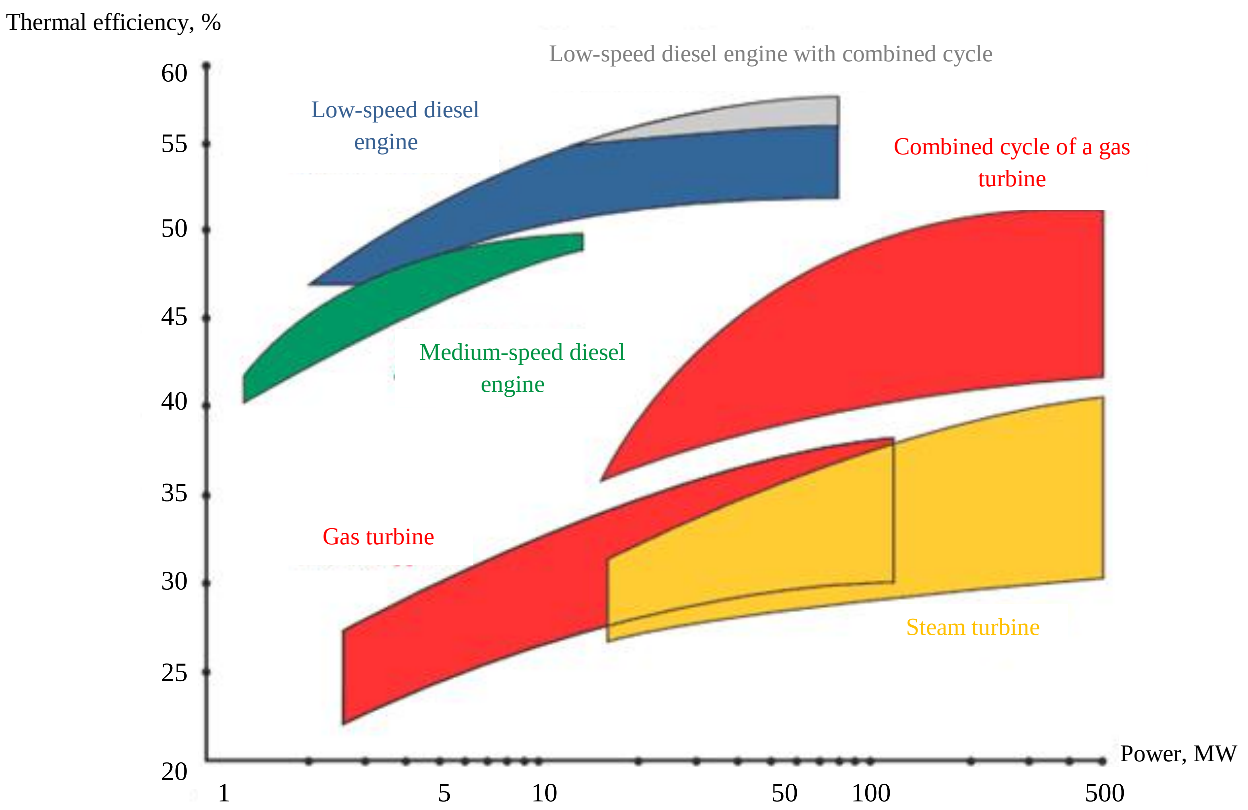

Fig. 2. Typical efficiency and fields of application of prime movers in accordance with ISO 3046

According to [1] the ME power is determined as follows:

$$N = a \cdot D_{wt} + b, \quad (1)$$

where *a*, *b* — coefficients values of the equation for different types of vessels; D_{wt} — vessels deadweight, thousand tons. The values of components *a*, *b* for ratio (1) are given in Table 1.

Currently, the choice of any of the methods of movement (diesel-mechanical, diesel-electric, combined with the use of batteries) will depend on its efficiency, determined by the efficiency factor.

Table 1

Parameters *a* and *b*, required to determine the minimum power of the main engines of various types of vessels [1]

№	Types of vessels	*a*	*b*
1	Bulk carriesr DWT (less than 145000 t)	0.0763	3374.3
	Bulk carriers DWT (more than 145000 t)	0.049	7329
2	Bulk carriers DWT (less than 75825 t)	0.0606	4195.2
	Bulk carriers DWT (more than 275825 t)	0.0273	13366.0
3	Gas carriers DWT (less than 29025 t)	0.23	793.6
	Gas carriers DWT (more than 129025 t)	0.0097	29224.0
4	Container carriers DWT (less than 92186 t)	0.5843	0.0
	Container carriers DWT (more than 92186 t)	0.054	48886.0
5	Liquid bulk carriers	0.0602	5495.5
6	Vessels for general cargo transportation	0.152	2399.5
7	Refrigeration	0.9809	-1831.2

One of the important environmental indicators is the amount of NO_x emissions from marine vessels. This indicator is shown in Figure 3.

