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NUMERICAL STUDIES OF NITROGEN OXIDES EMISSIONS IN THE MAIN PROPULSION ENGINE EXHAUST UNDER VARIOUS CRUISING CONDITIONS

Tomasz Kniaziewicz, Leszek Piaseczny

Polish Naval Academy
Faculty of Mechanical and Electrical Engineering
ul. Śmidowicza 69, 81-103 Gdynia, Poland
Tel.: +48 58 6262851, 6262665
E-Mail: t.kniaziewicz@amw.gdynia.pl

Summary

Measurements of nitrogen oxides concentrations in exhaust gases of marine engines under various cruising are difficult or impossible to perform due to their cost and technical difficulties. Such measurements are generally performed on engines under static load conditions, which are determined by appropriate tests, and this is the basis for computing the values of indicators and characteristics of NO_x emissions. The values of the following parameters are determined: specific emissions, emissions intensity, cruise emissions, as well as the propeller, regulatory, and adjustment characteristics of – most frequently – specific emissions. These indicators and characteristics are of limited use for the determining of the NO_xemissions level in the exhaust gas of engines belonging to a set of different vessels operating in a given sea area which e.g. due to stricter environmental requirements requires reliable information about the current level of pollution.

The authors have made a successful attempt at developing mathematical models in order to determine the resistance characteristics of the hulls of various ships and the power of their engines under different cruising conditions, and to estimate indicators and characteristics of NO_x emissions on the basis of numerical simulation studies. The computer program developed allows for the examination of various vessel types, and their various sizes, cruising speed distributions, and changing external conditions (e.g. water density and depth, sea state etc.).

The present paper will presented the course of the model's construction, the assumptions, and methods for determining the inter-relationships, and the results of numerical studies for a number of ships under various cruising conditions.

***Key words**: emissions of toxic nitrogen oxides, marine engines, emission models.*

1. Introduction

The problem of air pollution in harbors and harbor approach areas is all the more important because of the fact that harbors are typically located near or in large cities, and their limited area causes a large concentration of vessels in a small area.

The currently effective MARPOL 73/78 convention on the protection of the marine environment is limited to determining the allowable unit value of emissions of certain toxic exhaust gas components (nitrogen oxides and sulfur oxides), and to conducting qualification research as a condition of obtaining the certificate confirming the meeting of the international legal requirements by marine engines. and vessels in which they are installed. These studies should be conducted in accordance with the theoretical tests contained in the ISO 8178 standard, during the measurements taken at the manufacturing plant. The exhaust gases toxicity characteristics determined in this manner for an engine tested is then valid for the whole series (type, and even family) of similar engines. These studies are typically of a qualifying nature, and are not relevant to the actual operating conditions of the engines in the marine propulsion systems.

In reality operating conditions and emissions from a marine main propulsion engine are largely influenced by the so-called external conditions, of which, – due to their significant influence on the resistance of the hull – the following conditions may not be overlooked: navigation in shallow water, in channels with strong currents of water, and in storms, as well as an increase of draft (e.g. as a result of the increased cargo load, filling empty ballast tanks and the cargo space, or a decrease in the water density), as well as an increase in the number of appendages or the hull roughness as a consequence of the fouling and corrosion. It can thus be assumed that the vessel's actual operating conditions, regardless of the preset settings of the control and the propulsion systems, are characterized by a certain degree of dynamic changes in the propulsion system parameters, and hence emissions from propulsion engines. Engine operating conditions and emissions are also affected by changes of the vessel motion set by the crew (moving off, accelerating, braking). Therefore, operating conditions of ships indicate the necessity to develop a comprehensive method for determining the exhaust gases toxicity characteristics, with static and dynamic components, of the ship's main propulsion engine.

