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Problems of Nitrogen Oxides Emission Decreasing from Marine Diesel Engines to Fulfil the Limit of Tier 3

Jerzy Herdzik
Gdynia Maritime University, Poland
*corresponding author's e-mail: j.herdzik@wm.umg.edu.pl

1. Introduction

International shipping is the reason of emission about one million ton of the nitrogen oxides yearly to the atmosphere only on Baltic and the North Sea areas (Winnes 2016). Due to annex VI of International Convention on the Prevention of Pollution from Ships (MARPOL) the NO_x emission is limited. The International Maritime Organization (IMO) emission standards are commonly referred to Tier 1, Tier 2 and Tier 3 (see Fig. 1). The limit of Tier 1 was obligatory for new diesel engines (over 130 kW of power) built or installed on vessels from 1st January of 2000. The limit of Tier 2 is obligatory on vessels built after 1st July 2010 and limit of Tier 1 for existing pre-2000 engines. The more stringent requirements applicable to ships in Emission Control Area (ECA) where the emission limits concern to sulfur oxides (SO_x), particulate matters (PM) and nitrogen oxides (NO_x) (ABS Publication 2015, Herdzik 2011).

The NO_x emission limits are set for marine diesel engines depending on maximum operating speed (only) as graphically presented in Fig. 1.

2. The possibility of emission limits fulfillment

All marine diesel engines (installed on vessels) built after 2010 should comply with Tier 2 emission. Tier 3 is required on ECA-s: from 1st January 2016 on two hundred mile zone of USA waters and will be from 1st January 2021 on Baltic and North Sea. It debates about next areas i.e. Mediterranean or Black Sea.

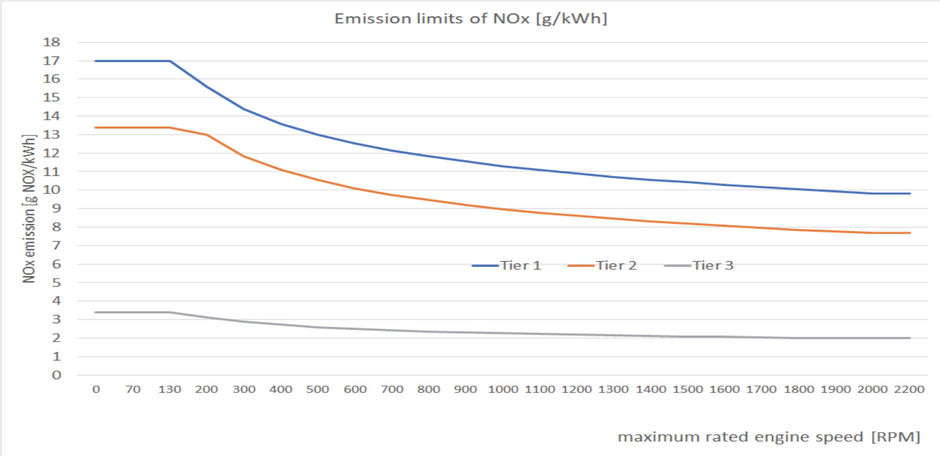

Fig. 1. MARPOL Annex VI NO_x emission limits

Tier 2 emission standard is expected to be met by combustion process optimization. The engine manufacturer may prepare the combustion process to fulfil the requirements through (Lloyd's Register 2005, Moreno-Gutierez et al. 2007, MAN B&W 2010, Pavlenko et al. 2014):

- fuel injection timing (delayed and divided into parts),
- decreasing the compression ratio and maximum combustion pressure,
- change fuel nozzle flow area,
- exhaust valve timing,
- cylinder compression volume,
- special water injectors,
- injectors for fuel-water emulsion, etc.

