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Impact of Nitrogen Oxides Emission Reduction Methods on Specific Fuel Consumption of Marine Diesel Engines

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Abstract The paper has been presented the methods of nitrogen oxides emission reduction to fulfill the Tier 2 and Tier 3 requirements of the Annex VI of MARPOL Convention. It has been shown the development of marine two-stroke diesel engines and the change of nitrogen oxides emission from 1960 to 2000 and later up to 2020 after the implementation of NO_x emission reduction methods. Specific fuel consumption before 2000, and as a prediction and given data in the manufacturers manuals for Tier 3 engines up to 2020, and as only a prediction up to 2030 has been analyzed and elaborated. Impact of nitrogen oxides reduction methods on the specific fuel consumption of the marine diesel engine has been evaluated. Additional emission of some gases to the atmosphere due to the implementation of reduction methods has been determined. EGR and SCR systems have got a lot of imperfections: required to install additional reduction systems (investment cost, required volume in the engine room), need maintenance and operation costs, produced wastes during treatment process. The estimated additional cost is about 0.8 USD/MWh of produced energy, taking into account only the cost of excessive used fuel. The whole increased cost may reach the level two-three times more due to cleaning systems investment costs, their operational cost and waste disposal. It has been the one of the reasons of worsening the transport effectiveness and competitiveness.

Keywords: ship operation: marine slow and medium speed diesel engine, emission to atmosphere, nitrogen oxides, nitrogen oxides emission reduction: specific fuel consumption

1. Introduction

The limited level of nitrogen oxides (NO_x) emission is a requirement due to Annex 6 of the International Convention on the Prevention of the Pollution from Ships, known as MARPOL 73/78 (IMO 1997, IMO 2005, IMO 2008b). The revised Annex 6, prepared in 2008, entered into force on 1st July 2010 (IMO 2008a). The amendments introduced:

- new fuel quality requirements beginning from 1st July 2010,
- Tier II and III emission standards for new built marine engines,
- Tier I requirements for existing pre-2000 engines.

It may be seen that global requirement is the Tier II, more stringent requirements applicable to ships in Emission Control Areas (ECA). On 1st January 2021 existing Emission Control Areas include (ABS 2015, ABS 2017, Dulebenets 2016, IMO 2018, IMO 2019):

- Baltic Sea (SO_x: adopted 1997, entered into force 2005; NO_x: 2016/2021),
- North Sea (SO_x: 2005/2006; NO_x: 2016/2021),
- North American ECA, including most of US and Canadian coast (NO_x & SO_x: 2010/2012),
- US Caribbean ECA, including Puerto Rico and Virgin Islands (NO_x & SO_x: 2011/2014).

Looking for undertaken measures to fulfill the requirements of Tier II, it may be enumerated the following methods: combustion process optimization, fuel injection timing, limitation of maximal combustion pressure, optimization of fuel nozzle flow area, implementation of electronic injection systems (with common rail), exhaust valve timing, change of cylinder compression volume etc. Because the Tier III NO_x emission requirement is four times lower than Tier II, the following technologies should be introduced: fresh water induction into the combustion process (with fuel as fuel-water mixture, wet scavenging air, or in-cylinder direct injection), exhaust gas recirculation (EGR), or selective catalytic reduction (SCR) systems (Herdzik 2011, Herdzik 2019, IMO 2009, IMO 2015). The target is to reach the emission limits according to various types of engine testing procedures incorporated in (Dieselnet 2021, ISO 2020). Engine emissions are tested on various cycles: E2 & E3 for various types of propulsion engines, D2 for constant speed auxiliary engines, C1 for variable speed and load auxiliary engines. Because the emission is measured in specified points of load and/or engine rotational speed, addition of "not-to-exceed" (NTE) testing requirements to the Tier III standards is being debated. NTE limits with a multiplier of 1.5 would be applicable to NO_x emissions at any individual load point in the E2/E3 cycle. Further technical details pertaining to NO_x emissions, such as emission control methods, are included in the mandatory "NO_x Technical Code" (IMO 2005, IMO 2019, IMO 2021, PRS 2020). As it was above mentioned, all new built marine diesel engines after 2010, should comply the Tier II limits. Complying the Tier III requires an implementation of additional systems. As important, currently the Tier III requirements should be fulfilled only on appointed ECA areas, outside ECA areas the same engines may work on Tier II limits. It means that the by-pas systems are in use and the earlier mentioned additional systems (EGR or SCR) are switched off. The by-pass systems are necessary in emergency situations as well.