Research conducted currently throughout the world, concerning atmosphere pollution caused by emission of toxic compounds from ship engines, conceived both globally [1,2], regionally [3,4], and also locally, e.g. in the vicinity of large sea ports [5] is based on simplified input data [2, 6, 7]. The existing data bases of harmful compounds emission from exhausts of ships operating in various regions of the world [7] cannot be used, however, for the estimation of emission in meso- and microscale, e.g. the Baltic Sea or the Gulf of Gdansk, as they lead to a considerable underestimation of emission indexes, which is mainly due to insufficient detail of vessel movement characteristics [8].

There is thus a need need for methods that allow a much more precise determination of the vessel movement characteristics, as well as emission factors.

2. Propulsion characteristics of vessels with displacement hulls under static and dynamic operating conditions

The preliminary statistical calculations, and the analysis of the data emitted primarily by AIS shows that in the established research concept the crucial role is played by the general identification of the actual operating conditions of typical vessels, and on its basis the development of relative (general) characteristics of marine propulsion system, described by a set of functional interrelationships of selected propulsion system parameters [10]. It should be stressed that this type of functional relationships, which by their nature describe phenomena related to the operating process of the ship's propulsion, are empirical. It was assumed that the basic parameters of the vessel movement under consideration will concern the waters of the Baltic Sea, and that the parameters of the routes and vessels will be determined on the basis of pilot books and information issued by AIS. It was also assumed that a typical marine propulsion system consists of a low-speed reciprocating internal combustion engine and a fixed pitch screw propeller.

In order to determine the parameters of the ship's propulsion system, necessary in the calculation of toxic compounds emissions intensity, it is necessary to know the broad set of parametric mathematical models. Because of the issue under consideration, and the availability of the necessary data, it was concluded that changes in the intensity of toxic compounds emissions resultant from changes in the external operating conditions of the vessel's propulsion system are in each case the consequence of a useful demand required change, due to the changed resistance of the hull, which means that they can be identified in an approximate manner based on the following set of predicted approximative equations and formulas:

- hull resistance characteristics, taking into account:
  a) influence of the fairway depth on the hull resistance;
  b) additional wind (air) and wave resistance during the storm;
  c) draft changes;
  d) hull roughness changes:
- power characteristics depending on the vessel speed;
- load characteristics;
- propeller characteristics of the main engine power;
- propulsion system parameters under nominal and transient load conditions during moving off, accelerating and braking – time t and distance S;
- toxic compounds emissions intensity.

In the presented method, the first to be determined is the analytical dependence approximating the resistance and its components according to the characteristics of the hull and vessel motion under the current external operating conditions. In particular, it is necessary to have the following data:

- the relationship between the wave height, the speed of its motion, and the wind speed;
- the share of the wind and wave resistance components;
- relative resistance of the emersed part of the ship (superstructures);
- deep- and shallow-water wave characteristics;
- data of the parameters of hulls and propulsion systems of vessels, and the current data concerning motion and the changes of vessel parameters;
- current weather data.

The aforementioned relationships are also the output data and the algorithm used for the development of computerized procedures for the determination of emissions of toxic compounds by the ship's main propulsion engines in real (steady and transient) operating conditions of the propulsion system. They are also the basis for updating and enriching the database, and for the development of exhaust gases toxicity tests to be increasingly accurate and adequate to the reality.

In generally applied methods of determining emissions of toxic compounds by internal combustion engines, the basis are the toxicity tests developed on the basis of empirical studies of the actual operating conditions. Therefore, the accuracy of the emissions estimation depends on the accuracy with which the developed tests reflect the actual engine operating conditions, usually described in terms of load parameters.

The analysis conducted showed that for the purposes of the considered problems of toxic emissions into the atmosphere from marine main engines, the dynamic nature of the impact of the propulsion system operating conditions, as well as external navigation conditions may in many cases be omitted. This is because the duration of dynamic operating conditions is negligibly short in comparison to the duration of operation with the load close to being steady. Operating conditions of that kind occur e.g. during the acceleration of the vessel. Presented mathematical description and performed calculations for transient (dynamic) operating conditions of a marine propulsion system were used to estimate the impact of the changes in the hull motion parameters on the load parameters of the main engine, and the characteristics of the vessel exhaust gases toxicity under a variety of external conditions. The detailed description of an algorithm used for modeling ecological characteristics of marine main propulsion internal combustion engines can be found in [11].

