PROBLEMS OF MODELLING NO_x EMISSION FROM MARINE DIESEL ENGINE

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Abstract

The development of marine diesel engines has so far been directed towards increasing their power, reducing fuel consumption, burning fuels of the lowest possible quality and the extension of operation time. The rising pro-ecological pressure has made atmosphere pollution by exhaust gases of marine engines one of the main problems of environmental protection of recent years. The Gdansk Bay area, just like sea ports or coastal regions, is vulnerable to the effect of noxious compounds contained in vessel exhaust gases, besides those coming from industrial plants, power plants or vehicles. This concerns vessels both in ports and in the roads. In order to determine the share of vessels in environmental pollution and to counteract the harmful effects of toxic compounds in marine engine exhaust gases, it is necessary to know the emission values of these compounds from particular vessels, which is possible with the knowledge of their movement parameters, concentration values of particular compounds for these parameters and the atmospheric conditions.

The report presents problems of modelling the NO_x emission in exhaust gases from main marine Diesel engines, such as problems with construction special models describing the marine vessels movement or define real value of toxic compounds emission.

Keywords: *emission, exhaust gases, engine, ship, modelling*

1. Introduction

Emergence of law regulations concerning accepted levels of toxic compounds emission [10] has forced both the engines producers, as well as the ship's operators to take measures aiming at the emission reduction. These activities influence the process of operation and ecological inspection of marine engines. It will result not only in technical modification of marine engines and installing additional systems aiming at fulfilling the requirements of exhausts toxicity standards, but will also necessitate introducing new methods describing directly or indirectly the toxic compounds emission levels in marine exhausts.

The above conditions make it necessary to identify the impact of engine operation conditions on the toxic compounds emission levels in exhausts. Although the impact of construction and operational factors on the engine operation indexes is quite known and applied in practice, their impact on indexes of toxic compounds emission (regarding marine engines) is far less known. Therefore, analysis of those impacts seems to be required.

The problem of air contamination in ports and their neighbourhood is especially important due to the fact that ports are usually located in or in the vicinity of big cities and their limited area causes high concentration of vessels in a small space. Operational conditions are also of high significance. These are: manner of the engine operation, frequency of appearance and characteristics of nonstationary states run, transient processes, which can be characterised by considerably higher emission of toxic compounds comparing to the conditions of the vessel operation in the open sea with the steady engine load. Of course, the toxicity of exhaust gases is no less affected by operational materials applied, such as the kinds of fuel and oil.

The subject of balancing the emission of the compounds in exhausts of marine vessels' engines are the processes of global emission, averaged in sufficiently long period of time. This time is determined first of all by the effectiveness of averaging variable conditions of the objects operation.

The factors determining the global emission of substances present in the exhausts of marine engines can be classified as follows [9]:

- vessel structure (with respect to their size and destination), engine size and kind, number of particular engine kinds on the vessel (main and auxiliary engines), and with respect to the vessel's technical condition, taking into consideration technical solutions, state of the hull and the wear of propulsion system elements as well as their number,
- vessel operational intensity,
- vessel traffic model,
- conditions of the surroundings: atmospheric conditions (waving, strong winds, icing), navigational water areas (ports, straits, canals and other dangerous and difficult to navigate areas, open waters), sailing in ice,
- vessel economic properties with respect to operational fuel consumption,
- ecologic properties of engines applied on vessels,
- fuel properties (*inter alia,* with respect to fuel kind, composition and content of pollutants).

From the above conditions it follows that the process of modelling the toxic compounds emission in marine engine exhausts is very complex and requires the knowledge of three groups of vessel movement parameters:

- vessel parameters - length, width, draft, technical state of propulsion system, kind of propulsion (including kind and number of engines), kind and number of screw propellers etc.
- vessel movement parameters - vessel speed and course,
- external conditions - wind direction and force, air and water temperature, atmospheric pressure, air humidity, state of sea.