Tier 3 emission standard requires dedicated NO_x technologies working many often in co-operation of few lower mentioned, such (MAN Energy 2018, ABS 2017a, ABS 2017b):

- water induction into combustion process with fuel emulsion, scavenging air (humified air) or injection into cylinder,
- exhaust gas recirculation (EGR) systems,
- turbocharger cut-out matching,
- selective catalytic reduction (SCR) systems,
- other methods approved by marine administration as equivalent to above mentioned.

In reality into operation there are two alternative methods to meet the Tier 2 and Tier 3 NO_x requirement for two-stroke engines depending on the area of vessel sailing. The exhaust gas recirculation (EGR) is an internal engine process to prevent the formation of NO_x by controlling the combustion process. The decreasing of oxygen content in and parallel by moisturizing the scavenging air results in decreasing of NO_x formation. The selective catalytic reduction (SCR) is an after-treatment method using a catalyst to reduce the generated NO_x into oxygen and water. It needs the proper and stable temperature of the process (unfortunately exhaust gas temperature depends of the engine load) and additional reagents like ammonia or solution of urea in proper quantity to NO_x concentration in exhaust gas. The SCR system is available in a high-pressure system (SCR-HP) and a low-pressure system (SCR-LP).

3. NO_x decreasing emission systems

The installation of NO_x decreasing emission systems increases the prize of engines. There is a necessary of using an additional equipment. The lifetime of proper robust work of mentioned equipment is not known. It should be specified by the supplier.

The dedicated systems are complicated and needs additional electric energy for work about 1-5 kW per 1MW.

An example of such complex system working in EGR mode for MAN 7G80ME-C engine is presented in Fig. 2.

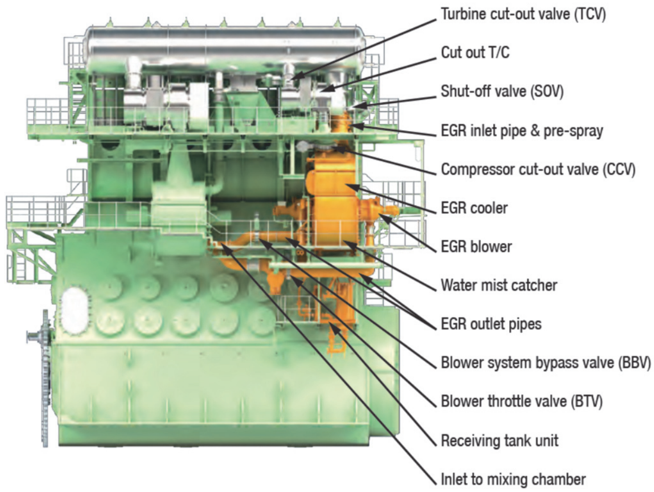

Fig. 2. Integrated EGR layout for by-pass matching (MAN Energy 2018)

The final effect of decreasing NO_x emission depends on co-operation of these elements of the system. The control valve operation depends on the power of engine and Tier 2 or Tier 3 mode. The idea of EGR system is presented in Fig. 3.

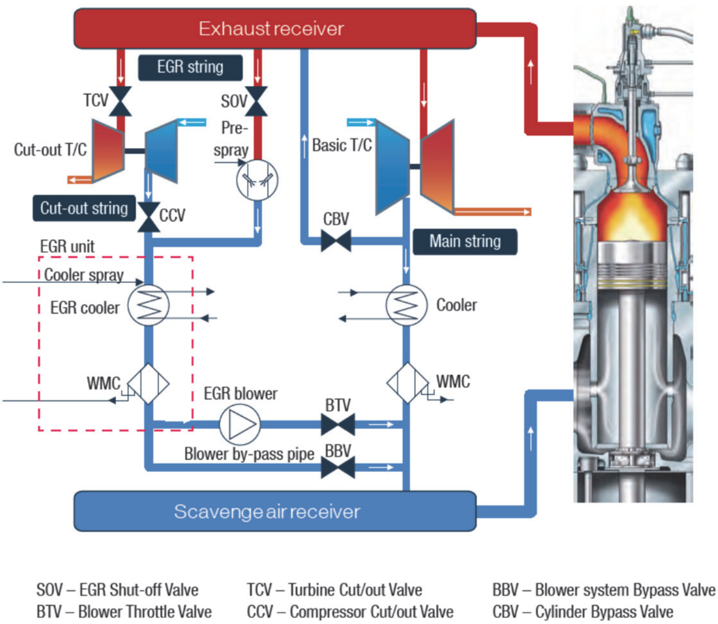

Fig. 3. EGR process diagram with turbocharger cut-out matching (MAN Energy 2018)

