NOx emission reduction in marine diesel engines

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Abstract

Pollutant gases emitted from marine thermal engines cause degradations of the eco-systems. The aim of this paper is to propose competent measures for the reduction of NOx emissions from marine diesel engines in order to be in compliance with the technical code alongside promoting energy efficiency and environmental sustainability in the marine sector. Based on the code's instructions, all marine ships constructed or renovated after January the 1st of the year 2000, that are propelled by diesel engines of power output over 130 kW, are obliged to be certified by the NOx technical code and also to meet the emissions' limit according to the Annex VI of MARPOL 73/78. To this end, recommendation for the most efficient and cost-effective resolution in relation to the studied engines is made. The findings can be applied to similar vessels that face similar levels of excess emissions

Keywords: NOx Emission; Marine Engines; Selective Catalytic Reduction: MARPOL 73/78 Technical Code

1. Introduction

Over the past decades, several agencies, institutes and national laboratories, such as the European Environmental Agency (EEA), the Environmental Protection Agency (EPA) and other various Non-Governmental Organizations (NGO's), have made measurements and observations on the pollutant gases emitted from marine thermal engines. As observed and studied, various pollutants are being released into the atmosphere through the use of these engines, such as Particulate Matter (PM) emissions, Sulphur Dioxides (SO_2), Nitrogen Oxides (NOx), and Carbon Dioxides (CO_2).[1]

With the ultimate purpose being the degradation reduction of these ecosystems and the environment protection, the European Union has decided to set an emission ceiling in the already over-emitted amounts of nitrogen. This particular study deals with limitation of Nitrogen Oxides (NOx) emitted by shipping transport which play a major role in the deterioration of the ecosystems. Apart from the damage to the eco-system and ~~to~~ the environment, negative effects are observed in human health, by shipping transport emissions. Research and studies suggest that due to international shipping emissions approximately 50,000 deaths occur every year in Europe alone [2].

Nitrogen Oxides (NOx) are indirect greenhouse gases responsible for the production of the gas 'ozone' through photochemical reactions which take place in the atmosphere. They are thermally produced from nitrogen and oxygen during high temperature combustion processes. NOx mainly causes acidification of soil and water, damaging respiratory tissues both in animals and humans, leading to nutrient enrichment of bodies of water, also known as eutrophication. [3]

In order to achieve the limitation of NOx emissions, the European Union member states set NOx emission limits in the shipping transport according to the IMO resolution of the Marine Environment Protection Committee MEPC.176 (58) [4], referred in Annex VI and the revised NOx Technical Code of the MARPOL Marine Policy. According to the IMO, the revised Annex VI for the reduction of NOx emissions came into force on July 1st 2010. According to Annex VI of the MARPOL 73/78 [4], ships constructed or undergone major customisations after the dates presented in the following table (Table.1) with engine power capacities higher than 130 kW, are obligated to occupy a NOx certification which establishes compliance with the limits set by IMO. Furthermore, different levels of emission limits, referred as Tiers (Fig.1) apply, depending on the construction date of the ship and the specific emission limit set in relation with the rated speed of the examined marine engine.

Table 1 MARPOL Annex VI NOx Emission Limits [2]

Tier	Ship construction date on or after	Total weighted cycle emission limit (g/kWh) n = engine's rated speed (rpm)		
		n < 130	n = 130 - 1999	n ≥ 2000
I	1 January 2000	17.0	$45 . n^{-0.2}$ e.g., 720 rpm – 12.1	9.8
II	1 January 2011	14.4	$44 . n^{-0.23}$ e.g., 720 rpm – 9.7	7.7
III	1 January 2016*	3.4	$9 . n^{-0.2}$ e.g., 720 rpm – 2.4	2.0

* In NOx Emission Control Areas (NECAs) (Tier II standards apply outside ECAs).

Any ship that cannot obtain a NOx certification due to exceeding the MARPOL emission limits is not permitted to operate and in case it does, there are accountable and strict fines.

2. Background Situation

The damage and degradation of human health and environment by air pollution is severe. Approximately, 49,500 premature deaths occurred in Europe in the year 2000 alone, due to international shipping air pollution. Additionally, the premature deaths are expected to reach the number of 53,200 by 2020 [2]. Clearly, there is a need to provide cleaner and "healthier" air in an international scale. Nevertheless, this is an already known situation for several decades in the European Union, but action has only been focused on establishing minimum quality standards for ambient air, relocating the problems of ozone and acidification only in land-based activities. The procedures followed to prevent air pollution are presented below.