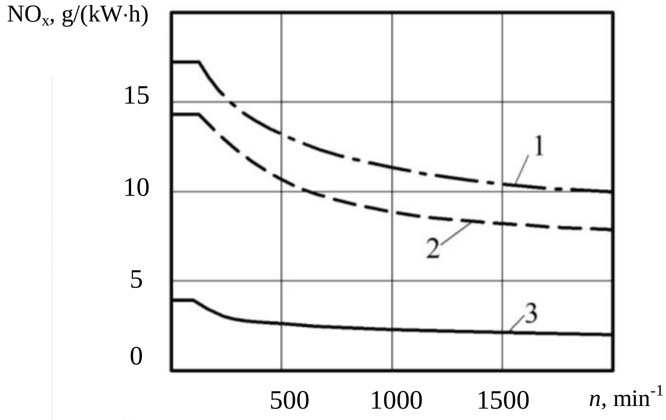

Fig. 3. NO_x emission standards from marine vessels:
1 — level I (ME > 130kW, new vessels since 2000); 2 — level II (ME > 130kW, new vessels since 2011);
3 — level III (ME > 130kW, new vessels since 2016 in emission control areas
Emission control areas (ECA): The West and East coasts of the USA, the Nordic countries)

As follows from Fig. 3, at rotation speeds of 100 rpm, which is typical for low-speed ME (LSE) produced by MAN B&W and WÄRTSILÄ-SULZER, the level of NO_x emissions remains constant. For a gas turbine with a rotation speed of 250 rpm, which is typical for Mitsubishi, emissions are significantly reduced. The greatest reduction is achieved at rotation speeds in the range of 350–2500 rpm. (This range is characteristic of medium- and high-speed ME (MSE and HSE, respectively), which is a weighty argument for switching to the EPI [4]).

Currently, one of the ways to reduce NO_x emissions is to install a selective catalytic reducer (SCR) on the ME. Basic and promising schemes of the SCR installation are shown in Fig. 4.

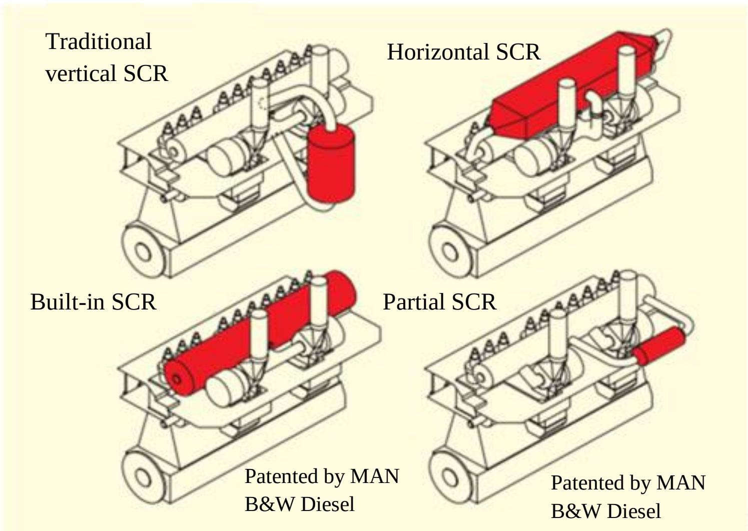

Fig. 4. Basic and promising schemes for the installation of a selective catalytic reducer

The efficiency of installation of selective catalytic reducers is shown in Table 2.

Table 2

Efficiency of installation of selective catalytic reducers

Engine type	Operating mode	Emission type	Efficiency indicator, %
6S35MC	only movement	NO_x reduction	above 93
6S50MC			93–95
9K80MC-Gl-S	movement and generation		above 93
4L35MC-S			above 93
2x7K60MC-S			above 93

Figure 5 shows a quantitative assessment of NO_x emissions depending on the load on diesel when switching to a water-fuel emulsion [6].

In addition to restrictions on NO_x emissions, new requirements have come into force since 2020, seriously limiting the permissible level of emissions of sulfur oxides, nitrogen and GHG in the Baltic, Northern and Mediterranean Seas (Fig. 6) [1–3].