2. Reasons of nitrogen oxides emission reduction on increased specific fuel consumption and performance of marine engines

Till 2000, the target of marine diesel engines manufacturers was the engine reliability, an increasing of engine power and medium effective pressure, a possibility of simple maintenance and the most important to reach the highest thermal and effective efficiency and as a consequence the decreasing of specific fuel consumption, especially in the range of 50-85% of nominal power, where the engines should mostly work. The information about 50-53% for the best marine diesel engine efficiency has been given (MAN 2021).

An implementation of NO_x emission reduction methods have induced disorders leading to the decreasing the engine efficiency and increasing the specific fuel consumption. How it was possible? Due to the main effect of maximal combustion temperature leading to producing the thermal NO_x, it has been decided to reduce the maximal combustion pressure and temperature by (Lloyd's 2002):

- decreasing the cylinder compression volume (geometric compression ratio) and as an effect, decreasing the maximal compression pressure,
- delaying the fuel injection and dividing onto two cycles,
- exhaust valve timing, mainly earlier opening and later closing, leading to engine power reducing.

It leads directly to decreasing the engine thermal efficiency (on a level 1-8% depends on the engine load). The other methods like: optimization of fuel nozzle flow area and implementation of electronic injection systems have a different impact on diesel engine performance.

To achieve the Tier III limits needs more radical steps. Preparing fuel-water mixtures, wet scavenging air and/or in-cylinder water injection cause the decreasing of maximal combustion temperature (due to water evaporation during that process) but increase the mass of work medium, and as a final result, complicate the engine systems having different effect on engine efficiency (approximately without any essential impact on efficiency).

These mentioned methods are not to be sufficient to fulfill the limit of Tier III. It must be implementing one of these (MAN 2012b):

- exhaust gas recirculation (EGR),
- or selective catalytic reduction (SCR) systems.

Exhaust gas recirculation method mixes the fresh compressed air with a part of cleaned and compressed exhaust gases before the inlet to engine (in the scavenge receiver). The rate of exhaust gases comprise from 5 to 30%. Exceeding the 30% of rate leads to significant deterioration of diesel engine performance. Due to addition flow resistance of exhaust gases system and the usage of electric energy for driving the exhaust gas compressor, EGR results in power and efficiency reduction of diesel engine.

Selective Catalytic Reduction method gives an addition flow resistance in exhaust gas system. The resistance is increasing during engine operation due to contamination and choking process inside the flow channels. Increased fuel consumption and decreasing of engine power are the final effect. An operation of SCR system needs an additional preparing process of ammonia or urea solution, control and dosing process to SCR system and possible overdosing the chemicals leading to ammonia slip to the atmosphere (Herdzik 2019).

3. Impact of NO_x emission reduction on specific fuel consumption and efficiency of marine diesel engines

During last 50 years it may be seen a significant development of two stroke low speed marine diesel engines. The output has grown up to 100,000 kW from one engine. From sixties years last century it was possible that only one diesel engine has been used for vessels propulsion. Due to first fuel crisis (seventies years last century) the decision of ship-owners has been to change the type of prime movers of vessels from steam turbines on diesel engines. The efficiency of diesel engines substantially has exceeded the steam turbine efficiency.

Diesel engines have emitted to the atmosphere many different substances, like: carbon dioxide and monoxide, water vapor, sulfur oxides, nitrogen oxides, unburnt hydrocarbons, particulate matters and many others. The emission quantity depends on the engine load, fuel and lubricating oil consumption, engine rotational speed, fuel type used, etc. Sulfur oxides emission has been meaningfully decreased by the usage of low-sulfur fuels or scrubbers. Ship speed reduction has been introduced to marine transport as a simple remedy for constricting shipping costs and CO_2 emission (Chang & Wang 2014, Faber et al. 2012). Carbon dioxide emission from marine transport has been monitored due to (Directive 2015). How to influence CO_2 emission and constrict has been indicated in (MAN 2014).

