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COMPARISON OF REDUCTION SYSTEMS OF HARMFUL SUBSTANCES INTO THE ATMOSPHERE IN ACCORDANCE TO REQUIREMENTS OF IMO TIER III

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Abstract

Degradation of the environment is nowadays believed to be the most alarming problem that needs to be solved. Global warming and environmental pollution are predicted to cause a catastrophic chain reaction leading to species extinction, mass emigration due to rising sea levels and global crisis. The only solution suggested by international organizations is the immediate reduction of greenhouse gases and other harmful substances. Marine transportation harmful substances into the atmosphere are recognized to be a significant source of global atmospheric pollution. Despite the high efficiency of marine diesel engines, their impact on the environment is considerable. Due to environmentally friendly policies, modern engines concerns about not only efficiency but also mainly about s aspects. This article analyses and compares marine s exhaust gases reduction methods. Especially the most harmful substances emitted by ships were taken into consideration. The article presents the most crucial law regulations of harmful substances to the atmosphere, pointing at actual and possible future implementations. The most complex methods allowing meeting the latest limits were presented. Pros and cons of available control methods were thoroughly described and methods were compared. The most adequate methods form the effectiveness and economical point of view was pointed out.

Keywords*: NOx, SOx, MARPOL, atmosphere pollution, marine transportation, dual fuel*

1. Introduction

Global warming, atmosphere and water pollution, and growing garbage dumps not only leads to environmental degradation and species extinction but also causes many diseases such as cardiovascular or respiratory diseases and cancers. Due to its scale, marine transport strongly influences environmental pollution. Harmful substances emitted by ships are a major example of pollutants. International organizations such as the International Maritime Organization, IMO, recognizing the atmosphere pollution problem started to issue regulations forcing ship owners to reduce s of harmful substances from their ships.

IMO regulations are continuously updated and limits made more and more challenging, thus manufacturers are required to implement new technology solutions and ship owners to undertake investments for more efficient methods of atmosphere pollution prevention. The problem of harmful substances into the atmosphere is probably the biggest challenge of the modern marine transportation industry.

According to researches exhaust gases ingredients have a serious impact on both environment and human health causing many diseases [19]. A higher concentration of harmful substances was observed in port and seaside areas close to main shipping lanes, because of fact that nearly 70% of ships take place in a range of 400 km from shore [1].

Among many harmful substances emitted into the atmosphere by a human, the article focuses on those particularly related to marine transport, which are carbon dioxide, sulphur oxides, nitrogen oxides, particular matter, and volatile organic compounds.

International Maritime Organization issued Annex VI of MARPOL Convention for the prevention of air pollution by ships. Compliance with those regulations is certified by the International Air Pollution Prevention Certificate and International Energy Efficiency Certificate.

By virtue of regulation 14 sulphur content in fuel, limits were implemented. Statement from October 2016 adjudicates that resources and availability of low sulphur fuels are sufficient to induct 0.50% m/m sulphur content in fuel limit globally from 1st of January 2020 and after this date. Convention allows using any fitting, material, appliance or apparatus in order to reduce sulphur oxides, provided that used method is at least as efficient as sulphur content in fuel limitation. Furthermore, nitrogen oxides are also regulated according to ship build date or area of operation. To reduce carbon dioxide International Energy Efficiency Certificate based on the Energy Efficiency Design Index, EEDI, and Energy Efficiency Operational Indicator, EEOI has to be issued for each ship.

EEDI is to determine the amount of CO_2 emitted by ship into the atmosphere. Specific correction coefficients for different ships and different situations are taken into consideration while calculating EEDI, such as technology availability, weather coefficient, or capacity coefficient.

EEOI is to be calculated for each finished voyage to prove compliance with assumptions of EEDI. Value of EEOI is affected by numerous factors not dependent on the crew or ship owner such as load capacity utilization, which depends on external factors, for example, market situation or cargo availability. Value of indicator is notably unfavourable for ships sailing in ballast [7].