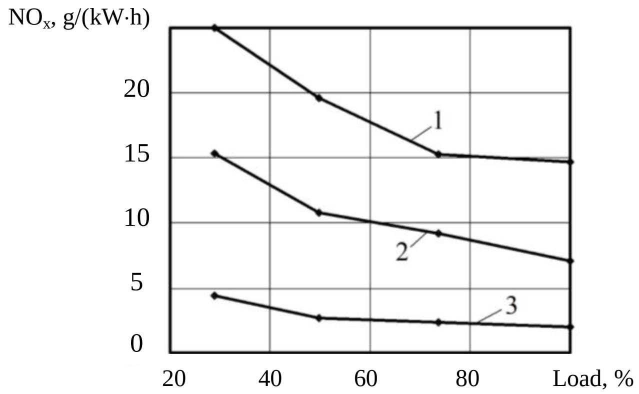

Fig. 5. Reduction of NO_x emissions during the transition to a water-fuel emulsion [6]:
1 — diesel fuel; 2 — methanol; 3 — methanol with water

The expansion of marine environmental monitoring areas and the adoption of measures to reduce the anthropogenic impact on the environment require shipowners to make cardinal decisions on this issue. At the same time, there is no universal approach and universal technical solutions for specific types of ships.

Fig. 6. Ship emissions control areas in North America and Northern Europe [3]

Reduction of GHG emissions should be determined in accordance with the amendment to Annex VI to MARPOL 73/78, which entered into force on January 1, 2013, using the Energy efficiency index (EEDI), which characterizes the energy capabilities of a technical means at the lowest cost of resources for energy generation and is determined in accordance with [1]:

$$EEDI = \frac{\left(\prod_{j=1}^{M} f_j\right)\cdot\left(\sum_{i=1}^{nME} P_{ME(i)}\cdot C_{FME(i)}\cdot SFC_{ME(i)}\right)+\left(P_{AE}\cdot C_{FAE}\cdot SFC_{AE}\right)+}{f_i\cdot f_c\cdot Capacity\cdot v_{ref}\cdot f_w}$$

$$\frac{+\left(\left(\prod_{j=1}^{M} f_j\cdot\sum_{i=1}^{nPTI} P_{PTI(i)}-\sum_{i=1}^{neff} f_{eff(i)}\cdot P_{AEeff(i)}\right)\cdot C_{FAE}\cdot SFC_{AE}\right)-\left(\sum_{i=1}^{neff} f_{eff(i)}\cdot P_{eff(i)}\cdot C_{FME}\cdot SFC_{ME}\right)}{f_i\cdot f_c\cdot Capacity\cdot v_{ref}\cdot f_w}, \quad (2)$$

where *SFC* — specific fuel consumption of the engine, g/kW h; C_F — dimensionless conversion factor between fuel consumption in the engine and CO_2 emissions determined by the carbon content in a particular fuel (grams of CO_2/ grams of fuel). Information on the carbon content in various fuels and specific CO_2 emissions is presented in [1, 3] and Table 3; P_{MEi} — power indicator of each main engine equal to 75 % of its rated power minus the power consumed by the generator (if available); P_{AE} — indicator of the required power of auxiliary engines to provide electricity at maximum load of the vessel; P_{PTI} — an indicator equal to 75 % of the rated power consumed by each electric propulsion motor, taking into account mechanical losses in it and excluding losses in the generator; P_{AEeff} — an indicator of reduction of electric energy due to the use of energy-efficient technologies (use of ME waste heat) which in [1] are called innovative.

It is noted in [4] that the stable operation of these systems is possible only at the ME rotational speed of 40–50 % of the nominal; P_{eff} — an indicator of reducing the ME power due to the use of innovative technologies in a propulsive installation at 75 % of the power of the ME (photovoltaic installations, fuel cells, wind generators). It is shown in [4] that the use of innovative technologies makes it possible to increase the energy efficiency index, but they do not have a decisive influence on their choice as the main sources due to their low power of tens to hundreds of kW; f_i — a factor that takes into account the need to meet the requirements for limiting the vessel's capacity, for example, the requirements that apply to ice-class vessels; f_j — a corrective factor that takes into account the specific design of ship elements, for example, ice-class vessels; f_w — a dimensionless coefficient that takes into account the speed reduction in a certain unfavorable sea condition, depending on the height and frequency of the wave, and also on the wind speed; f_{eff} — the coefficient of availability of each innovative technology; V_{ref} — the speed of the vessel measured in deep water, taking into account the corresponding capacity (deadweight or gross capacity, depending on the type of vessel). For more details on the calculation of the coefficients f_i, f_j, f_w and f_{eff}, see [2].

