ISSN: 1231-4005
e-ISSN: 2354-0133
DOI: 10.2478/kones-2019-0099

TECHNICAL AND ECOLOGICAL ANALYSIS OF DIFFERENT SOLUTIONS OF THE POWER SUPPLY OF A MARINE DIESEL ENGINE

Rafał Krakowski

Gdynia Maritime University, Faculty of Marine Engineering
Morska Street 83, 81-225 Gdynia, Poland
tel.: +48 58 5586398
e-mail: r.krakowski@wm.umg.edu.pl

Abstract

The article contains provisions on the prevention of sea pollution by ships, including, inter alia, the International Convention for the Prevention of Pollution from Ships, developed in 1973 (MARPOL). The convention aims to protect the marine environment from oil and its derivatives. Special areas, where extraordinary measures have been taken to prevent sea pollution, due to the intensity of ship traffic and the greater threat of damage to the marine environment have also been presented. In the further part of the article, the applicability of various pro-ecological solutions, i.e. the use of catalysts, low-sulphur fuels, and in the case of using residual fuels – exhaust gas scrubbers were described. In the main part of the article, a technical and ecological analysis was made. In addition, difficulties resulting from the use of pro-ecological solutions were described. The costs of using low-sulphur fuel meeting the emission standards, installing the scrubber and modification of the natural gas combustion unit were compared with the assumption of ten years of passenger-car ferry sailing. Then the problems that individual solutions create were shown. In the final part of the article, alternatives to those described, i.e. the liquefied natural gas (LNG) power supply, electric and hydrogen drives were presented.

Keywords: *technical analysis, special areas, exhaust gas scrubbers, alternative drives*

1. Introduction

The development of technology throughout history has always been aimed at facilitating human life. There is also a significant technological leap in shipbuilding. Unfortunately, this progress has its price. It is the degradation of the natural environment. Marine engines produce large amounts of toxic compounds into the atmosphere [14]. The most common is heavy residual fuel, which during the combustion reaction in the engine emits mainly sulphur oxides (SO_x), nitrogen oxides (NO_x) and carbon dioxide (CO_2). To reduce the impact of human activities in the seas and oceans, the International Maritime Organization (IMO) has introduced Emission Control Areas (ECAs) [16]. Emission Control Areas is sea areas in which stricter controls were established to minimize airborne emissions from ships as defined by Annex VI of the 1997 MARPOL Protocol. The easiest way to meet the limits of emissions of toxic compounds to the atmosphere is to switch from heavy fuel to a more expensive Diesel Oil with a reduced sulphur content. The disadvantage of this one is, unfortunately, the higher price and the greater wear of the mechanical components of the engine. Another option is the assembly of flue gas scrubber. However, this solution is expensive and it is not always possible to mount it on an existing ship. Another alternative is the adaptation of internal combustion engines to liquefied natural gas (LNG), because the gas supply significantly reduces the emission of harmful compounds into the atmosphere and fuel is cheaper [9]. More and more attention is paid to alternative ways of powering the fleet. When it comes to, for example, innovative ways of powering ferries, it must be not only competitive in terms of cost, but also ecologically. Both criteria can be met by hydrogen ferries. In addition, there will be more and more electrically powered units operating plug-in hybrid technologies. In this case, the batteries can be charged both when connected to shore power, as well as when the ship's engines are operating [19]. Slowly, it is also introduced to the operation of ships powered by only electricity stored only on the ship, and not produced on board [5, 20].

2. Special areas and regulations on the prevention of sea pollution by ships

After the ecological disaster of the SS Torrey Canyon supertanker in 1967 and MT Amoco Cadiz in 1977, it was recognized that regulations are insufficient to ensure the safety of the environment. Consequently, in 1973, the International Convention on the Prevention of Pollution from Ships (MARPOL) was developed and presented. The arrangements were modified and the additional attachments entered into force, as soon as they have been accepted by a specific number of countries. Annex I came into force in 1983 and aims to protect the environment against crude oil and its derivatives. It consists of provisions for fuel and cargo operations and presents permitted ways to remove water contaminated with oil-derived substances. Even more rules that are stringent apply in special areas (Fig. 1). The special area means maritime area, where it is desired to apply extraordinary methods of preventing pollution of the sea, due to the intensity of ship traffic and greater risk of the marine environment destruction. The following special areas have been designated for this annex: Baltic Sea, Mediterranean, North Sea, Black Sea, Red Sea, Antarctic and Grand Caribbean [11].