2. Methods of reduction of harmful substances

In order to comply with strict limits, manufacturers and maritime industry companies started to introduce various technological solutions. [17] They either focus on fuel, construction, or exhaust gases cleaning equipment. Some of those methods have a negative impact on performance causing for example higher specific fuel consumption or faster wear of elements. Unfortunately, despite the disadvantages, ship owners often are forced to decide on using those methods because of economical aspects or lack of possibilities to use a different method.

Low sulphur fuel – Basic way to meet sulphur oxides regulations is switching to low sulphur distilled fuel. According to ISO 8217 standards, maximal sulphur content in fuel for typical light fuels (DMB, DMA, DMX) varies from 1% to 2%. Ultra Low Sulphur Marine Gas Oil ULSMGO with declared 0.1% content of sulphur is not yet certified with corresponding ISO certificate. Pros and cons of low sulphur fuel oils are presented in articles [2, 12].

Scrubber – Scrubbers installed on ships are mainly of the waste wet type, based on the process of rinsing exhaust gases with either seawater or fresh water, sometimes with chemical additives. The process takes place in a special chamber fitted into the exhaust duct. This type of scrubbers is the simplest method of exhaust gases desulfurization. There are many studies describing this method, i.e. [2, 10].

Modification – Modifications such as injection timing retarding, injection nozzle modification or reducing compression ratio are successful methods of nitrogen oxides reduction by lowering combustion temperature. However, those methods do not influence positively on performance causing higher specific fuel consumption and higher of hydrocarbons. Many studies either experimental [13] or computational [15, 16, 18, 20] prove a correlation between retarded injection timing and reduced NO_X. Studies show a simultaneous increase of particulate matter and negative impact on specific fuel consumption, however, this method meets the assumptions of NO_X reduction. Unfortunately, mentioned methods in the majority do not meet the strictest limits of Tier III regulations, only meeting Tier II. In order to comply with rules inside nitrogen oxides control areas it is mandatory to use other, sometimes-additional methods [2].

Exhaust Gas Recirculation (ERG) – System based on the process of recirculating previously cooled part of exhaust gases back to the combustion chamber. It results with a lower percentage of oxygen and a higher percentage of other inert substances such as H_2O or CO_2, leading to the lower formation of nitrogen oxides [2].

Selective Catalytic Reduction (SCR) – SCR system installed on ships uses hydrocarbons or ammonia as a redactor, which in the presence of catalyst reacts with nitrogen compounds. Systems offered by leading manufacturers reach an efficiency of NO_X reduction up to 90%. This solution seriously complicates installation and requires significant interference with the exhaust system. One of the disadvantages of this system is the necessity of urea refilling [2, 14].

Water addition – Water added into the combustion chamber, thanks to its high heat capacity causes a decrease of local peak temperatures, which leads to lower nitrogen oxides formation. There are three effective methods of adding water into the combustion chamber known by the marine industry: direct water injection (DWI), fuel-water emulsion, and charging air humidifying [2, 5, 23].

Gas fuel – Gas fuels are characterized by excellent results in harmful substances s. They allow meeting all latest IMO regulation with no need to use any additional method, what is impossible for using liquid fuel oils even despite using some of reduction methods. Actually, due to exacerbation of limits more and more dual-fuels are used on ships and not only on gas tankers [2].

Batteries – One concept is to use batteries as an exclusive source of power. Another solution more likely applied on bigger, medium, and long-range ships is so-called hybrid propulsion. Electric motor linked with reduction gear can operate both in motor and generator mode; therefore, it can either support the main or charge the batteries depending on load. This solution allows running under optimal load, which leads to lower fuel consumption [2, 8].

Nuclear propulsion plant – Nuclear reactors for many years are successfully operated on navy ships such as aircraft carriers or submarines, and on icebreakers. Nowadays on a different stage, about 50 new projects of Small Modular Reactors are under construction. Research conducted by specialists i.e. from Lloyd Register proves the possibility to use SMR reactor on cargo ships, however, to apply this solution on a wide range, an update of actual guidance and regulations is needed [2, 6].