The main characteristics describing the operating conditions of the main engine being a component of the marine propulsion system is the vessel's resistance characteristics, and the characteristics of the propellers. It is also known that these two types of characteristics are determined experimentally during modeling tests. The degree of compatibility with the reality of the so-created characteristics is dependent on the accuracy of representation of the real object in the model, and the conditions in which the measurements and calculations were performed. Characteristics prepared in this manner should be included the technical and operational documentation of the vessel. In practice, however, such characteristics tend to be very difficult to obtain. Therefore, the most commonly used methods for computing the resistance characteristics are those developed on the basis of the available general data of a specific vessel [10].

Following the analysis of empirical approximate methods for calculating the resistance of vessels operating in deep (unlimited) water, methods [11] and [12] were selected for further consideration.

In the first of these relationships, the total resistance of the hull in deep water is described with the formula:

$$R = 0{,}0132 \cdot 9{,}81 \cdot \rho \cdot L \cdot B \cdot T \cdot \delta(48 \cdot Fn_V^2 - 29 \cdot Fn_V + 5{,}9)\frac{\delta}{\frac{L}{B}\left(\frac{B}{T}\right)^{0{,}2}}, \tag{1}$$

where:

R [kN] – resistance;
ρ [kg/m^3] – seawater density
Fn_V – Froude number relative to the volume of underwater hull $\mathrm{Fn_V} = \frac{\upsilon}{\sqrt{g\sqrt[3]{V}}} = \frac{\upsilon}{\sqrt{g\sqrt[3]{L \cdot B \cdot T \cdot \delta}}}$,
V [m^3] – underwater hull volume;
L, B, T [m] – hull dimensions,
δ – hull's block coefficient $\delta = \frac{V}{L \cdot B \cdot T}$ the volume ratio of the underwater hull to the volume of the cuboid circumscribed around the underwater hull,
g [m/s^2] – gravitational acceleration.

The application of the formula, however, was limited to the following ranges of the hull parameter changes. $Fn_V = 0.37 \div 0.77$; $\delta = 0.70 \div 0.86$; $L/B = 5{,}0 \div 9.5$; $B/T = 3.3 \div 13$.

Because of the above limitations in the application of the method described above, the calculation of the vessel's total resistance may also be performed using the method described in [12]:

$$R = g\left\{0{,}17 \cdot \Omega \cdot \upsilon^{1{,}825} + 1{,}45\left(24 - \frac{L}{B}\right)\delta^{\frac{5}{2}}\frac{D}{L^2}\upsilon^4\right\}, \tag{2}$$

where:
υ [m/s] – vessel speed;
B, L [m] – hull breadth and design waterline length
D [t] – vessel draft;
Ω [m^2] – wetted area;
g [m/s^2] – gravitational acceleration.

On the basis of equation (1) or (2), it is thus possible to determine the resistance characteristics of a particular vessel when cruising in deep (unlimited) water. Resistance characteristics determined in this manner allow to determine the effective towing capacity characteristics of the vessel, and the useful demand required by the propulsion engine from the general forms of equations

$$P_h = R \cdot v \tag{3}$$

$$P_e = \frac{R \cdot v}{\xi_o \cdot \eta_{LW} \cdot \eta_r} \tag{4}$$

where:
P_h [kW] – effective towing capacity,

R [kN] – total resistance of the vessel in deep-water conditions,
ξ_o [-] – propulsive efficiency $\xi_o = \eta_p \cdot \xi_r \cdot \xi_k$;
η_p [-] – free propulsor efficiency (free propeller) – at undisturbed water inflow;
ξ_r [-] — rotative efficiency, taking into account changes in speed and direction of water inflow,
ξ_k [-] – hull efficiency, and to be more specific, the impact factor of the hull on propeller operation
$\xi_k = (1 - t)/(1 - w)$,
η_{LW} [-] – shafting efficiency,
η_r [-] – reduction gear efficiency.