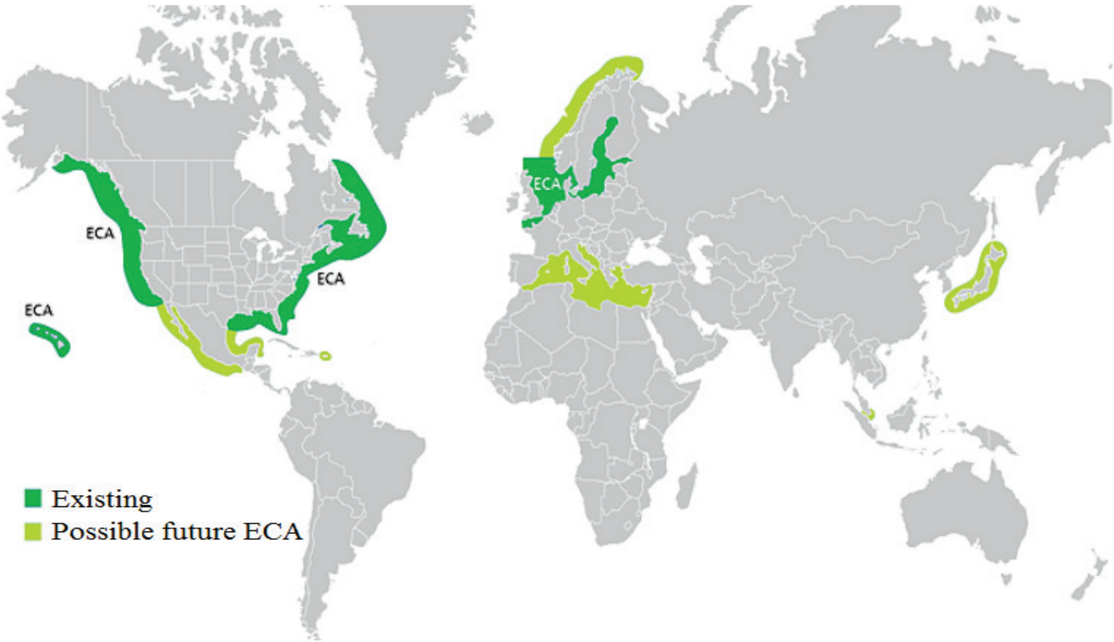

Fig. 1. Existing ECA areas and possible future zones [17]

In these zones, much more restrictive ecological requirements take place. Initially, they were named as Sulphur Emission Control Area (SECA) and NO_x Emission Control Area (NECA), but they have been renamed as Emission Control Area (ECA), and their meaning has been extended. Such zones also apply along the coast of the United States and Canada with a width of 200 nautical miles. There are SO_x, NO_x, particulate matter (PM), volatile organic compounds (VOC) emission restrictions to the atmosphere in the Emission Control Area [6, 8].

In 1997, Annex VI was added and accepted on 19 May 2005. The annex contains 23 regulations that aim to reduce air pollution by ships. In particular, regulations, the requirements to reduce emissions of nitrogen oxides (NO_x), sulphur oxides (SO_x), particulate matter (PM), volatile organic compounds (VOC) and substances that deplete the ozone layer were described [10]. The annex also regulates the technical requirements for ship equipment in incinerators and the quality of marine fuels. In this appendix, regulations regarding the sulphur content in fuel in special water reservoirs waters and globally have been specified. On 1 January 2015, the amendment of the sulphur directive came into force reducing the maximum sulphur content in marine fuel to 0.1% in the Emission Control Areas [11].

