Determining the NO_x emission from an auxiliary marine engine based on its operating conditions

Lukasz Rymaniak[1,*], *Jacek* Pielecha[1], and *Lukasz* Brzeziński[1]

[1]Poznan University of Technology, Institute of Combustion Engines and Transport, Piotrowo Street 3, 60-965 Poznan, Poland

Abstract. The article presents considerations regarding determining the NO_x emissions from auxiliary compression-ignition marine engines. In order to determine the real impact of a given object on air pollution, it is necessary to first carry out research aimed at determining its emission characteristics. Thus, it is necessary to conduct tests in real operating conditions or to calculate the ecological indicators based on the operating conditions. The paper presents the NO_x emissions intensity of an auxiliary Tier III standard marine engine, which is used in the drive system of various heavy, off-road vehicles and water vessels. Due to the structure characteristics of the considered engine group, the presented relations and results refer to only one cylinder. This data was used to calculate the NO_x emission of a marine auxiliary engine, which used the operating conditions obtained from dynamometer tests and the engine construction (the number of cylinders). The presented methodology of activities can be used to assess the ecological indicators of ships in actual navigation, including primarily the maneuvers performed in the port. The article is supplemented with theoretical considerations regarding the problem of pollutant emissions from auxiliary marine engines.

1 Introduction

Compression ignition engines are the main drive source for ships, power generating systems, locomotives, Non-road machinery and Heavy-Duty Vehicles (HDV). Engineers carry out various activities to minimize the environmental impact of diesel engines or try to implement alternative solutions [1–6]. As a result of burning hydrocarbon fuels, combustion engines emit harmful substances into the atmosphere in the form of: carbon monoxide and dioxide (CO and CO_2), hydrocarbons (THC), nitrogen oxides (NO_x), particulates (measured as particle mass PM and number PN), and sulfur oxides (SO_x). It is estimated that on a global scale about 70% of the harmful compounds emissions originating from maritime transport are released over 400 km away from the land, which significantly affects the air quality in the coastal areas. The growing awareness of the pollutant emissions impact from these engines on the natural environment and human health has caused regulations to be introduced in many countries, regulating the level of individual toxic compounds emissions. The issue of relevant regulations forced the development of

* Corresponding author: lukasz.rymaniak@put.poznan.pl

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appropriate measurement tests as well as methods to reduce the emission of toxic compounds in the exhaust gases [7]. Currently, the most basic aspect of reducing the exhaust gases toxicity is to reduce the nitrogen oxides emission. The term nitrogen oxides is defined as combinations of nitrogen with oxygen of the following types: NO, NO_2, N_2O, and N_2O_5. Nitrogen at ambient temperature is an inert gas that does not react chemically with other atmospheric gases, however, at temperatures in excess of 1100°C it becomes a reactive gas with a high oxygen affinity. Nitrogen oxides formed during the hydrocarbon fuels combustion process are one of the leading causes of acid rain and smog, and when inhaled by humans they enter the bloodstream and poison the body due to their toxicity [8]. In engines powered by light fuel (MDO – Marine Diesel Oil), the formation of nitrogen oxides usually involves the nitrogen in the air. In contrast, for Heavy Fuel Oil (HFO) engines, the fuel may contain up to 0.5% of this element, and thus it also plays a significant role of oxides formation. It was found that nitrogen content of heavy fuel can increase the concentration of nitrogen oxides in the exhaust gas of the internal combustion engine by up to 10%. There are various methods to reduce nitrogen oxides emission, which can be divided into:

1. Primary methods, which are aimed towards reducing nitrogen oxides during the combustion process inside the engine,
2. Secondary methods, which serve to remove or reduce the amount of nitrogen oxides in the exhaust gases – these usually use Selective Catalytic Reduction (SCR).

2 Nitrogen oxides emission limits

International requirements on the emission limits of nitrogen oxides, sulfur oxides and particulates are set out in the MARPOL Convention Annex VI (Regulation on the prevention of air pollution from ships). According to the legislation, the emission of nitrogen oxides of each marine compression ignition engine installed on a ship constructed after 1.01.2016 must meet Tier III emission standards when operating in the NO_x Emission Control Area in North America (Fig. 1). In Northern Europe these requirements will be in force from January 1, 2021 in the NO_x emission control area. While Tier II emission limits apply elsewhere [9].

Fig. 1. Emission Control Areas (ECA) – in the area of North America and the northern part of Europe that are currently in force [10].

The international NO_x emission limits for marine diesel engines, as defined by MARPOL Annex VI, are shown in Fig. 2 as a function of the rated engine speed. In addition to the emission limits set by the International Maritime Organization – IMO, there are also European Union regulations that address the problem of harmful compounds emissions and the need to take measures to limit them. In Polish legislation, laws and regulations were also established to regulate the emission levels of pollutants from the combustion of marine fuels, which are mainly based on international law.