Use of hydrogen – Since a few years, the use of hydrogen is suggested as a solution to the ecological energy problem. Although this idea does not find wide application in the shipping industry, there are two solutions, which could result in -free ship operation [2]:

– hydrogen fuel cells,
– Brown gas additive [3].

3. Criteria selection model

The wide variety of reduction methods available on the market allows both building the new vessels and the adaptation of already operational to meet the latest requirements. Thanks to high technical progress, further methods are still being designed, and existing ones are constantly being modernized and improved. Despite the industry's large involvement in the implementation of new methods, it has not been possible to create an ideal solution without drawbacks, such as increased fuel consumption or operational inconvenience. Most solutions are designed to meet specific regulations at the lowest possible cost, not always complying with the main objective of environmental protection.

Among the methods available on the market, there are those whose task is to limit of a specific substance in order to meet a given limits. Such methods, often at the expense of reducing s of one substance, negatively affect of another [22]. However, there are comprehensive, most advanced solutions that allow complying with all applicable standards. Unfortunately, in most cases, such solutions turn out to be much more expensive and not always economically viable.

Choosing a specific method of reducing s to meet MARPOL Convention requirements, ship owners consider different criteria. The basic criteria are economic criteria such as investment costs or operating costs. In addition, economic criteria that do not directly affect installation costs can be distinguished, which, however, due to a certain inconvenience related to the operation of this installation can indirectly affect the total cost of operating the ship. Such criteria include the necessity of additional crew training, potential failures that may generate high losses due to the exclusion of the ship from service or even the need to hire additional crew members to operate these installations.

In order to compare individual methods, a selection criteria scheme based on other comparisons of this type available in the literature was developed along with a 3-grade assessment within each criterion. The criteria have been divided into the negative and positive group, in which each method is assigned a negative and a positive grade, expressed as the number of pluses (+) or minuses (–) (min. 1, max. 3). Following criteria was adopted [2]:

- investment costs,
- operating costs (based on the recommended 25 years lifetime of the vessel),
- operational inconvenience defined as a collection of all operating disadvantages,
- installation size,
- NO_X reduction,
- SO_X reduction,
- CO_2 reduction,
- PM reduction.

The selection of criteria may vary depending on the type of ship or the operations area. Data for comparative analysis should be selected for a specific ship, due to possible differences in costs or disadvantages of installations depending on different types of ships. The presented model of criteria selection gives the possibility of assigning different weights to specific criteria if in the ship owner's opinion they will be more important. However, for the purposes of the work, equal weight was assumed for each criterion in order to conduct a general comparative analysis of the presented methods.

4. Reduction methods comparison

Not all methods mentioned in the article were included in the comparison due to the lack of sufficient data. Methods such as nuclear and hybrid power plants are not widely used on commercial vessels, and thus there is not enough data in the literature such as investment or operating costs. Other methods, such as the use of hydrogen as a fuel are still in the design phase and the projected data on their effectiveness and costs are not reliable enough to be used in comparative analysis.

The costs of individual methods for analysis were taken from data available in the literature [4, 9, 21] for a new built medium-sized tanker with a displacement of about 55000 DWT and the main power of about 9000 kW. For analysis purpose, the average annual fuel consumption was estimated at 12000 tons of heavy fuel. In the case of methods for which the criterion is not relevant, the cell has been filled with „not applicable" (N/A). The comparison was made by assigning a rating to each method in each positive and negative category. For each method, the plus points from the positive criteria and the negative points from the negative criteria were summed up, and their sum is a relative evaluation of the method. It can be assumed that the higher the rating, the better the method and the more suitable for use in the considered case. The results of the analysis are presented in Tab. 1.