It should be emphasized that the exceptional situations for which the regulations of the annex do not apply (an emission higher than the specified standard is allowed) include emergency states related to damage to the ship, saving lives, and thus the safety of ship and people's operations is put above ecological aspects [15].

3. Possibilities of applying various pro-ecological solutions

One of the problems affecting the natural environment is the sulphur content in the fuel, which is related to the origin of crude oil. During the combustion process, sulphur is oxidized, producing SO_2 and SO_3 trioxide. Emissions of sulphur oxides are subject to limits as SO_x. When considering technical solutions to reduce toxic compounds in ECA zones, the most important issues include costs related to the required fleet modernization. Costs are the factor that has the greatest impact on ship owners' decisions.

To compensate for the content of sulphur oxides in the exhaust, a number of different methods are used. One of them is the use of catalysts [5]. Catalysts may be in the fuel as residues after processing of crude oil.

Another way to reduce SO_x emissions is to use fuels with lower sulphur content, so-called low-sulphur fuels. The fuel system should be adapted to the combustion of low-sulphur fuels, because they contain higher amounts of paraffins. As a result, the fuel system unsuitable for low-sulphur fuels will have problems with the clogging of the filters and the patency of the entire system.

Most shipowners, however, apply residual fuel for economic reasons. The price of low-sulphur fuels is on average more than 50% higher than the price of residual fuel [1].

The methods for limiting the SO_x content in the residual fuel may be the purification of flue gas through their treatment in devices called scrubbers. These devices effectively remove sulphur oxides from exhaust gases, but the problem is neutralization of waste. However, the problem when switching to low sulphur fuels is the economic factor – fuel prices are related to the sulphur content. The reason is the expensive desulfurization process. Alkaline additives to lubricating oils in the engine neutralize a small portion of the sulphur contained in the marine fuel, converting it into neutral calcium compounds. However, the amount of neutralized sulphur in this way is so small, that it is not treated as an effective way to reduce SO_x emissions [5].

4. Technical and ecological analysis and difficulties resulting from the application of pro-ecological solutions

As different ecological solutions, the use of low-sulphur fuel meeting the emission standards, installation of the scrubber and modification of the engine to supply natural gas.

4.1. The use of low sulphur fuel

The main and auxiliary engines of the selected passenger-car ferry for calculations already at the time of production were able to supply of Diesel Oil, so in this case it is not necessary to replace the fuel pumps and injectors. In this way, the investment costs for this solution practically do not exist. The only problem in this case is the much higher price compared to residual fuels.

Low-sulphur fuel used in ECA zones was accepted for calculations with density $\rho = 863.4$ kg/m^3 [18]. Calculated actual specific fuel consumption by the main engine is $g_e = 160$ g/kWh, while the actual specific fuel consumption by the auxiliary engine – $g_e = 175.5$ g/kWh.

If we assume that during the ferry trip all four main engines and two auxiliary engines are working, this hourly fuel consumption is about 5 t/h.

Assuming that the ferry will sail for ten years, fuel consumption for this period has been calculated and is 320 000 tons/10 years.

Based on the assumption that the world price of low-sulphur fuel is constant at $ 440 per ton, the estimated cost of fuel consumed during this period is about $ 140 million.

4.2. Installation of exhaust gas scrubber

An alternative solution to increased sulphur oxide emission limits is the use of special equipment – flue gas scrubbers. Thanks to this solution, it is possible to use fuels with a high sulphur content, as this system reduces the sulphur oxide emission level to the atmosphere. As a result of the regulations introduced, companies such as MAN, Wärtsilä and Hamworthy have developed a suitable scrubber technology that can be used on ships [12].

Scrubbers can be divided into two main types, i.e. wet, which use seawater or freshwater as a rinsing medium and dry, in which a dry sorbent is used. Wet scrubbers can work in open, closed and hybrid cycles.