Table 4 provides a comparative analysis of the use of various types of fuel for marine ME and battery systems, as well as a reduction in emissions compared to fuel oil for level II [5]

Transition to LPG and LNG will increase the power of the internal combustion engine with minor changes to the fuel supply system according to expression [6]:

$$N_{\text{НОМ.ГАЗ}} = N_{\text{НОМ.ДИЗ}} \cdot \left(\frac{C_{\text{F,ДИЗ}} \cdot \text{НТС}_{\text{ГАЗ}}}{C_{\text{F,ГАЗ}} \cdot \text{НТС}_{\text{ДИЗ}}} \right)^{\frac{3}{2}}, \tag{3}$$

where $N_{НОМ.ДИЗ}$ — nominal power on diesel fuel, kW; C_F — dimensionless coefficient between fuel consumption in the engine and CO_2 emissions determined by the carbon content in a particular fuel (g CO_2/ g fuel); HTC — the lowest calorific value of fuel, kJ/kg.

Table 3

Carbon content in various fuels and specific CO_2 emissions [2]

Fuel type	Reference	The lowest calorific value, kJ/kg	Carbon content	C_F, t CO_2/t fuel
Diesel/gas oil	ISO 8217, grades from DMX to DMB	42.7	0.8744	3.206
Light liquid fuel (LLF)	ISO 8217, grades from RMA to RMD	41.2	0.8594	3.151
Heavy liquid fuel (HLF)	ISO 8217, grades from RME to RMK	40.2	0.8493	3.114
Liquefied petroleum gas (LPG)	propane	46.3	0.8182	3.0
	butane	45.7	0.8264	3.03
Liquefied natural gas (LNG)		48	0.75	2.75
Methanol		19.9	0.375	1.375
Ethanol		26.8	0.5217	1.913

Table 4

Comparison of alternative fuels for marine internal combustion engines and battery systems

Fuel types and sources	Specific energy, MJ/kg	Energy density, MJ/l	Corresponding capacity, m^3	Discharge pressure, bar	Injection pressure, bar	Emission reduction compared to fuel oil in accordance with Level II		
Fuel oil (HFO)	40.5	35	1.0	7-8	950	SO_x	NO_x	CO_2
Liquefied gas (LNG-162 °C)	50	22	1.59	300/ Methane 380/ Ethane	300/ Methane 380/ Ethane	90–99 90–97	20–30 30–50	24 15
Liquefied gas (LPG (propane/butane)	42	26	1.35	50	600–700	90-100	10–15	13–18
Methanol (wood alcohol)	18	15	2.33	10	500	90-97	30–50	5
Ethanol	26	21	1.75	10	500	-	-	-
Ammonia (liquefied -33 °C)	18.6	12.5	2.8	50	600–700	-	-	-
Hydrogen (liquefied — 253 °C)	142	10	3.5	-	-	-	-	-
High-energy marine battery system	0.5	0.54	64.8	-	-	-	-	-
Tesla 2170 elements	0.8	2.5	14.0	-	-	-	-	-

Let us touch upon the issue of hydrogen fuel. Hydrogen is not found in nature in in its pure form and it can be obtained from gaseous and liquid hydrocarbons or from water. These are the two most common and commercially important methods of hydrogen production [7]. For the successful implementation of the project, it is necessary to solve a number of problems. In order for fuel cells to provide 3 MW of power for 48 hours, about 68 m^3 of liquid hydrogen is required, which means much more storage space than for diesel fuel. To avoid leaks, special pipelines are required, and the hydrogen itself must be stored at a temperature below -253 °C. Figure 7 shows a hydrogen-air battery of BTE-P fuel cells with a capacity of 50.0 kW for megawatt-class power stations (Photo by: Krylov State Research Centre), and Figure 8 shows a marine hybrid power plant based on BTE-84 batteries with a capacity of 60 kW (Photo by: TSNII SET).