Assuming, based on reference literature [13, 14, 15], the average values of the coefficients for propulsion systems equipped with low-speed reciprocating internal combustion engines ($\xi_o = 0.65$, $\eta_{LW} = 0.985$, $\xi_k = 1$), the formula to calculate the approximate useful demand required will be simplified to the form

$$P_{e_w} \simeq 1{,}56 \cdot R \cdot v, \tag{5}$$

On the basis of data obtained from the AIS, relative basic (general) standard characteristics of marine propulsion system were determined, describing the static properties of marine propulsion system components (the ship's hull and propulsion engine) under normal operating conditions, which are shown in Fig. 1 [10].

a. *b.*

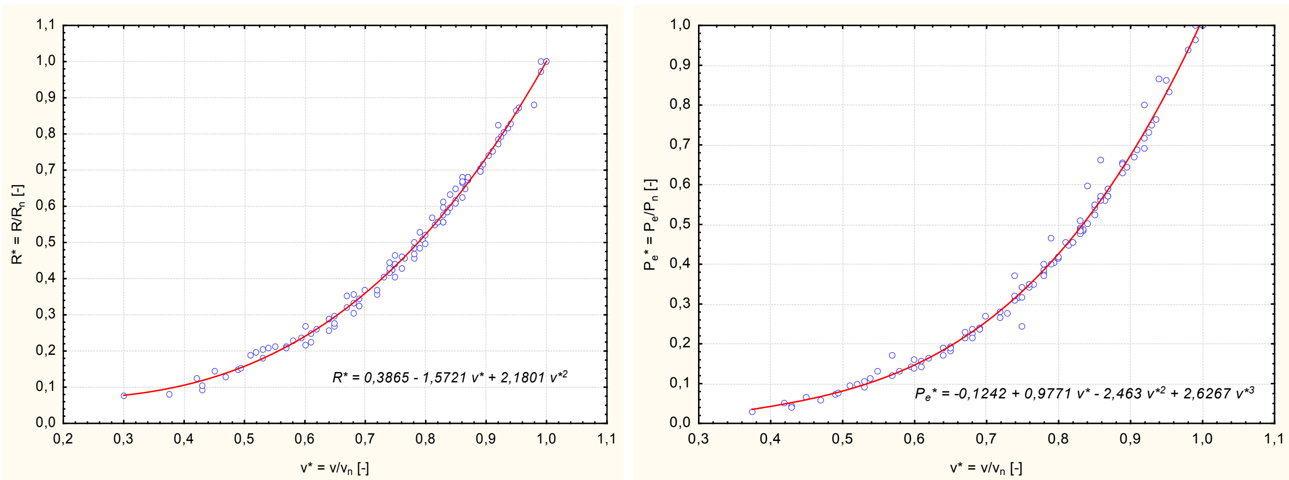

Fig. 1. Standard averaged a) resistance characteristics of the displacement hull vessel, b) dependence of the main propulsion engine power on the individual cruising speed of the displacement hull vessel[10]

Fig. 2 shows the characteristics of engine power (bundles of curves) in real operating conditions of the vessel in a limited water depth, and Fig. 3 – relative increase of the additional wave resistance ΔR_F depending on wind speed and storm condition operations.