A permanent international body, responsible for composing regulations for the safety of shipping, was established in 1958 known today as International Maritime Organization (IMO). In order to prevent and reduce the environmental damage and threats from shipping pollution, the IMO adopted the International Convention for the Prevention of Pollution from ships, also known as MARPOL, in November 1973. MARPOL is today a combination of the treaties of 1973 and 1978 along with any amendments made through the years [2]. In the year 1997, a new protocol was added to the convention - Annex VI- for the prevention of air pollution from ships. This Annex sets limits on Sulphur Oxides (SOx) and Nitrogen Oxides (NOx) emissions from ship exhausts.

The MARPOL's Annex VI defines certain maritime areas around the world as Emission Control Areas (ECA's). There are the "SOx Emission Control Areas" (SECA's) and the "NOx Emission Control Areas" (NECA's). Due to population density, sensitive ecosystems and sea traffic, these areas are under strict emission limits produced by nearby ships (Fig.1). However, according to the European legislation (Table.2) there are not yet any NOx Emission Control Areas in the European Union waters. Even the SOx Emission Control Areas are limited to the Baltic and North Sea.

Fig. 1 Global Emission Control Areas [6]

Table 2 Special Emission Control Areas, entry and effective dates [7]

ANNEX VI – Prevention of air pollution by ships (Emission Control Areas)			
Special Areas	Adopted	Date of Enforcement	In Effect From
Baltic Sea (SOx)	26 Sept 1997	19 May 2005	19 May 2006
North Sea (SOx)	22 Jul 2005	22 Nov 2006	22 Nov 2007
North American (SOx, NOx and PM)	26 Mar 2010	1 Aug 2011	1 Aug 2012
United States Caribbean Sea ECA (SOx, NOx and PM)	26 Jul 2011	1 Jan 2013	1 Jan 2014

As mentioned above, the European Union has implemented several laws in order to take action for the control of the NOx emissions produced by shipping transportation means within its coastal waters.

United States, Canada, Japan, Denmark and Germany did not favour this agreement and postponed the application of Tier III standards, so in the 66th session of the MEPC, a middle ground solution was reached, directing that Tier III standards would eventually be implemented in 2016 but for ships constructed on and after the 1st of January 2016, which would operate in emission control areas (ECA's) (Fig.1) in America (MEPC 66/6/6). However, there are no EU standards to control NOx emissions in European waters, so NGO's and some member states of the IMO continuously try to push the European Commission to apply measures for the reduction of NOx emissions produced by shipping. [8]

The aim of this investigation is to determine the current level of a particular ship's NOx emissions, compare it with the emission limits set by Annex VI of MARPOL and propose an adequate measure for the reduction of the emissions. There are several measures to reduce the NOx emissions of a ship's diesel engine. It can be stated here, that there are methods applied in the engine during the combustion process, referred as "primal methods" in this investigation, as well as methods that are applied after the combustion process is complete, and more precisely in the engine's exhaust gases, referred in the investigation as "secondary methods".

In the primal methods, the main objective is to achieve the reduction of the maximum temperature inside the combustion chamber, as this results in lower NOx emissions. Managing to have low NOx emissions, is in direct relation to the fuel injector times, the air fuel mixture ratio, and the compression ratio. Some possible primal methods are noted below. [9]

- Fuel Injection Modification
  - Modifying the fuel nozzles
  - Fuel injection in higher pressures
  - Delaying the fuel injection

- Water Addition
  - Stratified water injection
  - Direct water injection
  - Intake air humidification
  - Water emulsified fuel

- Engine Modification
  - Altering the compression ratio

- Treating the Combustion Air
  - Inlet and exhaust valve adjustment
  - Exhaust gas recirculation

In the secondary methods, the main objective is managing to remove the NOx from the exhaust gases with an after combustion treatment. This can be achieved with a method called Selective Catalytic Reduction (SCR) (Fig.2).