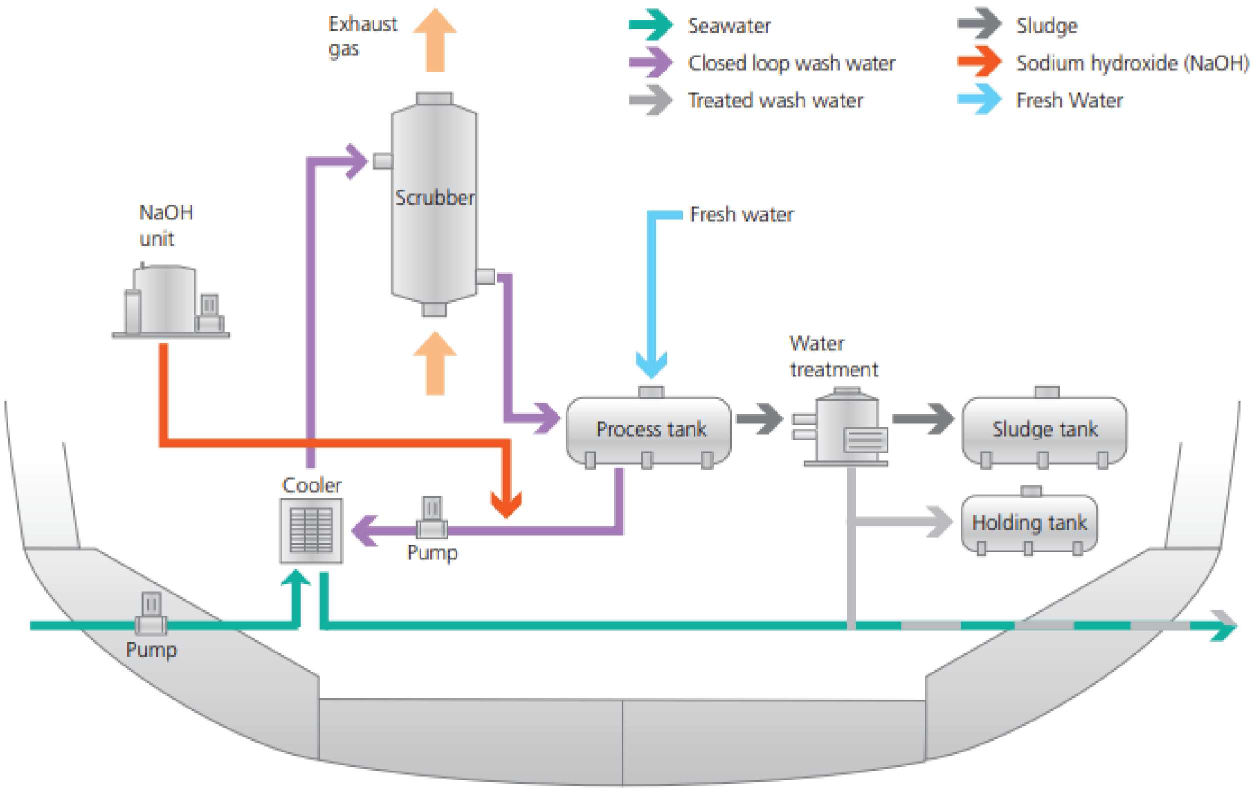

Fig. 2. A closed loop wet SO_x scrubbing system [7]

The scrubbers used in shipbuilding work in a closed system and use fresh water treated with sodium hydroxide NaOH as the flushing medium. As a result of this process, sulphur oxides SOx are removed from the flue gas as sodium sulphate. In contrast to open scrubbers, the rinsing water after the entire process and cleaning is re-circulated and used again. The disadvantage of the closed system is the increased dimensions due to the need to install additional tanks for rinsing water and the equipment necessary for storing and dosing sodium hydroxide.

Due to the fact that on the route of the ferry there is no possibility to discharge water from the scrubber cycle directly into the sea, as in the case of scrubbers in the open circuit, the wet scrubber in the closed loop will be most suitable (Fig. 2).

As the total cost of the scrubber and shipbuilding, costs were assumed as $ 5 million. This sum will be added to the purchase price of heavy fuel used to power main engines and generating sets.