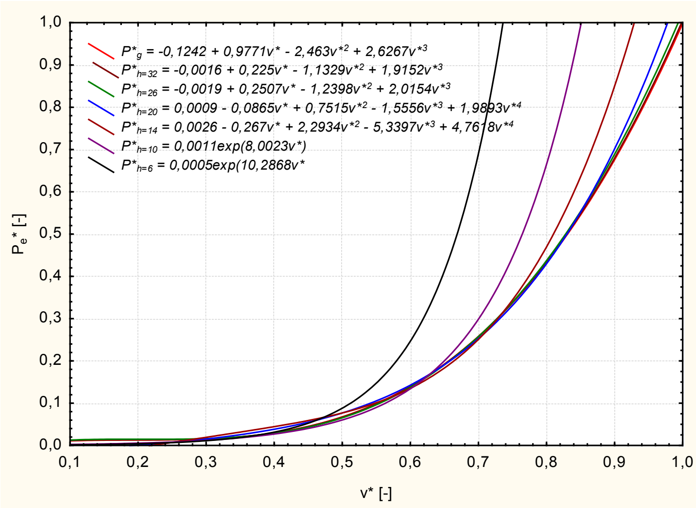

Fig. 2. Averaged relative dependence of the main propulsion engine power of a vessel operating in waters of different depths [10]

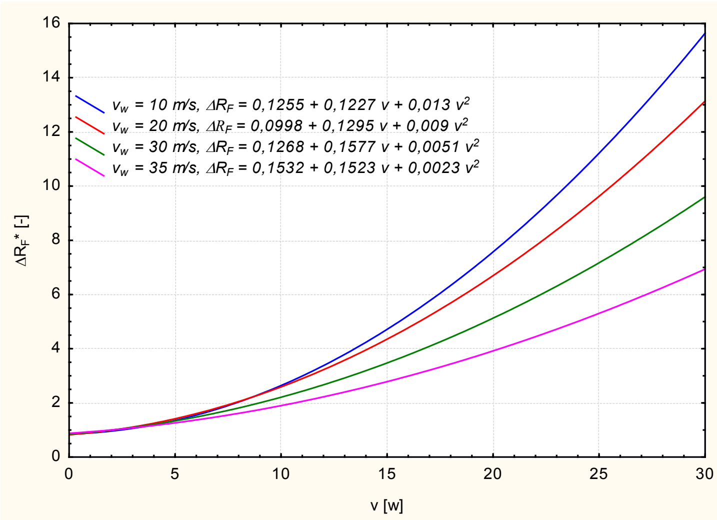

Fig. 3. Relative increase of the additional wave resistance depending on wind speed and storm condition operations [10].

3. Simulation model of nitrogen oxide emissions in the exhaust gas from the main engines in real operating conditions of the vessel

Conditions of toxic compound formation in a marine main propulsion engine are determined by load parameter values (effective towing capacity P_e, vessel speed v), thermal state parameters (exhaust temperature T_{sp}, water temperature in the cooling system T_w, oil temperature in the lubrication system T_o), and the parameters of the air surrounding the engine (temperature T_a, pressure p_a, relative air humidity φ) $\bar{p}_j = \left(P_e, v, T_{sp}, T_w, T_o, T_a, p_a, \varphi\right)$. Load and thermal state parameters also depend on the external conditions described in the set $\bar{p}_i$ [16].

The following indicators characterizing the level of toxicity of marine engines were adopted on the basis of the existing legislation concerning the issues under consideration:

- emissions of the toxic compound e_{ZT} [kg/(kW·h)];
- emissions intensity $E_{ZT} \simeq P_e \cdot e_{ZT}$ [kg/h];
- total emissions; $m_{ZT} = E_{ZT} \cdot t$ [kg];
- cruise emissions $b_{s_{ZT}} = \frac{m_{ZT}}{L_t} \left[\frac{\text{kg}}{\text{mila}}\right]$.

In the construction and testing of a stochastic model of traffic and emissions from vessels [11, 18-20] in a specific water area, it is necessary to know the number of vessels navigating in the analyzed area, their distribution in terms of their function, size, speed, power, and type of main engines, etc.

The routes analyzed for the purposes of statistical processing of marine vessel traffic streams were the approach fairways to the harbors of Gdynia and Gdańsk, and the fairway splitting into both these water lanes.