Currently, one of the pioneers of the program for testing marine internal combustion engines running on pure hydrogen is the Wärtsilä company (Finland). The company's concept is based on a combination of liquefied natural gas with steam to produce hydrogen and CO_2 [8]

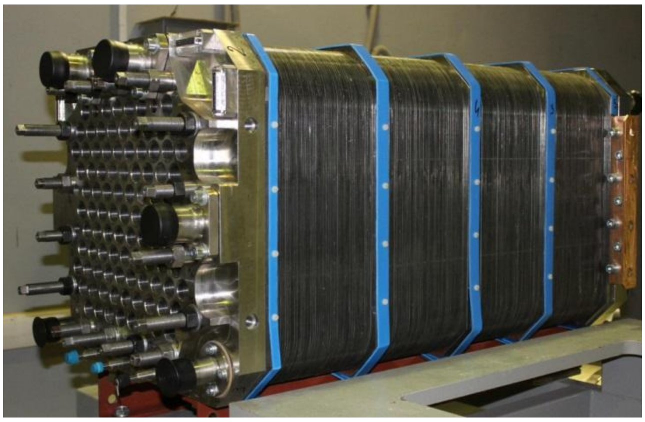

Fig. 7. Hydrogen-air battery of BTE-P fuel cells with a capacity of 50 kW for megawatt-class power stations [9]

Fig. 8. Marine hybrid power station based on BTE-84 batteries with a capacity of 60 kW/ [10]

One of the important indicators when choosing diesel engines is its price. It is these data that are the most necessary at the stage of the initial study of a project, although they are "limited" or "protected" in nature. In [11], a formula is proposed for calculating the price of marine and industrial diesel engines, based on the main functional characteristics:

$$Ц = К \cdot \frac{N_e^{0,073} \cdot T^{0,086} \cdot M^{0,763}}{g_e^{2,446} \cdot g_m^{1,138} \cdot S^{0,466}}, \qquad (4)$$

where N_e — nominal effective power of the engine, kW; M — mass, kg; g_e — specific fuel consumption for the rated power mode, kg/(kW·h); g_m — specific oil consumption for the rated power mode, kg/(kW·h); S — serial production, pcs.; K — proportionality coefficient equal to 0.023; T — resource to the first reassembly, h.

The exponents characterize the weight of each argument in the formula. The order of the values included in (4) is given in the relevant regulatory and technical documentation. Information on the specific fuel consumption of LSE, MSE and HSE is presented in [4].

Analysis [5] shows that currently a significant progress in the T development is associated with the use of lithium-ion batteries. But, despite all the attractiveness from an environmental point of view, it has a limited character due to significant weight, size and price indicators. At the same time, they can be used in combined EPI both together with diesel generator installations and individually.

Table 5

Specific mass, volume and price of large 1MW·h heavy lithium-ion batteries

Key indicators	System level	Group level	Modular level	Element level
Specific mass, kg/kW·h	11–30	7–28	6–24	6–8
Specific volume, 1/kW	12–35	10–12	7–10	1.5–2.5
Specific price, USD/ kW·h	500			200–250

Currently, MAN B&W has developed a "solid-state" generator MAN Hybrid EcoAux (Fig. 11). Its technical characteristics are given in [12] and Table 6.

a) *b)*

Fig. 11. "Solid-state" generator MAN Hybrid EcoAux: *a* — appearance; *b* — generator mix: 1 — energy storage (ES); 2 —transducer; 3 — protection system; 4 — bidirectional inverting converter; 5 — filter; 6 — separation transformer; 7 — motor-driven switch

Table 6

Technical characteristics of MAN Hybrid EcoAux "solid-state" generators

Standard size	Mains voltage, V	Frequency, Hz
625 kW·h (5C)*	400-690	50 or 60
405 kW·h (5C)	400-690	50 or 60
270 kW·h (5C)	400-690	50 or 60
135 kW·h (5C)	400-690	50 or 60

* C — charge rate. C = 12 min., i.e. 5C=5·12=60 min.

Possible layout solutions for the placement of electromechanical equipment in the engine room in the case of the use of EPI when powering the internal combustion engine from gaseous sources are given in [6, 8], and for systems that include batteries in [5, 13].

Discussion and Conclusion.

1. One of the effective ways to improve safety of technogenic and natural systems by reducing NO_x emissions is the installation of selective catalytic reducers (SCR) on the ME, which can reduce the amount of NO_x emissions to 93–98 %, depending on the design used. The transition to LPG and LNG will increase the capacity of the internal combustion engine by 22.6–49.6 % with minor changes to its design.

2. The existing innovative technologies for the production of electrical energy on board, such as solar panels, wind generators, etc., have an insignificant power of about 102 kW. The operation of the heat recovery system and the shaft generator begin to work steadily only at a rotation speed of 40-50% of the nominal. They have a significant impact on the energy efficiency index, and, consequently, on the reduction of CO_2 emissions. Thus, they cannot claim to be the driving motors of generators. Diesel generators with hydrocarbon fuels will remain the main source of energy production for the ME in the near future.