For fuel IFO 380 with density $\rho = 942.9$ kg/m^3 [18], actual specific fuel consumption by the main engine is $g_e = 164$ g/kWh, while the actual specific fuel consumption by the auxiliary engine – $g_e = 180$ g/kWh.

Calculations show that the ferry will use 330 000 t/10 years of heavy fuel within ten years. Assuming that the global price of fuel is fixed at $ 248 per ton, the estimated cost of fuel consumed for a given period is approximately $ 82 500000. The average cost of using the scrubber (purchase of NaOH sodium hydroxide and transfer of sludge in ports) is $ 11 500000. In the final account, we also include the cost of purchase and assembly of the flue gas scrubber with the assumed value of $ 5 million, which gives a total of approximately $ 99 million. This amount is lower than when using a low-sulphur fuel ferry for the same period.

4.3. Reconstruction of the unit for supplying liquefied natural gas (LNG)

The future solution for the reduction of sulphur oxide emissions is the supply of marine engines by Liquefied Natural Gas (LNG) and methane. This solution is interesting because it reduces the SO_x emission enough to meet the high requirements in the ECA zones and it is 20-40% cheaper than crude oil. LNG does not contain sulphur and heavy metals such as cobalt, lead, mercury, which is why sulphur oxides and dust do not form during combustion. There are also no solid combustion wastes such as slag, ash or soot. In comparison with traditional fuels used on ships, natural gas burned emits significantly less nitrogen oxides and carbon dioxide. As a result of LNG combustion, about 85-90% less emissions of nitrogen oxides are produced and 15-25% less carbon dioxide emissions than in the case of combustion of conventional fuels [6].

The passenger-car ferry can be adapted to work on liquefied natural gas by exchanging main engines and auxiliary engines for dual fuel engines [2, 3, 4, 13].

Natural gas consumption was calculated for the calorific value 34.43 MJ/m^3 for gas GZ-50 under normal conditions (temperature 0ºC, pressure 101.3 kPa). The hourly gas consumption in one main engine is 1600 m^3/h.

The natural gas consumption for auxiliary engines was calculated for the calorific value of 34.43 MJ/m^3, for gas GZ-50 under normal conditions and is 290 m^3/h.

In 10 years, the ferry will use 430 million m^3/10 years of natural gas and 2500 t/10 years of Diesel Oil. Assuming that one cubic meter of natural gas costs $ 0.15 and Diesel Oil $ 44 per ton, the total fuel cost has been calculated for approximately $ 67 million. As the cost of replacing the main engines, generator sets, LNG tanks and auxiliary equipment assumed $ 20 million [20], which gives a total amount of about $ 87 million.

In order to better illustrate the results obtained, the costs were compared, which are then presented in Tab. 2.

Tab. 2. Comparison of costs of various pro-ecological solutions

SO_x emission reduction method	Estimated cost [$]
The use of low sulphur fuel	140 000 000
Exhaust gas scrubber + Heavy Fuel Oil (HFO)	99 000 000
Supply of Liquefied Natural Gas (LNG)	87 000 000

All given solutions, have their advantages and disadvantages. Each ship-owner should carefully analyse which solution is the most advantageous in his case. In order to fully illustrate, the given solutions, the advantages and disadvantages of the analysed methods for the reduction of sulphur oxides are presented.

The use of low sulphur fuel

Advantages:
- meeting the sulphur oxide emission standards,
- a developed network of fuel bunkering,
- fuel known to the ship's crew,
- low investment, or lack thereof.

Disadvantages:
- increased fuel costs compared to HFO by 30-40%,
- change of fuel during the cruise may cause the so-called *blackout*,
- problems related to lower ignition temperature,
- no reduction of NO_x.

Variables:
- availability of low-sulphur fuel,
- fuel price.

Exhaust gas scrubber + Heavy Fuel Oil (HFO)

Advantages:
- meeting the sulphur oxide emission standards,
- no need to mount new fuel tanks,
- using cheaper heavy fuel,
- lower investment costs than the case of LNG supply.