Control valve operation for engines of bore ≥80 cm is presented in Table 1. It means that only inside ECA areas the engine is switched on Tier 3 mode, on other areas may work on Tier 2 mode.

Two parameters are measured in exhaust gas receiver before the EGR system: NO_x and oxygen concentrations. Of course the load of engine and pressure in scavenge air receiver should be known as well.

Engine emissions are measured on the test bed according to the mode of work. The ISO 8178 gives various cycles for various types of engine. E3 cycle is applied for propeller-law-operated engine. The test cycle type E3 is presented in Table 2.

Table 1. Control valve operation for engines of bore ≥80 cm (used abbreviations explained in Fig. 3) (MAN Energy 2018)

<table>
<tr><th></th><th colspan="3">Tier 2 mode</th><th colspan="3">Tier 2 mode – TC cut-out</th><th colspan="3">Tier 3 mode</th></tr>
<tr><th>% of load</th><th>SOV BTV</th><th>CBV</th><th>TCV CCV BBV</th><th>SOV BTV</th><th>CBV</th><th>TCV CCV BBV</th><th>SOV BTV</th><th>CBV</th><th>TCV CCV BBV</th></tr>
<tr><td>100</td><td rowspan="5">closed</td><td rowspan="5">closed</td><td rowspan="5">open</td><td colspan="3">Not applicable</td><td rowspan="5">open</td><td>closed</td><td rowspan="5">closed</td></tr>
<tr><td>75</td><td rowspan="4">closed</td><td rowspan="4">closed</td><td rowspan="4">closed</td><td rowspan="3">partly open</td></tr>
<tr><td>65</td></tr>
<tr><td>50</td></tr>
<tr><td>25</td><td>closed</td></tr>
</table>

Table 2. Parameters of engine during NO_x test bed measurement (CIMAC 2012)

<table>
<tr><td rowspan="3">Test cycle type E3</td><td>Speed</td><td>100%</td><td>91%</td><td>80%</td><td>63%</td></tr>
<tr><td>Power</td><td>100%</td><td>75%</td><td>50%</td><td>25%</td></tr>
<tr><td>Weighting factor</td><td>0.2</td><td>0.5</td><td>0.15</td><td>0.15</td></tr>
</table>

It means that the NO_x emission is estimated (according to requirements presented in Fig. 1) only in four points on one of propeller-law-operated characteristics. The marine diesel engines work on different propeller-law-operated characteristics due to changing hull resistance during vessel operation. So addition of not-to-exceed (NTE) testing requirements is being debated. Probably it will be agreed that NTE limits with multiplier 1.5 would be applicable to NO_x emissions at any individual load point in the E3 (and E2) type cycle (CIMAC 2012). Important remark – engines are tested using distillate diesel fuels, in real life operation they work on residual oils (heavy fuels). The real emission of NO_x is not recognized in that case.

The SCR systems are dedicated for four-stroke medium speed engines due to higher than in two-stroke low speed engines exhaust gas temperatures. There are solutions of SCR systems for two-stroke engines as well (UK Maritime 2009, US Code 2009, IMO Resolution 2009, IMO Resolution 2015).

An essential parameter of proper process of SCR system is an exhaust gas temperature on the inlet to this system. The problem is the formation of sulfuric acid in the gas at low temperature which forms a sticky product ammonium bisulfate, which may accumulate in the SCR elements. The required minimum temperature is presented in Fig. 4.