The results of the analysis clearly show that for the analysed case the use of dual-fuel s is the best solution to the problem of harmful substances into the atmosphere. Due to the constant low price of LNG gas and good performance parameters of dual-fuel s, no additional operating costs were taken into account because they do not exceed the operating costs of a traditional heavy fuel. However, in order to meet the latest NO_X standards in special areas and with a high-pressure gas system should be additionally equipped, for example, with an exhaust gas recirculation system. Operation parameters modification by changing the injection timing or replacing injectors with a new type is a good solution, but also requires a combination with another method in order to meet all standards. It is worth paying attention to the assessment of low-sulphur fuel. Due to the operating costs over the period of 25 years twelve times exceeding the costs of the remaining methods, it was decided to add an additional negative point over the provided criteria selection model scale. Both using of low-sulphur fuel and scrubber require an additional method to meet nitrogen oxide standards, as well as methods that do not affect the reduction of sulphur oxides should be used in combination with other SO_X reduction methods. Due to the quantification of rating in individual criteria, the assessment of the combined methods should include data for the total assessment to avoid, for example, double counting of negative points for big size of the installation.

Tab. 1. Results of the analysis and assessment of reduction methods [2]

Type of method	Investments' costs	Operating costs	Operational inconvenience	Size	NO_X reduce.	SO_X reduce.	CO_2 reduce.	PM reduce.	Total
ULSMGO	N/D	––––	–––	N/A	N/A	+++	N/A	+	–3
Scrubber	––	–	––	–––	N/A	+++	N/A	+++	–2
EGR	–	–	–	–	+++	N/A	N/A	N/A	–1
DWI	–	–	––	–	++	N/A	N/A	N/A	–3
Fuel-water emulsion	–	–	––	––	++	N/A	N/A	N/A	–4
Charging air humidifying	–	–	––	––	++	N/A	N/A	N/A	–4
Low pressure gas injection	–––	N/A	–	––	+++	+++	++	+++	+5
High pressure gas injection	–––	N/A	––	––	++	+++	+++	++	+3
modification	–	–	–	N/A	+	N/A	N/A	N/A	–2
SCR	––	–	–––	–––	+++	N/A	N/A	+	–5

Tab. 2. Results of combined methods analysis [2]

Type of method	Investments' costs	Operating costs	Operational inconvenience	Size	NO_X reduce.	SO_X reduce.	CO_2 reduce.	PM reduce.	Total
ULSMGO / EGR	–	––––	–––	–	+++	+++	N/A	+	–2
Scrubber / EGR	––	–	––	–––	+++	+++	N/A	+++	+1
High pressure gas injection / EGR	–––	–	––	––	+++	+++	+++	++	+3
Scrubber / DWI	––	–	–––	–––	++	+++	N/A	+++	–1

Combined methods meeting the latest regulations were selected based on the analysis of the results from Tab. 1. The analysis for comparison of those combined methods presented in Tab. 2 shows that the use of the exhaust gas recirculation system combined with other methods makes it possible to meet standards without reducing the total assessment of the method. It is worth noting that the exhaust gas recirculation combined with a scrubber, which received low scores as independent methods, obtained a very good rating as a combined method. This is due to a significant increase in the usability of these methods as a combined method, by enabling the most demanding standards to be met. Among the methods based on the water additive, direct water injection was chosen as the method with the highest rating. In combination with a scrubber, this is a good solution for ships with an operating area outside of special zones. Due to the very low rating of the catalytic reduction method, this method was not included in the analysis of combined methods.

5. Summary

The conducted analysis is a preliminary assessment of the methods of reducing harmful substances to the atmosphere. It does not allow for the accurate selection of a particular method for a particular ship, but it suggests which methods and criteria should be taken into account when planning to adapt the ship to the regulations of s from marine diesel s. The results of the analysis are in line with trends visible in the maritime industry or in the literature. In order to conduct a comprehensive comparative analysis, it would be necessary to collect data such as costs of a method for a particular ship, ship size and power, ship type, planned operation area, as well as possible changes in fuel prices and the possibility of introducing additional control areas.