Based on the data obtained from the AIS, it was possible to create i.a. distributions of vessel incidence in each category (Fig. 4), and their speed (Fig. 5) [16].

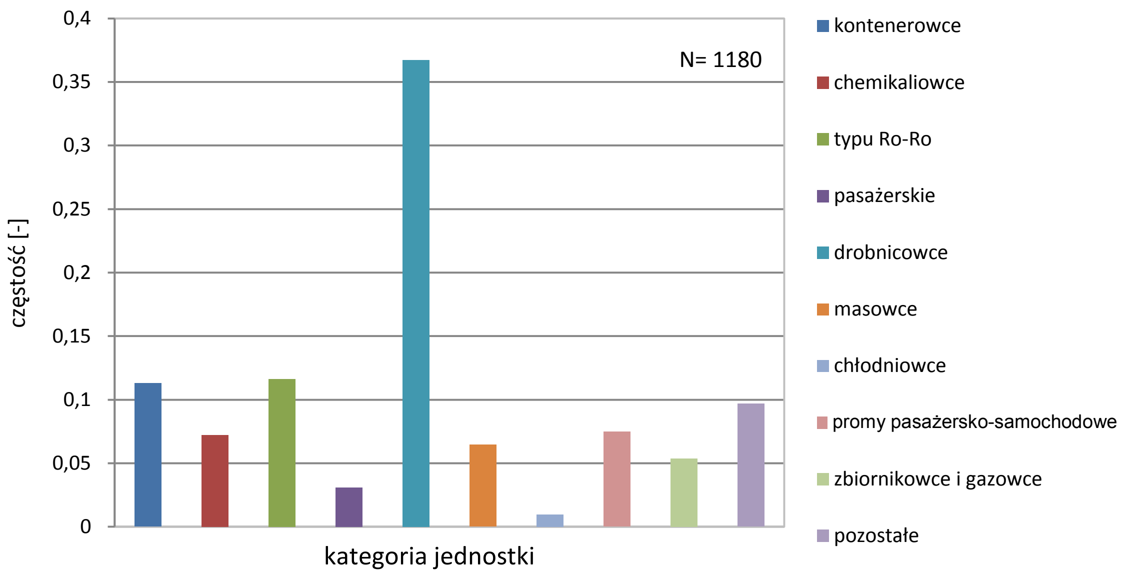

Fig. 4. Vessel incidence in particular categories for the Port of Gdansk [16]

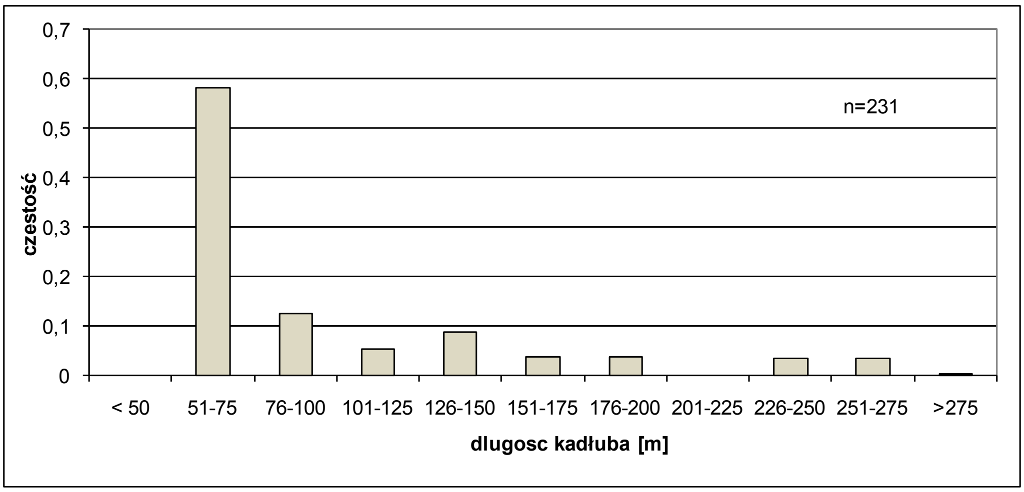

Fig. 5. Length distribution of tankers navigating to the Port of Gdansk [16]

The mathematical model of toxic compounds in exhaustgases of the main propulsion engines, which was developed by the authors, served as a basis for the determination of the power output characteristics in the function of velocity $P_e = f(v)$ of a selected tanker (L = 60 m, B = 6 m, T = 4.1 m, v_{max}=12 kt), (Fig. 6).