On the other hand, the exhaust gas temperature (better in the inlet to SCR systems) must not be too high. The upper limit is up to about 500°C.

If temperature is increased the oxidation of ammonia is accelerated and the dose of urea should be increased. Additionally, the catalyst material starts to sinter at temperatures above 500-550°C. The exhaust gas temperatures should be within a certain temperature window 300-500°C.

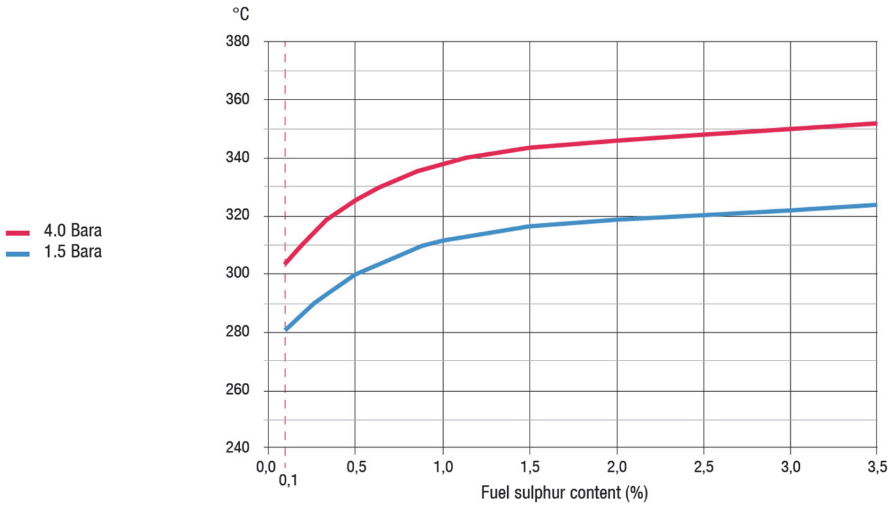

Fig. 4. Required temperatures for SCR related to sulfur content and exhaust gas pressure (in bar absolute pressure) (MAN Energy 2018)

Other methods are under research process to decrease the NO_x emission like ballast water injection into exhaust gas (to remove the NO_x) (Szkarowski et al. 2017a, Szkarowski et al. 2017b).

4. Reasons for change of vessel resistance and propeller characteristics

During vessel operation the size of ship total resistance depends on many reasons in general named sailing conditions. They can change according to outer conditions e.g. weather and sea conditions (state of sea, force and direction of currents and winds), technical state of hull (hull fouling due to corrosion, sea grows, hull deformation, paint layers damages), change of draft due to weight of cargo and ballast, sailing on shallow and narrow water etc. In stable conditions the vessel resistance is approximately proportional to vessel speed in square exponent but the power of engine is proportional to vessel speed in the third exponent. The extended marine engine work area is presented in Fig. 5. There is shown MAN engine contract parameters area (area inside lines L1-L2-L3-L4-L1) and point "O" as nominal parameters (power and speed) of engine. Because the diagram is executed in logarithmic scale propeller curves are shown as straight lines (here is presented: normal operation and heavy running operation, there is no line for light running operation) (MAN B&W 2010, MAN Energy 2018).

As a result the point of engine work should be inside the allowed area (inside engine work area), better inside the area of no restrictions (with possibility of continuous rating). Due to the possibility of propeller curve modification during vessel operation, the point of engine parameter shifts so it is one of the reasons of change the NO_x emission.