Typical emission level from the two-stroke marine diesel engines, before introducing the limitations in 2000, has been presented in Table 1.

Table 1. Typical main diesel engine fuel consumption and emission before 2000 per 1000 kWh produced mechanical energy (own elaboration)

Type of main engine	Specific fuel consumption	Lubricating oil consumption	Carbon dioxide emission	Nitrogen oxides emission	Sulfur oxides emission*	Hydrocarbons emission
Low speed, two-stroke	170 kg	1.5 kg	530 kg	17-20 kg	15.3 kg	0.15-0.2 kg

* for 4.5% sulfur content in the heavy fuel oil (HFO)

An implementation, of the NO_x emission reduction from 2000, has been constituted a new era in the diesel engines development (MAN 2018). A usage of different methods constricted NO_x emission has been caused the increase of specific fuel consumption (SFC) and decrease the efficiency of marine diesel engines. Data concerning to SFC and efficiency up to 2020 and between 2000 and 2030 with a prediction for diesel engines performance with and without NO_x limitation has been presented in Table 2.

Table 2. Specific fuel consumption and efficiency of marine diesel engines for vessel's propulsion in 1970-2030, a prediction beyond 2020 (own elaboration)

Year	**1970**	**1975**	**1980**	**1985**	**1990**	**1995**	**2000**
SFC [kg/kWh]	0.213	0.208	0.185	0.178	0.170	0.168	0.170
SFC without NO_x limitation [kg/kWh]	0.213	0.208	0.185	0.178	0.170	0.168	0.160
Efficiency [%]	39.58	40.53	45.57	47.36	49.59	50.18	49.59
Efficiency without NO_x limitation [%]	39.58	40.53	45.57	47.36	49.59	50.18	52.68
Year	**2005**	**2010**	**2015**	**2020**	**2025**	**2030**	–
SFC [kg/kWh]	0.167	0.170	0.168	0.165	0.163	0.160	–
SFC without NO_x limitation [kg/kWh]	0.155	0.150	0.147	0.145	0.142	0.140	–
Efficiency [%]	50.48	49.59	50.18	51.09	51.71	52.68	–
Efficiency without NO_x limitation [%]	54.38	56.20	57.34	58.13	59.36	60.21	–

It has been elaborated on a base of accessible information from manuals, and project guides issued by the marine diesel engines manufacturers (Sulzer, B&W, MAN, Mitsubishi, Wartsila and others) from 1970s up to 2020.

It may be seen the difference between SFCs after 2010 on a level of 0.02 kg/kWh. It means that the difference of fuel consumption comprises about 14% and as a consequence the total emission to the atmosphere has been increased at the same level.

4. Additional carbon dioxide emission due to increased fuel consumption as a result of nitrogen oxides reduction systems implementation

An increased specific fuel consumption, due to a use of NO_x emission reduction methods, leads to an additional emission to the atmosphere all substances mentioned above. A profit and loss account for selected parameters has been presented in Table 3. It has been elaborated on a base of information and prediction in Table 2 and (Dulebenets 2016, Herdzik 2019, MAN 2012a, MAN 2012b, MAN 2018).

Table 3. Profit and loss account due to the usage of NO_x reduction methods (own elaboration)

Parameter	profit		loss	
Decreasing of NO_x emission	13.6 g/kWh*	80%		
Specific fuel consumption			20 g/kWh	14%
Additional cost of HFO**			0.8 US¢/kWh 0.8 USD/MWh	
Real decreasing of NO_x emission	11.7 g/kWh	68.8%	1.9 g/kWh	14%
Additional CO_2 emission			62.4 g/kWh	14%
Total CO_2 emission			500 g/kWh	
Electric energy demand for SCR			5 kW/MW SMCR	0.5%
Electric energy demand for EGR blower			7 kW/MW SMCR	0.7%
Diesel engine output				2%

* difference between NO_x emission Tier 1 and Tier 3
** HFO price – 400 USD/mt

It may be seen that a profit of 11.7 g/kWh lower NO_x emission effects on 62.4 g/kWh increased CO_2 emission (it gives 5.3 g CO_2/g NO_x). Other losses – like: additional investment cost of NO_x reduction system, additional required volume in the vessel power plant, operational cost, additional labor expenditure, waste management of residues after cleaning treatment – are not evaluated.