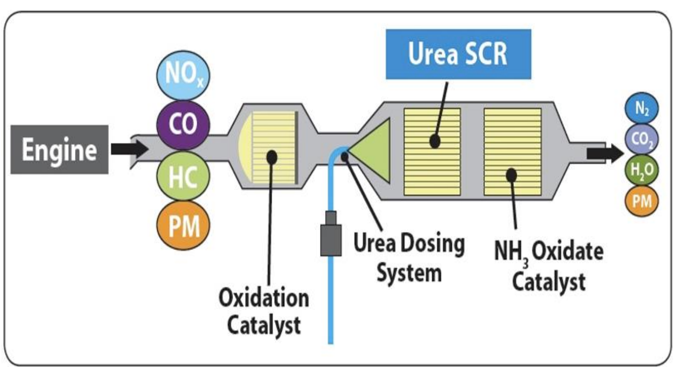


Fig. 2 Typical Selective Catalytic Reduction set up [10]

The selective catalytic reduction of nitrogen oxides by ammonia (NH_3) or urea (CH_4N_2O) is considered to be the most commonly used method to remove nitrogen monoxides from the exhaust gases. It utilizes catalysts from materials such as vanadium/titanium because of their ability to be stable in high temperatures. This process works by injecting urea or ammonia into the exhaust gases of the engine and as they pass through the catalyst converter a reaction takes place, which results in the transformation of nitrogen monoxides and urea into nitrogen (N_2) and water (H_2O). Reactions (1), (2).

Catalyst chemical reaction:

$$4NO + 4NH_3 + O_2 \leftrightarrow 4N_2 + 6H_2O \quad (1)$$

$$6NO_2 + 8NH_3 \leftrightarrow 7N_2 + 12H_2O \quad (2)$$

It can be observed in the above reaction that from the conversion of nitrogen oxides no secondary pollution occurs as the only products created are nitrogen and water.

The amount of nitrogen monoxide that can be removed from the exhaust gases is in direct relation to the amount of ammonia or urea injected into the exhaust gases. If higher amount of ammonia is injected into the exhaust gases, then higher amounts of NOx will be removed from the gases. However, it is observed that the ammonia injected is not completely absorbed, so in higher amounts of ammonia injected, a higher amount of ammonia stays unabsorbed. This is known as the ***ammonia slip,*** a problem solved with electronic control of the proportion of the nitrogen monoxides produced from the diesel engine. [11]

3. Methodology

3.1 The NOx Technical Code Procedure

The measurement procedure will be implemented on board of a marine vessel, thus according to the NOx Technical Code the bellow steps should be followed.

In order to measure meaningful results for onboard confirmation, the gaseous emission concentrations of NOx will be measured in accordance with the appropriate test cycle. The weighting factors (WF) and the number of modes (n) used in the calculation shall be in accordance to Table 3. More specifically, the NOx technical code suggests that the examined engines should be tested when they run under a percentage of engine rated speed and the engine output should, for the specific engine speed, be calculated as a percentage of the total output (Table.3).

Table 3 Test cycle for Propeller-law-operated main and propeller-law-operated auxiliary engine application [4]

Speed	100%	91%	80%	63%
Power	100%	75%	50%	25%
Weighting factor	0.2	0.5	0.15	0.15

The engine torque and speed must be measured as well, though if not possible, the brake power may be estimated by any other means recommended. Additionally, the oil consumption must also be measured but since high difficulty has been recorded, this can be retrieved from the engine's performance curves. The following table (Table.4) shows the engine performance parameters that can be measured or calculated at each mode, during an on-board NOx monitoring.

Table 4 Engine Parameters to be measured and Recorded [4]

Symbol	Parameter	Dimension
n_d	Engine speed	min^{-1}
p_C	Charge air pressure at receiver	kPa
P	Brake power (as specified below)	kW
P_{aux}	Auxiliary power (if relevant)	kW
T_{sc}	Charge air temperature at receiver (if applicable)	K
T_{caclin}	Charge air cooler, coolant inlet temperature (if applicable)	°C
$T_{caclout}$	Charge air cooler, coolant outlet temperature (if applicable)	°C
T_{Sea}	Seawater temperature (if applicable)	°C
q_{mf}	Fuel oil flow (as specified below)	kg/h