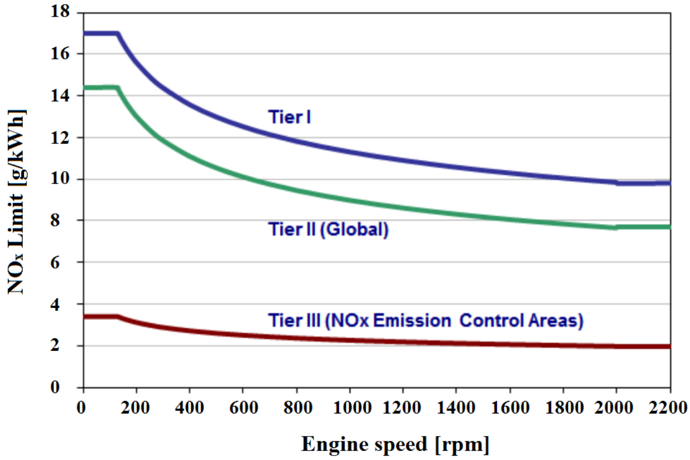

Fig. 2. The established limits for nitrogen oxides emission as a function of the engine speed [9].

Annex VI of the aforementioned regulations contains the permissible values of sulfur content in fuel as a means to control the sulfur oxides emission and indirectly also emission of particulate matter (because there are no clear limits on this emission in place). For Sulfur Emission Controlled Areas (SECA), there are special regulations regarding fuel quality (the expected sulfur content is 0.1%). Deadlines for introducing changes and acceptable values of sulfur content in fuels (gas and diesel) are given in Figure 3.

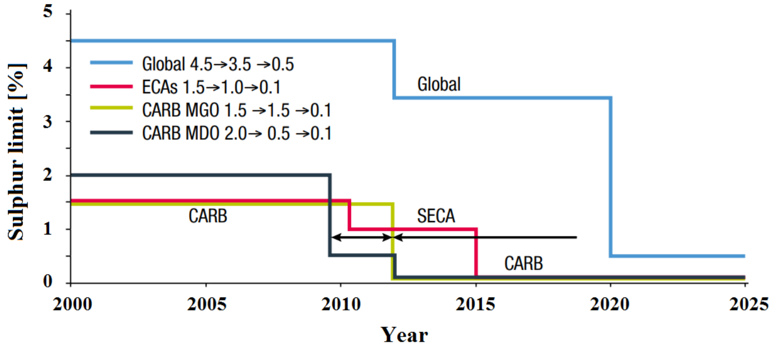

Fig. 3. Limits on the sulphur content in fuel ECA [11].

It is assumed that meeting the Tier II emission standards is achievable through optimizing the combustion process by modifying the fuel injection into the combustion chamber. Meeting Tier III standards, however, requires the use of additional technologies that reduce the emission of harmful substances, such as in the case of nitrogen oxides – the SCR system.

3 Determining the pollutant emissions in terms of the cylinder number and engine operating conditions

3.1 Marine auxiliary engines operating conditions

Medium-speed marine engines used on ships as main or auxiliary propulsion units are operated in a range of load characteristics. Their operating parameters variability range is limited to torque changes only. The change of crankshaft rotational speed occurs only during the engine start and stop and during the transition between individual load characteristics – reacting to the energy demand change by the receiver. The most commonly used crankshaft rotational speeds are 720 rpm, 750 rpm, 900 rpm, 1000 rpm and 1200 rpm. Manufacturers offer engine types in which similar design solutions are used, and individual types differ primarily in the number of cylinders, which has a direct impact on the power output. The power of the ship's engine is selected based on the characteristics of the receivers or the propulsion system. Modern marine combustion engines meet the requirements of IMO Tier II MARPOL Annex VI emission standards, and with the use of selective catalytic reduction system they also meet the requirements of IMO Tier III.

3.2 Pollutant emissions calculation exemplified with nitrogen oxides

The problem of pollutants emissions from transport means equipped with combustion engines, especially marine engines, is very important due to their large local impact on the natural environment. This is particularly true for port areas as well as for areas with unique flora and fauna. For this reason, it is necessary to take action to learn about the threat and methods of reducing it effectively. Due to the specificity of naval operation the emission modeling tool is very useful. The article focuses on issues related to the emission of nitrogen oxides, however, the presented methods can be successfully used for other toxic compounds as well.