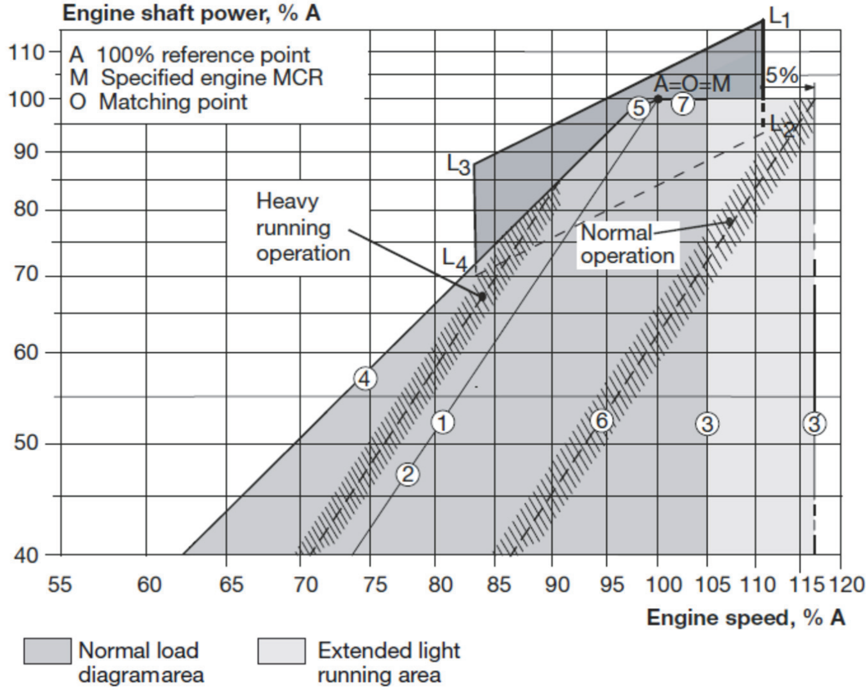

Fig. 5. Extended marine engine work area (MAN B&W 2010)
Line 1 – propeller curve through matching point “O” – layout curve for engine,
Line 2 – heavy propeller curve – fouled hull and heavy seas (extreme hull resistance),
Line 3 – speed limit,
Line 4 – extended speed limit (provided torsional vibration conditions permit),
Line 5 – mean effective pressure limit,
Line 6 – increased light running propeller curve (clean hull, calm weather);
possible lighter condition for ballast voyage,
Line 7 – power limit for continuous rating.

5. Problems of proper work controlling the systems of NO_x emission decreasing

All manufacturers of marine diesel engines have tried to solve the problems of proper work controlling the systems of NO_x emission decreasing. The Onboard Survey Methods should be prepared for the vessel crew by engine manufacturer. By reading or measuring certain performance engine parameters and comparing to limit values, the compliance of NO_x emission is verified. It is not known the real NO_x emission because it should be measured the actual exhaust gas mass flow and the NO_x content in exhaust gases. The parameters may be quickly evaluated due to the change of engine load, technical state of the engine, ambient air parameters (pressure, temperature, humidity), sea conditions etc. It is impossible to react quickly in transient states for proper adjustment of NO_x decreasing emission systems (Borkowski et al. 2011).

Certain cases may result of non-error situations where the system is not reducing NO_x (MAN Energy 2018):

- engine load change is faster than the guidance load change curve,
- rough sea conditions resulting in oscillating engine load,
- time during engaging and dis-engaging control valves,
- engine load and ambient conditions are outside the operating window for the emission control system as specified in the NO_x Technical File,
- other transient situations.

At low loads (below 15% of maximum continuous rating power) depending on type of the engine and sulfur content in fuel the urea injection (SCR system) will be suspended in order to prevent deposits in SCR system caused by insufficient exhaust gas temperatures (see Fig. 4). The other possibility is an increasing the exhaust gas temperature to the required level, part of the exhaust gas from the high pressure side if the turbine (turbocharger) is bypassed, controlled by an Exhaust Gas Bypass valve or EGR shut-off valve (SOV see Fig. 3), and directed to low pressure side. Using this method increases the specific fuel oil consumption (SFOC) (decreases the engine efficiency and increases the emission of carbon dioxide).