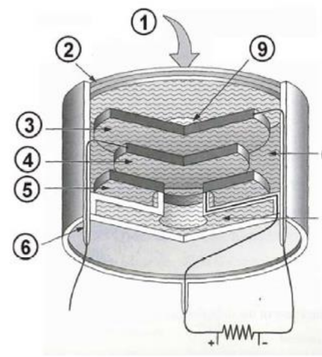
3.2 The Measurement Apparatus

A series of equipment has been used in order to retrieve measurements: a gas analyser, a climatic conditions measurement device and a laser tachometer. The gas analyser has been used for measuring the values of the exhaust gases emitted by the diesel engines. Humidity, barometric pressure and ambient temperature have been measured with the climatic conditions measurement device, while the rotational speed of the engines in each test mode has been recorded using the digital tachometer. Furthermore, additional data has been retrieved from the manufacturer's performance curves, such as intake air flow, engine temperature, engine's power and fuel consumption.

3.2.1 The Gas Analyser

The gas analyser used in the measurements is the flue gas analyser VarioPlus Industrial, manufactured by MRU GmbH. Based on MRU, VarioPlus is an exhaust gas emission analyser that can be used in various applications, one of them being control measurements and compliance testing of diesel engines. It is able to measure pressure, temperature and a range of toxic gases such as carbon monoxide (CO), carbon dioxide (CO_2), hydro-carbons (HC), nitrogen oxide (NO), nitrogen dioxide (NO_2), sulphur dioxide (SO_2), hydrogen sulphide (H_2S) and oxygen (O_2).

This device is equipped with 6 electrochemical sensors. These sensors (Fig. 3) are based on the gas diffusion technology and contain two or three electrodes, in interaction with an electrolyte. Due to the fact that the gas supply is limited by diffusion, the permanently generated signal is direct proportionally and linear to the volume concentration (% or ppm) of the analysis gas components. [12]



Pos.	
1	Sample gas
2	Particle filter
3	Sensing electrode
4	Reference electrode
5	Counter electrode
6	Connecting pin
7	Electrolyte reservoir
8	Bilk electrolyte
9	Capillary diffusion barrier

Fig. 3 Electrochemical sensor of the VarioPlus [12]

3.2.2 The Climatic Conditions Measurement Device

Air humidity, ambient air temperature and atmospheric pressure were measured with the use of Kimo AQ 200 device [13]. These values are necessary for the correction of the NOx emission measurements.

With the climatic conditions module, which is equipped with a capacitive hygrometry sensor, the Kimo AQ 200 can measure the air humidity. Furthermore, this module is equipped with a semiconductor temperature sensor, capable of measuring the environmental temperature. The absolute temperature of the environment is proportional to the difference in base-emitter voltages of the two identical transistors.

Finally, the climatic conditions module can measure the air pressure by a capacitive sensor.

3.2.3 The Digital Tachometer

Two different ways were used in order to measure the engine's speed during the measurement procedure. The first one was by recording the values of the engine's digital tachometers. The second way, being much more precise and accurate in the register of the speed values was with the use of a portable microprocessor based photo tachometer.

A beam light is directed by the photo tachometer, which detects the light pulse reflected back from a reflective tape mark applied on the engine axis. The laser tachometer used in the measurements was the LUTRON DT-2234A (Fig.4)

Test Range	5 to 100,000RPM, auto ranging
Resolution	0.1 RPM (1 RPM (>1,000 RPM)
Accuracy	± 0.05% + 1 digit
Sampling Time	1 second

Fig.4 LUTRON DT-2234A laser tachometer specifications [14]

3.3 The Experimental Ship Vessel

The specific marine vessel (Fig.5) used for this investigation was a tugboat operated under the Greek flag, built in 1983. During 2013 it was retrofitted and the two old diesel engines were replaced with two previously used ones but of higher capacity. According to the NOx technical code, when a ship replaces its engines it is subject to major conversion. What is meant by this is that the ship has to accomplish an initial engine certification survey. During this initial engine certification, the new engines are tested and measured as to whether they comply with the respective NOx emission limits. These engines fall in Tier II of the MARPOL Annex VI because its engines were installed in 2013. The specification sheet of the engines is shown in Table 5.

The measurement procedure used to receive the data is the one set by the NOx technical code. This technique is highly standardized in order to produce comparable results.