Disadvantages:
- takes up additional space on the ship,
- the need to collect sludge in the port,
- costs related to service,
- the large cost of the scrubber itself.

Variables:
- changes in emission standards in the future.

Supply of Liquefied Natural Gas (LNG)

Advantages:
- meeting the sulphur oxide emission standards,
- lower costs of use than in the case of scrubbers,
- low fuel price.

Disadvantages:
- very large investment costs,
- insufficiently developed network of bunkering,
- LNG tanks take up a lot of space,
- small experience of crews, the need to retrain.

Variables:
- LNG cost compared to HFO,
- LNG final price for the customer.

5. Other alternatives

Naturally, electric drives are a natural step towards ecology, especially in smaller areas (Fjords in Norway), because they have some limitations that are mainly related to range. For example, a ferry with a length of 80 meters and a width of 20 meters, is powered by two electric engines, with a capacity of 450 kW each. The unit is made of light aluminum and is therefore twice as light as a typical ferry. The power system was developed by Siemens, and all energy is stored on board in 120 lithium-ion batteries. Charging the ship's battery takes place at the port at night. The ship may also be partially loaded during boarding and disembarking passengers. Using an electric drive means reducing the fuel consumption by 60% for the ship-owner. The ship consumes about 2 million kWh per year. During this time, the traditional ferry burns one million dm^3 of Diesel Oil and thus emits 570 tons of carbon dioxide and 15 tons of nitrogen oxides [19].

In connection with the problems caused by electric drive, that is the limitation of the range, the technology associated with hydrogen drive becomes more and more popular, which is able to eliminate this obstacle. In this solution, the drive system is equipped with a tank in which hydrogen is stored under high pressure. Fuel cells generate electricity from the oxidation reaction of the fuel continuously supplied to it from outside. The majority of fuel cells for the production of electricity use just hydrogen at the anode and oxygen at the cathode (hydrogen cells). The energy production process does not change the chemical nature of the electrodes and the electrolytes used. The generated electricity will be able to supply not only on-board devices, but also an electric motor that has been installed on the ship [18]. The advantage of hydrogen cells is the small air pollution they cause. The exhaust gases created in them consist exclusively of environmentally neutral water vapour.

6. Conclusions

There is also a gigantic technological jump in shipbuilding. One of the examples may be the ship's propulsion, which has changed from simple ways like sail, through steam engines to commonly used internal combustion engines.

The simplest way to protect the environment, although not without the disadvantages, is the use of low sulphur fuel, but a much higher price compared to residual fuels.

An alternative solution to increased sulphur oxide emission limits is the use of special equipment – flue gas scrubbers. The biggest environmental problem in this case is the use of wet scrubbers, because it does not reduce the amount of sulphur emitted to the ecosystem, but only changes the direction of emission, bypassing virtually the sulphur emission phase into the atmosphere. Therefore, the wet scrubber in the closed circuit will be the most suitable in this respect.

Therefore, the future solution for example may be supplying ship engines with Liquefied Natural Gas (LNG) and methane. As a result of LNG combustion, about 85-90% less emissions of nitrogen oxides are produced and 15-25% less carbon dioxide emissions than in the case of conventional fuels.

A natural step towards ecology is also electric drives. Unfortunately, these drives also have some limitations, which relate primarily to range. Due to these problems, the technology that is able to eliminate this obstacle, i.e. the hydrogen propulsion, is becoming more and more popular. In addition, in this direction will be the further development of environmentally friendly drives.

Reference

[1] Giernalczyk, M., *Metody redukcji rmisji do atmosfery związków toksycznych oraz CO_2 przez statki*, Logistyka, No. 6, pp. 655-665, 2014.

[2] Haller, P. Jankowski, A. Kolanek, C. Magdziak-Tokłowicz, M. Wróbel, R. *Impact analysis of air humidity on operating parameters of diesel engine*, Journal of KONES, Vol. 22, No. 3, DOI: 10.5604/12314005.1165966, pp. 37-42, 2015.