In case of system failures, the engine control system will issue an alarm code and text, allowing for the situation to be corrected. Such cases make many troubles for engineers because they have only few possibilities (like check: the valve positions, urea level in the tank, electric power supply) to remove the alarms and failures. The emission control systems are protected by manufacturers against the undesirable intervention of vessel crew.

6. Dosing of urea. Ammonia and hydrocarbons split

The SCR systems need during work the injection of urea or ammonia solutions. The consumption of reducing agent depends on the agent type, the engine load and the NO_x reduction rate. The urea or ammonia consumption may be calculated by the engine calculation program (CEAS for MAN engines). It is very important because the NO_x reduction rate will be too low due to too low dose, and on other hand the reduction NO_x rate may be proper but the urea or ammonia dose may be too big increasing the consumption (additional costs) and caused the ammonia slip (one of the green-house gases) to the atmosphere. The estimated specific consumption of urea and ammonia to reduce the NO_x from Tier 2 level to Tier 3 level is shown in Tab. 3.

Table 3. The estimated consumption of urea or ammonia solutions in SCR systems to reduce the NO_x emission from Tier 2 to Tier 3 (MAN Energy 2018)

Reducing agent	g/kWh	dm^3/MWh
Urea – 40% solution	17.9	16.1
Ammonia – 24,5% solution	16.6	18.4

The slip of ammonia from SCR system is dangerous to the exhaust gas boilers as well. The ammonia with sulfur originated from fuel can lead to deposits of ammonium bisulfate (ABS) on low temperature surfaces into the boiler. Furthermore, the deposits of ABS formed in the boiler are easily removed by standard cleaning methods of the boiler.

Engine operation on heavy fuel oils may cause of hydrocarbons (HC) split due to unburned hydrocarbons (UHC) directly during combustion process, next their absorption and desorption by the engine lubricating oils. Operation on heavy fuel oils gives the possibility of UHC formation as deposits on the cylinder walls, head and piston crown. Unburned hydrocarbons from within quench region in engines are expelled during the exhaust process. There are many problems (especially for the last 20-30 years) with the usage of heavy fuels in diesel engines due to:

- fuel stability,
- fuel compatibility,
- ignition quality (need heating for proper viscosity),
- contamination with waste products (e.g. used lubricating oils, hydrofluoric acid, organic chlorides, polypropylene, polystyrene, polyethylene, catalyst fines), etc.

Ship-owners or charterers always purchase the cheapest fuels.

7. Final remarks. How to improve the systems of NO_x emission decreasing?

The expectation is minimizing the threats of transport to the sea and environment. Is it possible to reach the Tier 3 limit emission (or better in the future) for the NO_x for all engines in the worldwide marine transport? The answer is difficult. There is a strong pressure for doing it. The new proposed emission limits are the challenge for engineers. They try to find out the remedy but we should remember the efficient marine transport is crucial for worldwide economy. The usage of SCR systems or/and EGR systems to fulfill the Tier 3 limit provides during operation to increasing the specific (and total) fuel consumption up to ten percent. The manufacturers tell that the difference is in a range from three to five percent. That may be true but this is difference between engine operation on mode Tier 2 and Tier 3. Taking account between engines built before 2000 year and now the difference is from five to ten percent. NO_x emission decreasing systems need additional electric energy. It generates costs for ship-owners and decreases the economy of marine transport.

The basic method for decreasing the NO_x emission (and total fuel consumption) is lowering the vessel speed and engine load. The fuel change on low-sulfur fuels on the ECA areas reduces mainly the sulfur oxides and particulate matters emission. Apart from isolated applications biofuels are not a real alternative for marine engines in long distance voyages. The idea of switching the vessel supply in electric energy from the port facilities during vessel stay in the ports only locally decreases the emission to the atmosphere. The Tier 3 limit is in effect only on the ECA areas. Methods for more efficient vessels are during searching. The expectancy is in minimizing the vessel hull resistance, increasing the total propulsion efficiency, finding out the methods of recovering the waste heat from engines for reaching the best energy efficiency operational index (EEOI index), etc.