Additional required volume for EGR or SCR systems has a significant meaning during design process of the vessel power plant. Two way approach for Tier 3 engines – EGR and SCR (here - high pressure) has been presented in Figure 1.

Fig. 1. Two way approach for Tier 3 engines – EGR and SCR solutions (MAN 2012)

5. Environment effect of nitrogen oxides reduction systems operation

Due to the increasing of marine diesel engine power and load through the construction of the bigger cylinder liner diameters, longer piston stroke up to superlong-stroke (stroke/diameter ratio = 4.5) and more number of cylinders (up to 14 for two-stroke and 20 for four-stroke V type engines), and mainly through the increasing mean effective pressure (MEP) starting in 1960s from 6 bar up to 22 bar (for two-stroke) and 27.5 bar (for four-stroke) in 2010s – the NO_x emission has been still increased reaching the level over 20 g NO_x/kWh in 1990s. Two-stroke marine diesel engine NO_x emission development has been shown in Figure 2.

From 2000, it may be seen the process of decreased NO_x emission due to Annex VI of MARPOL 73/78 requirements up to reach the level of Tier 3 on ECA areas.

NO_x reduction emission systems – EGR and SCR, have been caused in the increased fuel consumption. Apart from this fact, it makes an additional fuel cost, it comprises the influence on the marine environment. Decreasing the NO_x emission has had a direct effect on the increasing of CO_2 emission, about 5.3 g CO_2/g NO_x approximately. The global warming potential (GWP) for NO_x is estimated as 30-33 and 7-10 for the respective time horizon 20 and 100 years. So, it may be said that the reduction of NO_x emission decreases, in that part of NO_x effect, about six times the warming effect. The result is that through various processes the nitrogen oxides interact with trace gases in the troposphere and stratosphere which do absorb in the spectral range to the greenhouse effect (infrared wavelengths). Additional result is (Lammel & Grassl 1995) the catalytic role of NO_x in the production of tropospheric ozone provides the most prominent contribution.

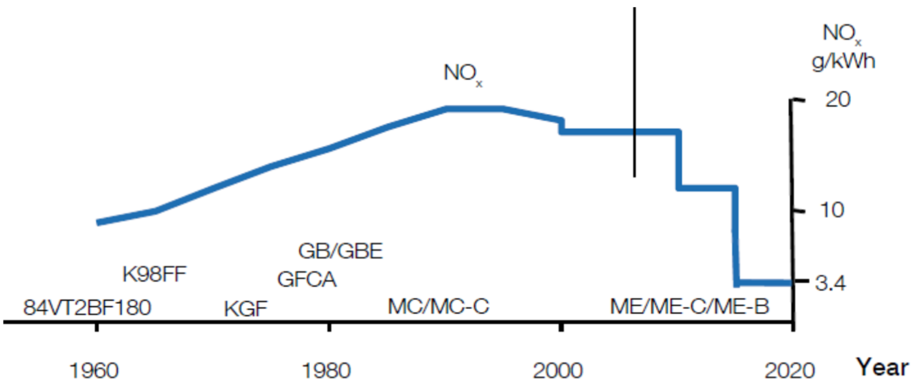

Fig. 2. Engine NO_x emission development (MAN 2014)

An official data for marine two-stroke diesel engine performance only at 75% of nominal load for variations of different EGR system configuration has presented in Table 4. Without EGR system, the engine fulfill the Tier 2 of NO_x emission reduction. A use of EGR system, allows to fulfill the Tier 3 level for tested engine. An increase of SFC (dSFC, SFC penalty) is observed without consideration of required additional electric energy for the EGR auxiliaries. It should be mentioned an increase of carbon monoxide emission from 2 up to 7 times (for max. EGR) and a decrease of oxygen (O_2) content in the scavenge air receiver from 21% down to 16% (average decreased about 21%).

The decreasing of NO_x emission reduction has observed during the tests above mentioned. The investigation on the 4T50ME-X test engine has shown that IMO Tier 3 NO_x compliance is achievable by the use of high pressure EGR system. Additionally, the not-to-exceed (NTE) level of 5.1 g NO_x/kWh was obtained at each engine load point 25, 50, 75 and 100%. The obtained results has shown in Fig. 3 (sign ◆ means the points at 100% of load).