Table 5 Tugboat Diesel Engine Specifications [15]

Manufacturer	CATERPILLAR
Type	3512 B
Cycle	4-stroke diesel
Number of cylinders	V-12
Bore	170 mm
Stroke	190 mm
Compression Ratio	13,5:1
Power	1077 bkW
Revolutions	1800 rpm
Consumption	270 l/h

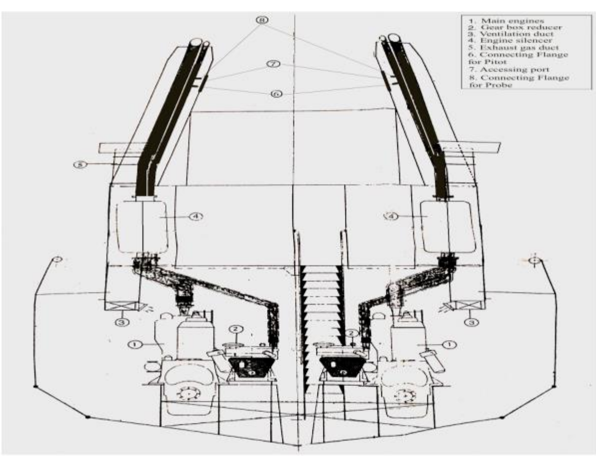


Fig. 5 Sectional Elevation of the experimental vessel [15]

3.3.1 The exhaust gas flow

The technique applied for the measurement of the exhaust gas flow, was one acceptable method of the NOx Technical Code. It was the direct measurement technique, which involves the direct measurement of the exhaust gas flow using the VarioPlus instrument with the Pitot tube. The sample point for the instrument is of high importance for the prevention of possible errors in the gas flow measurements.

3.3.2 The Performance Curves

The engine's performance curves received from the manufacturer were of high value as the engine's power, oil consumption and air inlet temperature, was recorded. The measurement procedure took place on board, thus it was impossible to install a dynamometer to retrieve values like force, torque and power. All these values were taken from the performance curves.

3.3.3 Weighting Factors

The engines were examined in accordance with the NOx technical code. The most suitable weighting factor table, found in the NOx Technical Code in relation with the characteristics of the examined engines is shown in Table 3.

3.3.4 Test Sequence

As directed by IMO during each mode of the test cycle (Table3), after the initial transition period, the specified speed was held within ±1% of the rated speed or ±3 min^{-1}, whichever was higher. The determined torque was defined in relation with the speed-torque curves of the engine, provided by the manufacturer. The speed that corresponds to the specified torque of every tested mode was held so that the average over the period during which the measurements were being taken was within ±2% of the rated torque at the engine's rated speed.

3.3.5 NOx Reduction Algorithm

NOx emissions are affected by the ambient temperature and humidity. In order to be able to compare the measured data from the engines, for different ambient air conditions, correction factors have been developed [16]. The correction factors used in this investigation were those set by the NOx technical Code [17]. The purpose of correcting the measured values is for normalizing the NOx emissions under certain standard reference conditions. According to the NOx technical Code the reference value for air temperature is 25ºC and for air humidity of 10.71 g/kg. The NOx emissions were corrected in accordance to equation 1 which is valid for compression ignition engines when they have intermediate air cooler as in the case presented.

Equation. 1

$$k_{hd} = \frac{1}{1-0{,}012*(H_a-10{,}71)-0{,}00275*(T_a-25)+0{,}00285*(T_{SC}-T_{SCref})}$$

where:

H_a: is the humidity of the intake air at the inlet to the air filter in g of water per kg dry air.

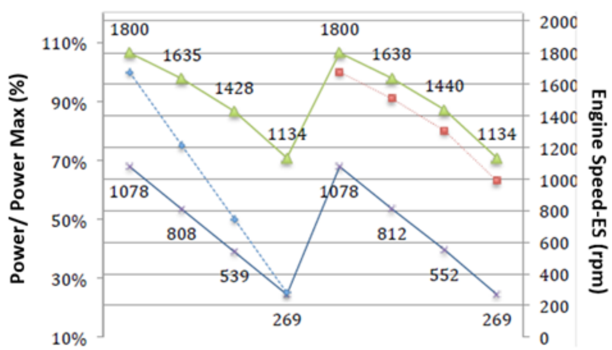
T_a: is the air temperature at the inlet to the air filter in Celsius degrees.