Taking into account the design characteristics of auxiliary marine engines, the consideration should include the nitrogen oxides emissions intensity from one cylinder at a specific operating point. To model the total emission it is necessary to use the relation:

$$e_{\mathrm{NO_x}i} \cdot j = e_{\mathrm{NO_x}} \tag{1}$$

where: $e_{\mathrm{NO_x}i}$ – NO_x emission intensity from a single cylinder of a combustion engine at a given operating point, j – number of cylinders, $e_{\mathrm{NO_x}}$ – total NO_x emission intensity in a given operating point.

Time density characteristics or *TD* (Time Density) have been used for several decades in the construction and optimization of combustion engines, propulsion systems as well as the means of transport as a whole, e.g. [12, 13]. Using its assumptions, it is possible to determine the harmful compounds emission intensity and time density shares of the internal combustion engine in the crankshaft rotational speed and load ranges during tests in a given measurement cycle. For marine engines, such characteristics have a limited area of the crankshaft rotational speed variability, which makes their determination much easier.

Two conditions that must be met for correctly designated characteristics are:

$$\sum_{k=1}^{N}\sum_{p=1}^{M} t_{(k,p)} = t_c \tag{2}$$

$$\sum_{k=1}^{N}\sum_{p=1}^{M} TD_{(k,p)} = 1 \tag{3}$$

where: N – crankshaft rotational speed area, M – torque area, k and p – operating points at a given time, t_c – test cycle duration.

Based on the measurements performed on a modern engine used to drive various types of heavy, off-road and water vehicles, the characteristics of the NO and NO_2 emission intensities were determined in the aspect of operating parameters (Fig. 4). The provided data include three rotational speeds of 750 rpm, 850 rpm and 1200 rpm. The tested engine met the Tier III emission standards, was powered with light fuel, and one of the exhaust gas aftertreatment systems was an SCR. Due to the high SCR reduction efficiency, NO emission values were much higher (nearly 20 times). The average NO emission intensity for individual rotational speeds was: 21.82 mg/s, 16.67 mg/s and 26.71 mg/s; while for the emission of NO_2 these values were: 1.15 mg/s, 0.94 mg/s and 0.42 mg/s. The SCR system had the greatest impact on the obtained results, the degree of conversion depended on many factors, including exhaust gas mass flow and its temperature.

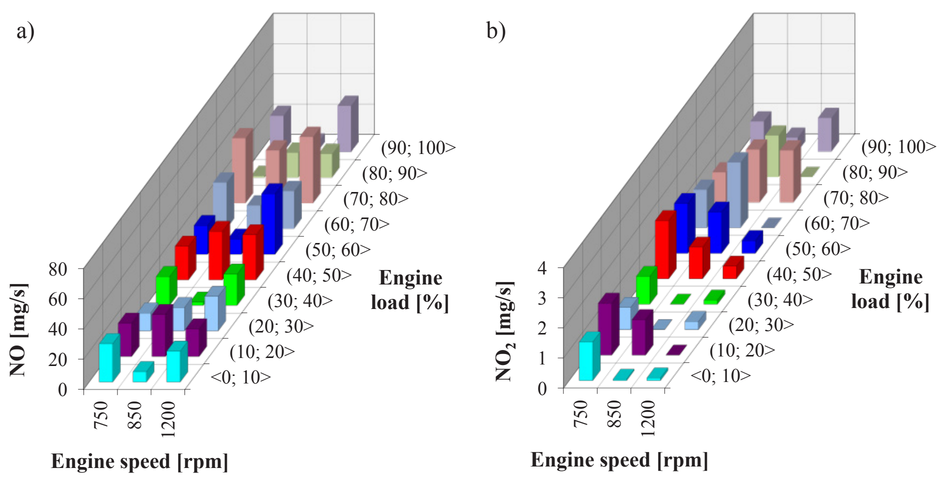

Fig. 4. Emission intensity a) NO and b) NO_2 from a single cylinder of a combustion engine.

Taking into account the engine construction (number of cylinders) and the operating conditions, it is possible to determine its emission parameters. For a given mode of operation of auxiliary marine engines, it is possible to calculate the total specific emission value of NO, NO_2 or selected harmful compounds (E) for the entire conducted test cycle or cruise, using the following formula:

$$E_{\mathrm{NO_x}} = t_c \cdot \sum_{k=1}^{N}\sum_{p=1}^{M} TD_{(k,p)} \cdot e_{\mathrm{NO_x}} \tag{4}$$

4 Nitrogen oxides emission from auxiliary marine engine in product tests on a dynamometer

Based on the conducted emission tests the NO_x emission intensity was determined in terms of the load intervals for a single auxiliary engine cylinder, where the rated engine power was 94 kW (Fig. 5a). During the product dynamometer tests, measurements are made at set combustion engine operating parameters, where different time density values for particular loads have been determined. The test presented in Fig. 5b was proposed by the authors. Its form has been developed on the basis of tests performed in real operating conditions. It presents the time density values for various loads, and it includes tests in all engine speeds set for a given unit. Its total duration is 1200 s.