3. The use of battery systems alone is limited due to significant weight and size and price indicators. Their capabilities can be significantly expanded in combination with diesel generators. The use of MAN Hybrid EcoAux "solid-state" generators opens up wider prospects in this matter.

4. In the long term, hydrogen fuel cells can be considered as a real alternative to hydrocarbon fuels, but economic factors will limit the deployment of new expensive infrastructure. However, if hydrogen is produced directly on board, this alternative to diesel fuel becomes much more attractive for investors and users.

References

1. Air pollution and energy efficiency. Background information to document MEPC 64/4/13. Submitted by the International Association of Classification Societies (IACS), 2012. Available from: https://www.researchgate.net/publication/315642914_Background_information_to_document_MEPC_64413 (accessed 30.03.2020).

2. MARPOL. Book III, revised Annex VI to MARPOL "Rules for the Prevention of Air Pollution from Ships". Electronic fund of legal and regulatory documents. Available from: http://docs.cntd.ru/document/499014496 (accessed 30.03.2020). (In Russ.).

3. Guidelines on the Application of the Provisions of the International Convention MARPOL 73/78. ND No.2-030101-026. Russian Maritime Register of Shipping. Saint-Petersburg, 2017. 163 p. (In Russ.).

4. Trudnev S. Yu., Rak A. N., Marchenko A. A. Sudovye avtomatizirovannye elektroenergeticheskie sistemy: Sudovye istochniki elektricheskoi energii. Chast' I. Novokuznetsk: Znanie-M, 2021. 188 p. (In Russ.).

5. MAN Energy Solutions. Batteries on board ocean-going vessels. Available from: https://www.man-es.com/docs/default-source/marine/tools/batteries-on-board-ocean-going-vessels.pdf (accessed 22.03.2020).

6. MAN Energy Solutions. MAN B&W ME-LGIP dual-fuel engines. Available from: https://www.man-es.com/marine/products/planning-tools-and-downloads/technical-papers/2 (accessed 22.03.2021).

7. Radchenko R. V., Mokrushin A. S., Tyulpa V. V. Vodorod v energetike: ucheb. posobie. Ekaterinburg: Ural University Publishing house, 2014. 229 p. (In Russ.).

8. Wärtsilä razrabatyvaet sistemu dlya proizvodstva vodorodnogo topliva na bortu korablei. Available from: https://building-tech.org/Tekhnologii/wärtsilä-razrabativaet-systemu-dlya-proyzvodstva-vodorodnogo-toplyva-na-bortu-korabley (accessed 22.03.2022). (In Russ.).

9. V 2023 godu my smozhem predstavit' pervoe polnotsennoe sudno na vodorodnom toplive. Available from: https://www.korabel.ru/news/comments/v_2023_godu_my_smozhem_predstavit_pervoe_ polnocennoe_sudno_na_vodorodnom_toplive.html (accessed 22.03.2022). (In Russ.).

10. Suda na vodorode — uzhe real'nost'. Available from: https://www.korabel.ru/news/comments/vodorod_na_flote_uzhe_davno_ne_fantaziya_kak_v_rossii_razvivaetsya_vodorodnaya_energetika.html (accessed 22.03.2022). (In Russ.).

11. Dorokhov A. F., Provatar A. G., Vorobyyov A. V. Quality and reliability of marine diesel engines. Vestnik of Astrakhan State Technical University. Series: Marine engineering and technologies. 2015;2:48–55. (In Russ.).

12. MAN Energy Solutions. MAN Hybrid EcoAux. Available from: https://www.man-es.com/docs/default-source/document-sync/man-hybrid-ecoaux-eng.pdf?sfvrsn=98d91b1c_0 (accessed 22.03.2022).

13. Gutarevich V. O., Ryabko K. A., Ryabko E. V., Zakharov V. A. Review of structural battery designs used on mine electric locomotives. News of the Higher Institutions. Mining Journal. 2020;2:109–118. (In Russ.).

Received 29.09.2022.
Revised 10.10.2022.
Accepted 10.10.2022.

About the Author:

Rak, Aleksandr N., Associate professor, Department of Technological Machines and Equipment, Kamchatka State Technical University (35 Klyuchevskaya Str., Petropavlovsk-Kamchatsky, 683003, RF), Cand. Sci. (Eng.), ORCID, lion15ua@rambler.ru