T_{SC}: is the temperature of the charge air.

T_{SCRef}: is the temperature of the charge air at each mode point corresponding to a seawater temperature of 25°C. T_{SCRef} is specified by the manufacturer.

4. Results and discussions

In the measurement procedure eight different operating modes (OM) were used for each engine under real weather and operation conditions, (Fig.6). The operating modes were chosen in accordance to the directions of the NOx technical code for a propeller law operated engine. Both diesel engines were of the same type, tuned to equal performance, thus having matching performance values. Under these modes, the examined engine type was operated in 100%, 75%, 50% and 25% of its rated power and 100%, 91%, 80% and 63% of its rated speed.



	Mode 1	Mode 2	Mode 3	Mode 4	Mode 5	Mode 6	Mode 7	Mode 8
Engine Speed (rpm)	1800	1635	1428	1134	1800	1638	1440	1134
Engine Power (bkW)	1078	808	539	269	1078	812	552	269
Power	100%	75%	50%	25%				
Speed					100%	91%	80%	63%

Fig. 6 Engine Performance for different Operating Modes

For the various operating modes (Fig.6), different values were measured for producing normalized comparable results. Figure 7 illustrates the recorded values of NOx emissions produced by the two tested diesel engines and measured subsequently. The green value presents the NOx emissions of the engine No.1 under "Steady Trial". This is a trial conducted by measuring the exhaust emissions when the ship vessel is pushed against an unmovable object. It was performed only for engine No.1 at the 80% of its rated speed.

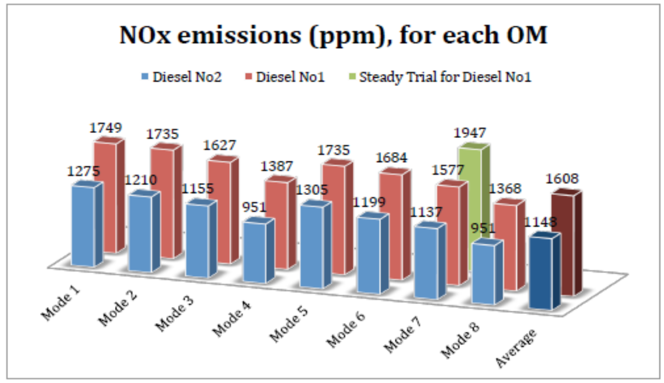


Fig. 7 NOx Emission levels produced by the two diesel engines under different operating modes

In the following figure the comparison of the NOx specific emissions of the two diesel engines with the limits set by the NOx Technical Code is presented. Due to the date of the engine's installation, the NOx emission limits fall into Tier II and are not permitted to exceed them. As it can be observed from figure 8, the produced emissions of the two engines are even higher than the limits of Tier I. The average value of the produced NOx emissions from the diesel engine No.1 was 20.71 g/kWh and from engine No.2 was 14.62 g/kWh, when the average value of Tier II is 8.74 g/kWh. That means that the NOx emissions from engine No.1 were 2.36 times higher than the limit and 1.67 times higher from engine No.2. Additionally, the produced NOx specific emission of the No.1 engine is 41% higher than engine No.2.

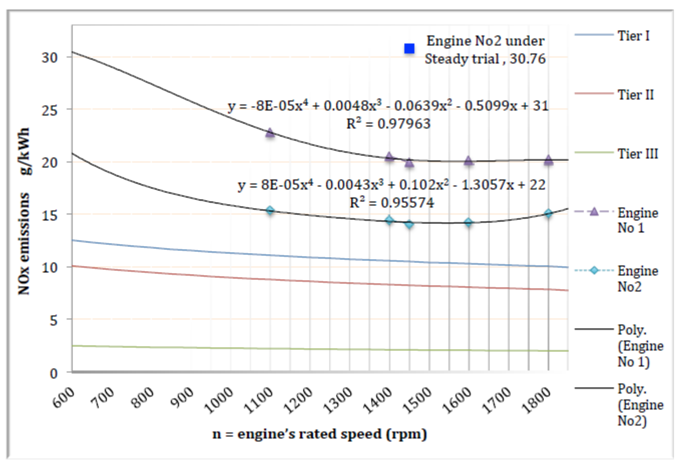


Fig. 8 Engines NOx specific emissions (g/kWh) in comparison to Tier I, II, III

Finally, the following table (Table.6) shows the deviation of the NOx emissions from TIER II limits.