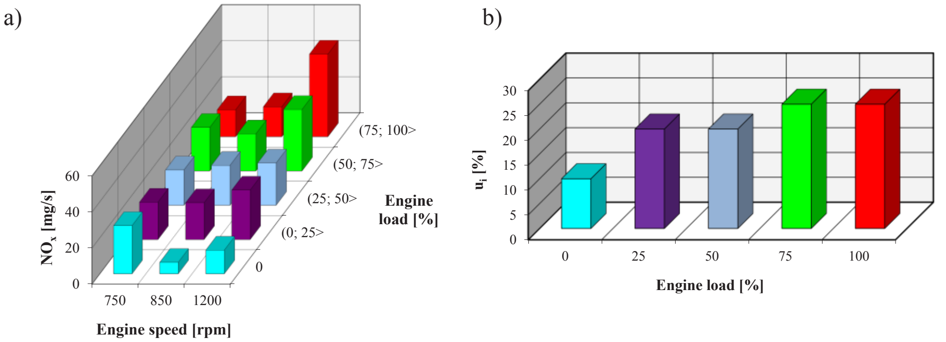

Fig. 5. Data necessary to calculate the emissions in the product test: a) NO_x emission intensity from one cylinder of the internal combustion engine and b) time density in the test.

The specific emission value of NO_x was calculated according to formula (4), for a 6-cylinder engine in a series configuration. Its maximum power is 552 kW. From this data, it was determined that the NO_x ecological indicators for individual rotational speeds reached the values: 0.23 g/kWh, 0.21 g/kWh and 0.35 g/kWh (Fig. 6). Comparing the obtained results to the Tier III standards presented in Figure 2, it can be stated that the tested engine meets the legislative requirements. However, it should be noted that the test for which the calculation was performed is not a type-approval test, and its setup is different from that of the official tests. The use of the SCR system, which very effectively reduces NO_x at the combustion engine's set operating points, lead to obtaining results nearly five times smaller than the Tier III limit values.

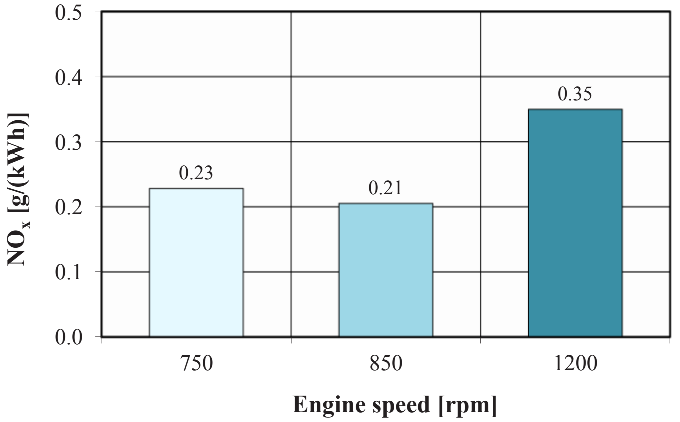

Fig. 6. Determined NO_x unit emission of the auxiliary marine engine (6 cylinders, 552 kW).

5 Conclusion

In the research field of exhaust gas emissions from internal combustion engines used in the transport sector, advanced research work is carried out in addition to emission limiting activities. This research mainly concerns determining the pollutants emission value in actual operation. It is not always possible to assess the ecological indicators for normal operating conditions. Therefore, appropriate mathematical operations should be used, which allow for a very approximate determination of numerical values. In order to achieve this, the characteristics of the engine, its operating conditions and emission data determined empirically in tests, e.g. in the laboratory or in the test bench, should be taken into account.

The article presents such analysis for the 6-cylinder auxiliary ship engine, the specific NO_x emission value was determined in product tests. Based on the results obtained, it was found that the engine meets the Tier III legislative standards. The presented method of determining the exhaust emissions can be successfully used to assess the marine engine's ecological indicators during specific research cycles or in real operating conditions (e.g. when traveling).

The international law regulations, regarding the emission levels of harmful substances in exhaust gases from marine engines that are currently in force, are being made increasingly more stringent. They force the manufacturers of engines and users of newly built ships to make use of the newest solutions that significantly reduce the emission of harmful compounds. The use of selective catalytic reduction systems using urea as a source of ammonia as a reducing agent for NO_x is the most widespread of all the numerous solutions that limit the specific emission of nitrogen oxides. It should be noted, however, that ammonia is also a harmful compound and, when conducting a full emission assessment of a given cobustion engine, this compound should also be taken into consideration and measured appropriately.

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