Leading marine manufacturers have been developing dual-fuel s in recent years, which show that they plan a future with this type of s. Due to its properties, gas fuels almost fully resolve the problems of the modern maritime industry related to the pollution of the atmosphere. Although the phenomenon of methane slip is a serious threat from the point of view of global warming due to the methane high global warming potential, due to improvements introduced by manufacturers and lower s of carbon dioxide, the total impact of Exhaust gases on global warming is lower than in conventional s. Ship owners more and more often see the potential of this solution and decide to use DF s not only on LNG gas carriers but also on other cargo and passenger ships despite the need to use additional gas tanks. However, the phenomenon of the prevalence of LNG as a marine fuel may result in an increase in gas prices in the future, causing a decrease in the profitability of this solution [5]. Therefore, it is likely that in the future, the use of low-sulphur fuels or other methods of reducing s will be an increasingly good alternative. It is a mechanism directly based on economic mechanisms because in the maritime transport the basic criterion of choice is the profit criterion.

Methods such as exhaust gas recirculation, scrubbers, or electric propulsion can allow meeting the regulations, but can also result in the problem being transferred elsewhere, for example, increased fuel consumption, water pollution or problematic scrubbing waste treatment, as well as the necessity of increased land-based industrial s in the area much more environmentally sensitive than the seas and oceans. For example, the production of electricity in coal-fired power plants for the propulsion of electric ships or other electric vehicles emits many harmful substances contributing to the formation of smog in urban areas. What is more, by introducing further limits and regulations, increases the costs of sea transport, which is the most efficient mean of transport. This may result in an increase in the prices of all products and, as a result, a decrease in the standard of living of the population. It is easy to notice that the most developed countries with the highest standard of living undertake pro-ecological activities to protect the environment. In turn, societies living at a relatively lower level do not focus as much on ecology due to the fact that environmental protection is an idea that stands much higher in the hierarchy of needs than satisfying consumption needs. With this in mind, decisions on regulations introduction by international organizations should be made responsibly and prudently, aiming not only at the industry image aspect but also above all with a real concern for the environment. An example worth noting is the planned reduction of carbon dioxide s by ships. This could lead to a significant increase in sea transport prices or the transfer of part of the s to onshore facilities. There is a great danger that such actions will have completely opposite effects than assumed, shifting pollutant s from the sea to land, thus causing a growing threat to human health.

The solution to the atmospheric pollution problem may be the use of nuclear energy. Its disadvantage is the danger associated with waste radioactivity and the risk resulting from potential failures, but due to the large development of technology, modern reactors are highly reliable with multiplied security systems and advanced security features. Radioactive waste is still a huge challenge for nuclear energy, but thanks to the technology of recycling used fuel cores, the amount of waste can be significantly decreased and their radioactivity time reduced from millions to hundreds of years. However, nuclear power still requires development to which it is necessary to educate societies about its true advantages and disadvantages.

References

[1] Chłopek, Z., Szczepański, T., *Ocena zagrożenia środowiska cząstkami stałymi ze źródeł cywilizacyjnych,* Inżynieria Ekologiczna, Nr 30, pp. 174-193, 2012.

[2] Czmyr, S., *Przegląd i porównanie systemów ograniczenia emisji szkodliwych substancji do atmosfery zgodnie z wymogami IMO Tier II*, Uniwersytet Morski w Gdyni, 2019.

[3] Czmyr, S., *Właściwości i możliwości zastosowania gazu Browna*, Konferencja Kół Naukowych Akademii Morskiej, Gdynia 2015.

[4] *project guide*, MAN Energy Solutions, 2018.

[5] Haller, P., Jankowski, A., Kolanek, C., Walkowiak, W., *Potential Non-Toxic Aqueous Emulsion as a Diesel Fuel,* Journal of KONES, Vol. 22, Issue 3, DOI: 10.5604/12314005.1165969, pp. 43-48, Warsaw 2015.