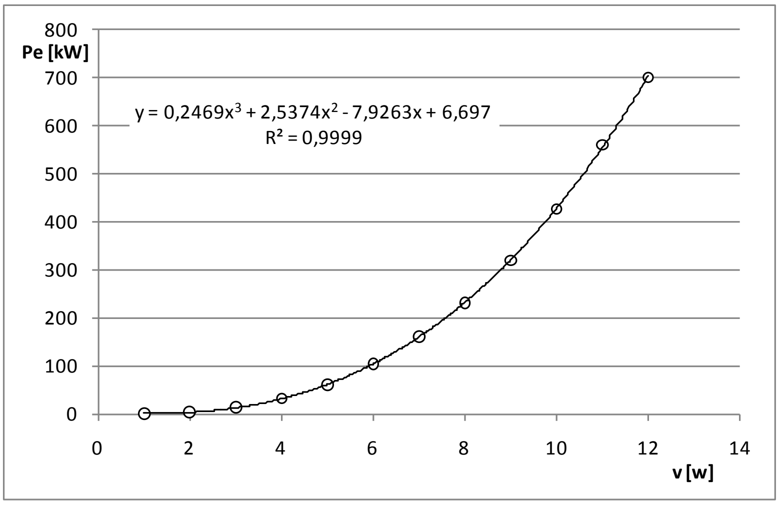

Fig.6. Characteristics of power output as a function of velocity $P_e = f(v)$ of a selected tanker navigating to the Liquid Fuel Terminal (L=60m, B=6m, T=4,1m, v_{max}=12w) [16]

Because the amount of toxic compounds emitted into the atmosphere depends primarily on the engine load, it was subsequently possible to determine, on the basis of the propeller characteristics of specific toxic compound emissions, the value of, among others, the intensity of nitrogen oxides emissions depending on the cruising speed of the tanker $E_{NOx} = f(v)$ (Fig..7)

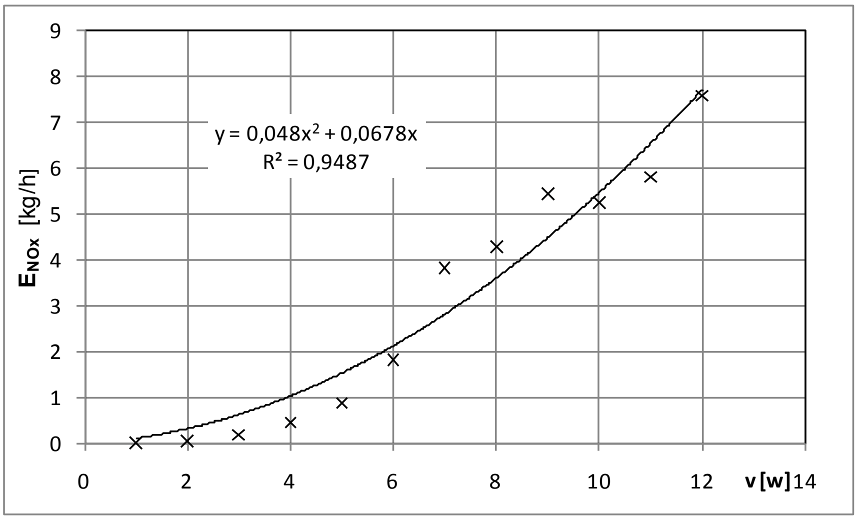

Fig. 7. Calculated dependence between the NO_x emissions intensity and the velocity $E_{NOx} = f(v)$ of a selected tanker navigating to the Liquid Fuel Terminal (L = 60m, B = 6m, T = 4.1 m, v_{max}=12w)[17]

The obtained statistical data on vessel traffic [19, 22] also served as a basis for the development of typical characteristics of the vessel speed changes as a function of time for line service vessels. Based on the motion characteristics of passenger-car ferries, it was possible to determine the intensity of the emissions of toxic compounds in the exhaust of their main engines [17].