[3] Haller, P. Jankowski, A. Kolanek, Cz. Walkowiak, W. W. ,*Research of water − fuel microemulsions as fuel for diesel engine,* Journal of KONES, Vol. 19, No. 3, pp. 165-170, 2012.

[4] Haller, P., Jankowski, A., Kolanek, C., Walkowiak, W., *Research of Water − Fuel Microemulsions as Fuel for Diesel Engine,* Journal of KONES, Vol. 16, No. 3, DOI: 10.5604/12314005.1138110, pp. 165-170, Warsaw 2009.

[5] http:// www.cleanmarine.no.
[6] http://classars.com/circulars.php?NewsID=91.
[7] https://www.energetyka24.com/w-usa-powstaje-pierwszy-na-swiecie-prom-zasilany wodorem.
[8] https://www.gospodarkamorska.pl/Stocznie,Offshore/wybudowany-w-gdansku-pierwszy-elek tryczny-prom-juz-pracuje.
[9] https://www.wartsila.com/marine/build/engines.../dual-fuel-engines.
[10] *Microemulsion as a Means of NOx Reduction in Exhaust Emission of Diesel Engines,* Journal of KONES Powertrain and Transport, Vol. 23, No. 3, DOI: 10.5604/12314005.1216479, pp. 225-232, Warsaw 2016.
[11] Kidacki, G., Krause, P., Rajewski, P., *Techniczno-eksploatacyjne aspekty redukcji emisji* SO_x *na statkach*, Zeszyty Naukowe Akademii Morskiej w Szczecinie, No. 10 (82), pp. 245-247, 2006.
[12] Kołwzan, K, Adamkiewicz, A., *Zapobieganie zanieczyszczaniu powietrza przez statki w świetle najnowszych wymagań Załącznika VI do Konwencji MARPOL*, Zeszyty naukowe Akademii Morskiej w Szczecinie, No. 18 (90), pp. 66-70, 2009.
[13] Kowalski, M. Jankowski, A. *Research performance of novel design of diesel engine,* Journal of KONES, Vo. 24. No. 4, DOI: 10.5604/01.3001.0010.3157, pp 99-108, 2017.
[14] Kowalski, M., Jankowski, A., *Research Performance of Novel Design of Diesel Engine*, Journal of KONES, Vol. 24, Issue 4, DOI: 10.5604/01.3001.0010.3157, pp. 99-108, Warsaw 2017.
[15] Lloyd's Register, *Understanding exhaust gas treatment systems*, Londyn 2012.
[16] Łosiewicz, Z., Łukasik, Z., *Zespół napędowy spalinowo-elektryczny na statkach offshore – założenia projektowe w aspekcie zdatności do wykonania zadania eksploatacyjnego i bezpieczeństwa żeglugi*, Autobusy: Technika, Eksploatacja, Systemy Transportowe, T. 18, No. 6, pp. 886-890, 2017.
[17] Merkisz, J., Pielecha, I., *Wymagania i kierunki rozwoju napędów zasilanych gazem ziemnym CNG/LNG*, Zeszyty Naukowe Politechniki Częstochowskiej, Mechanika, No. 26 (162), pp. 458-475, 2006.
[18] Międzynarodowa Konwencja o Zapobieganiu Zanieczyszczaniu Morza Przez Statki 73/78, 2015, Tekst jednolity, 299-338, TransBaltic, *Implications of new regulation regarding sulphur content in ship's fuel on maritime transport sector within Baltic Sea Region*, Helsinki 2012.
[19] Witkowski, K., *Problematyka zanieczyszczenia atmosfery przez statki wykorzystywane w transporcie morskim*, Autobusy: Technika, Eksploatacja, Systemy Transportowe, T. 17, No. 6, pp. 468-473, 2016.
[20] Wojtyto, Z., *Problemy eksploatacji dwusuwowych silników okrętowych na paliwach nisko-siarkowych według doświadczeń firmy MAN Diesel*, Silniki Spalinowe, No. 45 (3), pp. 77-89, 2006.

Manuscript received 07 September 2019; approved for printing 09 December 2019