Table 6 Diesel Engine NOx Emissions and Tier II Levels

a/a	Diesel Engine No1	Diesel Engine No2	Tier II
NOx specific emissions mean values gr/kWh	20,87	14,85	7,85
Declension from Tier II	+ 166 %	+ 89 %	---

As it is obvious, the need to install a device able to reduce the NOx emissions of the diesel engines ~~of ship~~ is mandatory in order for the ship to be able to meet the limitations of the NOx Technical Code. As referred previously on this paper, the reduction methods are separated in primary and secondary. Primary methods are able to reduce the NOx emissions from 10% up to 60% depending on the engine technology as well as on the specific reduction method. The following figure (Fig.9) shows the engines NOx production behaviour after the use of the adBlue liquid, an aqueous urea solution made with 32.5% urea and 67.5% deionized water, that tends to reduce the NOx emissions.

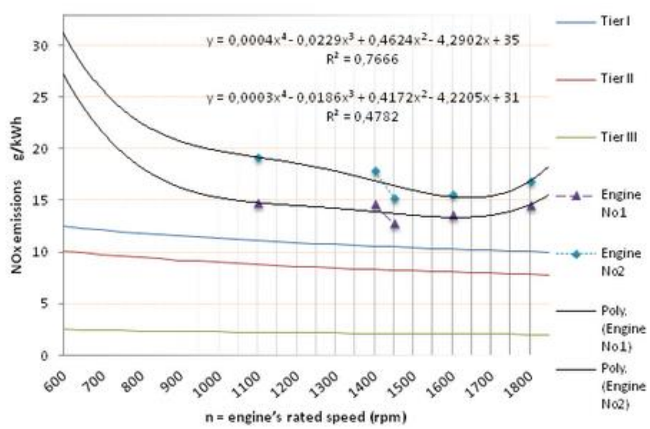


Fig. 9 The NOx production behavior after using the adBlue liquid

The secondary methods aim to remove the emitted NOx from the exhaust gases and are considered to be way more effective since they can reduce 80-90% of the NOx emissions.

The most appropriate reduction measure, for the examined ship vessel is considered to be a secondary method. More precisely, the NOx emission reduction could be achieved with the installation of a Selective Catalytic Reduction (SCR) set up in the exhaust system of the diesel engine. With the implementation of this measure the NOx emissions are estimated to be reduced by approximately 53%. This will drop the emissions down, into the acceptable limits of the Tier II limits.

5. Conclusions

The present research provides a review for the importance of the regulations and standards to achieve the NOx emission limits in the shipping transport according to IMO. A standard best practice on board measurement process was proposed and tested on a vessel case in order to achieve the optimum solution for marine diesel engines.

A series of on-board tests and high quality measures under variable conditions of speed, load and real weather conditions were performed before and after engine service and maintenance. Differences were detected on the exhaust emissions of the two marine engines, even though they belong to the same type of diesel engines. The reasons affecting the emissions' variation of the same type engines are related to the general condition of an engine (total running hours, last time serviced, fuel nozzle condition, deterioration of engine components, etc.) or/and to micro adjustments on the engine (fuel rack position, timing, etc). A small decrease of NOx level was detected keeping the emissions above the TIER II limit line.

A classification and a brief description of the main ways of NOx reduction were analyzed and the use of SCR was decided to be the first choice due to the large potential for lowering the NOx emissions. The on-board vessel tests and measurements were repeated using the additive adBlue Urea solvent to verify the potential of the SCR to drastically change the engines' emissions. The engine improvement was measured indicating as a final proposal for the next phase, the use of a small-scale SCR adapted in the marine engine exhaust system.

The proposed solution as well as the whole procedure, for reaching better marine engines NOx emission levels, may also be applied on other marine vessels facing similar compliance obligations.

Abbreviations

IMO - International Maritime Organization
ECA - Emission Control Areas
MARPOL - The International Convention for the Prevention of Pollution from Ships
MEPC - Marine Environment Protection Committee
NECA - NOx Emission Control Areas
SCR - Selective Catalytic Reduction
SECA - SOx Emission Control Areas

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