Fig. 8 shows the changes of the nitrogen oxides emissions intensity E_{NOx} as a function of time during changes in speed (active braking) of ferries entering the port in Gdynia.

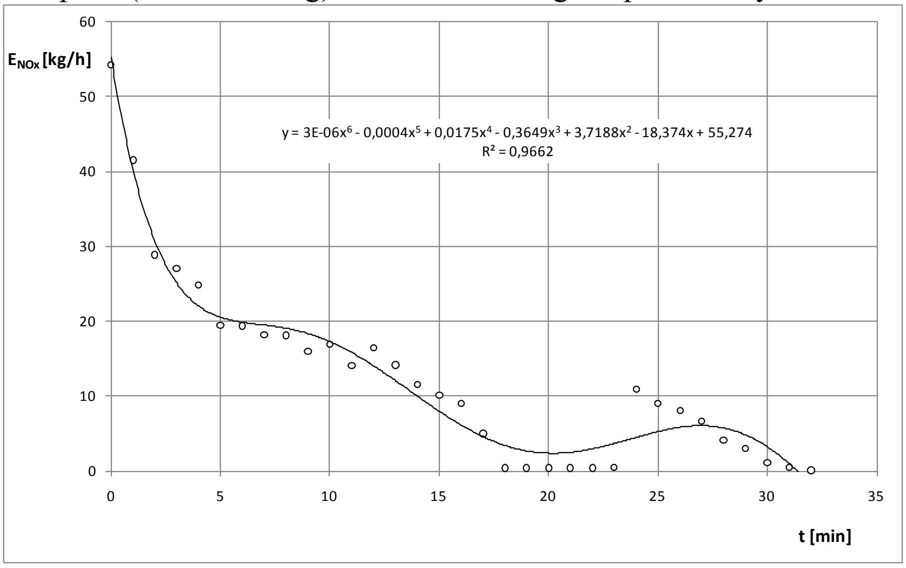

Fig. 8. Changes of the nitrogen oxides emissions intensity E_{NOx} as a function of time during changes in speed (active braking) of ferries entering the port of Gdynia [17]

4. Conclusions

Modeling emissions of harmful compounds is a very important, and at the same time very complex issue. Many attempts are undertaken worldwide aimed at estimating the models of harmful compounds emissions in vessel exhausts. Unfortunately, due to the fact that the structure of the model depends not only on its purpose, but also, to a large extent, on the quantity and quality of input data, and that many studies are based on the insufficient amount and quality of data, frequently obtained from a variety of sources, and the need to use simplifications, all this significantly translates into the credibility of the model.

The possibility of obtaining data from the AIS, such as: the name, length, breadth, and type of ship, universal time related to the passing through a "gate", course and velocity over the ground (COG and VTG), and the ship's draft, permits the creation of innovative models describing vessel traffic in the area under consideration, and toxic compounds emissions from exhausts, both for a single vessel, and the whole area.

The presented a mathematical model for calculating the power of the vessel's main propulsion system is universal and can subsequently be utilized, based on data obtained from the AIS, for the calculation of the toxic compounds emissions in the exhaust of seagoing vessels.

It should be added that apart from the problems with which automotive professionals struggle while modeling toxic emissions, in the case of vessels the parameters interfering with the accurate determination of the emissions levels of particular compounds may additionally include the technical condition of the engine, particularly its fuel system, and weather conditions (especially wind force and direction).

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