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Abstract

The paper presents problems of limitation the nitrogen oxides emission from marine diesel engines. The emission of noxious substances from combustion of marine fuels is restricted in respect of the atmosphere protection, International Maritime Organization (IMO) regulations and others. The IMO requirements were determined by time of being in force. The first tier started in 2000 year, the second in 2011, the third is being valid from 2016 on USA waters and in some chosen port areas (from 2021 will be obligatory on Baltic Sea, North Sea and English Channel) and it is a necessity to comply those last requirements. In case of NO_x – between the first and second tier the emission was limited 20%, while the third step was limited 80% of the first one. This is a very great challenge, because in nowadays marine diesel engines and marine heavy and diesel oils generally applied, it would seem impossible comply those requirements. It was formed environmental controlled areas of NO_x emission (ECA) and they will extend. Governments of some countries (USA, Norway) were introduced on own territorial waters the requirements of NO_x and SO_x emission. In case of exceeding the limits (or a lack of the proper certificates) it was imposed an ecological charge (a form of tax) or the interdict of entrance on regulated water zones. In the paper it was given an attention to the new challenges for engine producers and ship-owners of fulfilling tier 3 standards or search new substitute solutions. The applying solutions for nitrogen oxides emission limitations cause the decreasing of engine efficiency and increasing the fuel consumption (and carbon dioxide emission) up to ten percent. Due to regulations of marine environment protection they generate additional investment and operation cost for ship-owners and charterers.

Keywords:
nitrogen oxides, marine engine, emission to the atmosphere, Tier 3 limit

Problemy zmniejszenia emisji tlenków azotu z okrętowych silników wysokoprężnych w celu spełnienia limitu emisji 3

Streszczenie

W artykule przedstawiono problemy ograniczania emisji tlenków azotu z okrętowych silników wysokoprężnych. W celu ochrony atmosfery przed emisją szkodliwych substancji z procesu spalania paliw okrętowych wprowadzono regulacje Międzynarodowej Organizacji Morskiej (IMO) i inne. Wymagania IMO określają czas wejścia w życie (obowiązywania). Pierwsze ograniczenie emisji tlenków azotu (Tier 1) obowiązuje od 2000 roku, drugie (Tier 2) od 2011, natomiast trzecie (Tier 3) obowiązuje od 2016 roku na wodach amerykańskich i wybranych obszarach portowych (od 2021 roku będzie obowiązywać na Morzu Bałtyckim i Północnym oraz Kanale La Manche) oraz zachodzi konieczność spełnienia tych wymagań. Dla tlenków azotu (NO_x) – pomiędzy pierwszym a drugim limitem jest różnica 20%, podczas gdy trzeci limit jest o 80% mniejszy od pierwszego. Jest to wielkie wyzwanie, ponieważ w okrętowych silnikach wysokoprężnych stosuje się paliwa ciężkie i oleje napędowe, wydaje się niemożliwe spełnienie tych wymagań. Utworzono obszary kontroli emisji (ECA) tlenków azotu i te obszary będą się powiększać. Rządy niektórych krajów (USA, Norwegia) wprowadziły własne wymagania na ich wodach terytorialnych odnośnie emisji tlenków azotu i tlenków siarki. W artykule zwrócono uwagę na nowe wyzwania dla producentów silników i armatorów statków w celu spełnienia standardów emisji w limicie Tier 3 lub poszukiwania innych równoważnych rozwiązań. Stosowane rozwiązania ograniczenia emisji tlenków azotu zmniejszają sprawność silników oraz zwiększają zużycie paliwa (i emisji dwutlenku węgla) nawet o dziesięć procent. Z powodu wprowadzenia regulacji chroniących środowisko morskie, generują one dodatkowe koszty inwestycyjne i eksploatacyjne dla armatorów i czarterujących.

Słowa kluczowe:
tlenki azotu, silnik wysokoprężny, emisja do atmosfery, poziom emisji 3