2. Modelling the emission of NO_x ship exhausts

The amount of noxious compounds emitted in the exhaust gases of a marine engine depends on values describing the condition of the engine's work, such as: torque M_o, rotational speed n, thermal state of the engine J, technical state of the engine Z (parameters of charge exchange system, state of TPC system, technical state and correctness of injection apparatus), conditions of surroundings G (e.g. temperature of surroundings, pressure, air humidity) and changing resistance of the vessel O (vessel resistance in shallow waters, vessel resistance during movement in a canal, air resistance and wave effect) [11]. It can thus be written down that the emission of the n^{th} noxious compound in exhaust gases e_n , will have the following form:

$$e_n = f\,(M_o, n, J, Z, G, O), \tag{1}$$

Road emission can be written down as the functional of value courses describing the combustion engine work state i.e. of torque M_o, rotational speed n and the vectors describing the thermal state of the engine $\mathbf{J}(t)$, conditions of the surroundings $\mathbf{G}(t)$ and the changing vessel resistances $\mathbf{O}(t)$:

$$b_t = \wp\,[\,M_o(t), n(t), \mathbf{J}(t), \mathbf{G}(t), \mathbf{O}(t)], \tag{2}$$

where: $\wp$ - operator transforming torque, rotational speed and the vectors of the engine's thermal state, movement resistance and conditions of the surroundings into average road emission from a vessel.

Power required to operate the vessel with the speed v_s can be determined with the use of various methods [16], characterised by more or less significant errors. In the research aiming at determining the emission values of particular toxic compounds, two methods were applied: admiralition standard, giving good results when proper admiralition coefficient C_0 is selected, and the method of E. E. Papmiel, based on analysis of the model research and real vessels tests. This formula, like the admiralition formula, can be applied in modelling the processes of toxic compounds in exhausts only for estimating the vessels propulsion power. That is because regarding the vessels operating in a given area, some parameters, such as hull block coefficient and pressure resistance coefficient, are unknown.

The effects of external conditions on the vessel's propulsion system and its functional interrelations are presented in Fig. 1 [12].

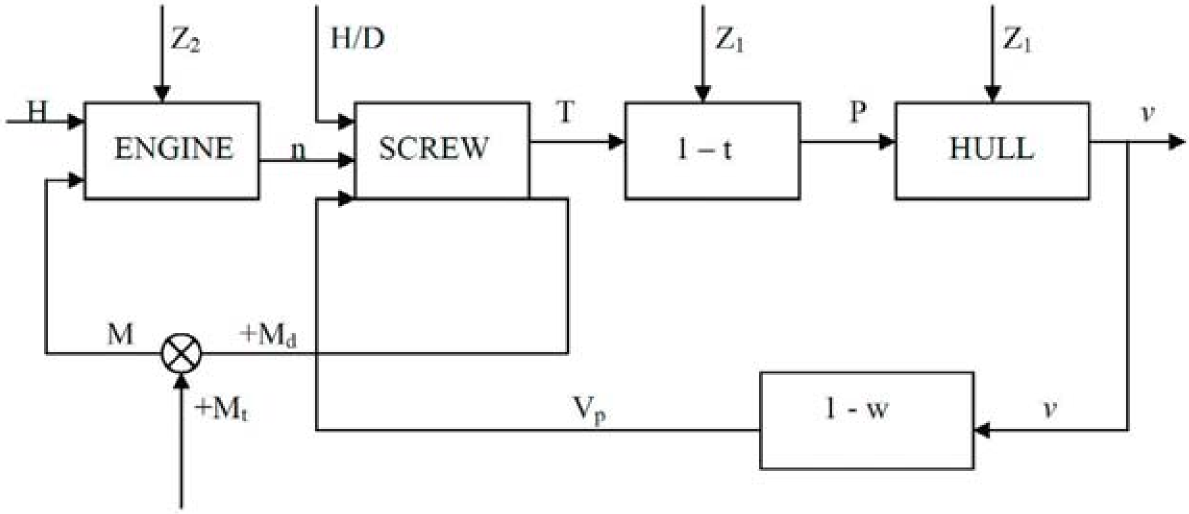

Fig. 1. Effect of external conditions on the vessel's propulsion system [12]