Similar effects of NO_x emission reduction may be obtained by the use of the Selective Catalytic Reduction (SCR) system (MAN 2012a, MAN 2012b, MAN 2018).

Table 4. Test results from 4T50ME-X engine parameter variations at 75% engine load (MAN 2012b)

	NO_x (g/kWh)	dSFC* (g/kWh)	CO (g/kWh)	P_{max} (bar a)	EGR rate (%)	O_2 (vol. %)
No EGR	17.8	0	0.65	152	0	21
Max. EGR	2.3	+4.9	4.17	151	39	16
EGR ref.	3.7	+3.0	2.57	151	36	16.8
Incr. P_{comp}/P_{scav}	4.0	+2.5	2.18	156	36	16.8
Incr. P_{hyd}**	4.2	+2.8	1.83	151	37	16.6
Incr. P_{scav}	3.6	+1.9	2.12	156	37	16.6
Incr. T_{scav}	3.9	+3.6	2.82	156	34	16.8
Tier 3 setup	3.4	+0.6	1.34	157	41	16.2

* auxiliary power for EGR lower, separator and pumps are not included in dSFC, SFC penalty
** hydraulic pressure in fuel system

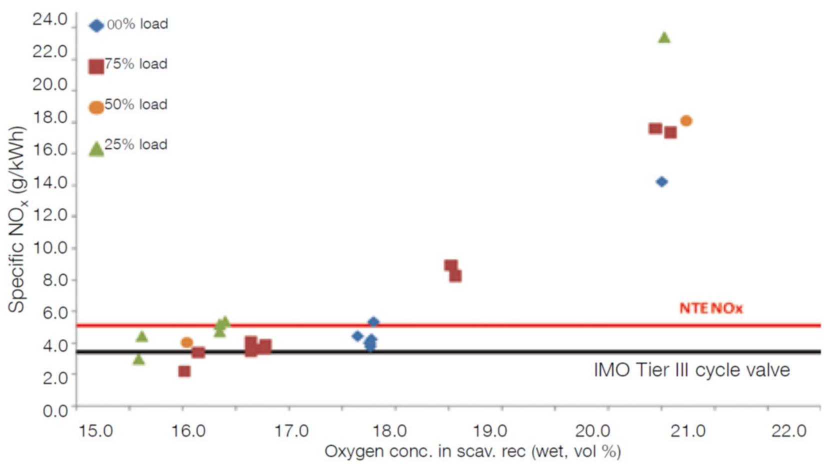

Fig. 3. NO_x emission at different 4T50ME-X engine loads as a function of oxygen content in the scavenge air (MAN 2012b)

Very interesting results have been achieved during the test bed investigation of marine diesel engine operating on ammonia (MAN 2020). Full decarbonization of marine fuels is the aim. Ammonia seems to be an attractive product as a marine fuel, more accessible and transport friendly than hydrogen or methane (LNG or CNG). Physical and chemical properties of anhydrous ammonia govern many of the design aspects of an ammonia-fueled propulsion system and auxiliary systems.

6. Final remarks

Searches, for the fuel additives preventing the NO_x emission, have turned out fruitless. Forementioned, applied methods, lowering the nitrogen oxides emission to atmosphere to required limits from marine diesel engines, have had an essential impact on their performance and specific fuel consumption.

They have got a lot of imperfections: required to install additional reduction systems, need maintenance and operation costs, produced wastes during treatment process and the most important – increased the total fuel consumption (on a level 2-10%) and decreased the available power of the marine diesel engines (on the level 1-5%). The estimated additional cost is about 0.8 USD/MWh of produced energy, taking into account only the cost of excessive used fuel. The whole increased cost may reach the level two-three times more. It has been the one of the reasons of worsening the transport effectiveness and competitiveness.

It may be seen, the NO_x emission reduction methods have been increased the emission to the atmosphere other substances like: carbon dioxide, carbon monoxide, ammonia (the slip from SCR systems).

Improvement of NO_x reduction emission methods is a challenge for the engine manufacturers and researchers.

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