[6] Herdzik, J., *Consequences of using LNG as a marine fuel*, Journal of KONES, Vol. 20, No. 2, pp. 159-166, 2013.

[7] Herdzik, J., *Modyfikacja wskaźników efektywności energetycznej statków różnych typów i konstrukcji*, Logistyka, Nr 6, pp. 706-711, 2014.

[8] Hirdaris, S. E., et al., *Considerations on the potential use of Nuclear Small Modular Reactor (SMR) technology for merchant marine propulsion*, Ocean Engineering, Vol. 79, pp. 101-130, 2014.

[9] http://www.dnvgl.com/maritime/advisory/battery-hybrid-ship-service.html, (access 23.05.2019).

[10] https://www.wingd.com, access 17.05.2019.

[11] Jankowski, A., Kowalski, M., *Creating Mechanisms of Toxic Substances of Combustion,* Journal of KONBiN No. 4(36), DOI 10.1515/jok-2015-0054 pp. 33-42, 2015.

[12] Kidacki, G., Krause, P., Rajewski, P., *Techniczno-eksploatacyjne aspekty redukcji emisji SOx na statkach*, Zeszyty Naukowe, Akademia Morska w Szczecinie, pp. 245-258, 2006.

[13] Kim, A. R., Seo, Y. J., *The reduction of SOx s in the shipping industry: The case of Korean companies*, Marine Policy, Vol. 100, pp. 98-106, 2019.

[14] Kowalski, M., Jankowski, A., *Research Performance of Novel Design of Diesel,* Journal of KONES, Vol. 24, Issue 4, DOI: 10.5604/01.3001.0010.3157, pp. 99-108, Warsaw 2017.

[15] Osipowicz, T., *Wpływ parametrów regulacyjnych silnika z zapłonem samoczynnym na emisję substancji toksycznych do otoczenia oraz zużycie paliwa*, Autobusy: technika, eksploatacja, systemy transportowe, Nr 12, pp. 318-323, 2011.

[16] Raeie, N., Emami, S., Sadaghiyani, O. K., *Effects of injection timing, before and after top dead center on the propulsion and power in a Diesel* , Propulsion and Power Research, Vol. 3, No. 2, pp. 59-67, 2014.

[17] Sindhu, R., Rao, G. A. P., Murthy, K. M., *Effective reduction of NOx s from diesel using split injections*, Alexandria Engineering Journal, Vol. 57, No. 3, pp. 1379-1392, 2018.

[18] Skrętowicz, M., Jankowski, A., Haller, P., Woźniak, J., Janas, M., *Risk Evaluation of Driver Exposure to Exhaust Fumes Inside the Passenger Car Cabin in Urban Traffic Conditions,* Journal of KONES, Vol. 23, No. 3, DOI: 10.5604/12314005.1216394 pp. 457-464, Warsaw 2016.

[19] Springer, G. Ed., *Engine Emissions: pollutant formation and measurement,* Springer Science & Business Media, 2012.

[20] Stężycki, P., Kowalski, M., Jankowski, A., *Researches on the Influence of the Piston Ring Insert on Temperature Distribution in Piston*, Journal of KONES, Vol. 25, Issue 4, DOI: 10.5604/01.3001.0012.7995 pp. 563-570. Warsaw 2018.

[21] Stocker, T. F., et al., *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA 2018.

[22] Yang, Z. L., et al., *Selection of techniques for reducing shipping NOx and SOx*, Transportation Research Part D: Transport and Environment, Vol. 17, No. 6, pp. 478-486, 2012.

[23] Zurek, J., Kowalski, M., Jankowski, A., *Modelling of Combustion Process of Liquid Fuels under Turbulent Conditions,* Journal of KONES, Vol. 22, Issue 4, DOI: 10.5604/12314005.1168562, pp. 355-364, Warsaw 2015.

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