The setting of injection pump h and load torque M are input values to the main engine. Pitch coefficient H/D, rotational speed n and forward speed V_p are input values to the screw. Screw torque M_d, increased by friction moment on the shafting (bearings and gears) M_t puts the engine under load. Effective pressure of the screw $P = T(1\text{-}t)$ (t - suction coefficient) causes the hull to move and in stationary states determines its speed V. The forward speed of the screw V_p depends on hull speed $V_p = V(1 - w)$ (w - wake fraction). Disturbances Z_1 change the hull's resistance characteristic, of suction coefficient t and wake fraction w, and therefore also of the screw's forward speed and engine load. Disturbances Z_2 affect the system's work by changing the engine characteristic. They result from the change of temperature, pressure and relative humidity of the surrounding air, changed calorific value of fuel and the engine's technical condition. Thus, the course of the working process depends on controllable values like the setting of injection pump and screw pitch (in the case of adjustable screws) and a number of uncontrollable values, described as external conditions or disturbances Z_1 and Z_2. Disturbances Z_1 (draft, trim, state of hull surface, state of the sea, wind speed and direction, under-keel clearance etc.) do not effect a change in the engine's characteristic, but they do change the nature of its load.

It follows from this that existing methods of operating the power transmission systems do not allow the precise programming and determining engine's working point in real operational conditions, also when conducting the research on exhausts toxicity.

The current research, concerning atmosphere pollution caused by emission of noxious compounds from traction engines, mainly concern vehicle engines [1, 2, 3, 4, 8, 13] and aircraft engines [10]. They constitute a very large input into the development of modelling the emission, dispersion and imission of toxic compounds from combustion engines, yet because of both different topographic, hydrometeorologic conditions and the specificity of vessel operation, they cannot be applied for imission estimation in coastal regions. Moreover, in the research, emission of particular toxic compounds is determined as the average value measured in a given point (points) in relation to the average number of emitters (vehicles). In the research, the size, number and kind of engines emitting toxic compounds are not taken into account.

In case of vessels, such an approach resulted in errors discrediting research results [12].
Theoretical vessel trajectory can be described with the use of glued functions of the first order. When considering the trajectory of a vessel as the realisation of stochastic process $\{\mathbf{S}(t) = (X(t), Y(t)): \quad t \geq 0\}$, assuming that this process is the process of multidimensional distribution of continuous type and continuous realisations [12, 15], it can be stated that the realisation of the process is a two-dimensional and time-dependent trajectory $\{\mathbf{s}(t) = (x(t), y(t)): \quad t \in T\}$. Random change in the vessel speed at time *t* is described by vectorial stochastic process $\{\mathbf{V}(t) = (V_X(t), V_Y(t)): \quad t \in T\}$. At a given time *t*, this value is a two-dimensional random variable indicating a momentary speed vector. It should be noticed that between the random processes: $\{\mathbf{S}(t) = (X(t), Y(t)): \quad t \geq 0\}$ and $\{\mathbf{V}(t) = (V_X(t), V_Y(t)): \quad t \geq 0\}$ there exist the obvious relations: $\frac{d\mathbf{S}(t)}{dt} = \mathbf{V}(t), \quad t \geq 0$; $\mathbf{S}(t) = \int_0^t \mathbf{V}(x)dx, \quad t \geq 0$; $V_X(t) = \frac{dX(t)}{dt}$; $V_Y(t) = \frac{dY(t)}{dt}$; $v_X(t) = \frac{dx(t)}{dt}$; $v_Y(t) = \frac{dy(t)}{dt}$. After appropriate transformations, the length of the speed vector is determined [13]:

$$|\mathbf{v}(t)| = \sqrt{[v_X(t)]^2 + [v_Y(t)]^2}, \tag{3}$$

The intensity of emission E being a function of time $m_t(t)$ from a particular source in relation to time t can be written down as follows:

$$\mathrm{E(t)} = \frac{d\mathrm{m_t(t)}}{d\mathrm{t}}, \tag{4}$$

where m_t - mass of a given noxious compound.

Road emission [10] is defined as emission derivative, being a function of the road $m_s(s)$ from a source, which is the vessel, in relation to road s covered by her:

$$\mathrm{b_s} = \frac{d\mathrm{m_s(s)}}{d\mathrm{s}}, \tag{5}$$

On the basis of equation (3) it can be written down that emission on road S will be equal to:

$$\mathrm{m_s(S)} = \int_0^{\mathrm{S}} \mathrm{b_s(s)}d\mathrm{s}, \tag{6}$$

and in time T:

$$\mathrm{m_t(T)} = \int_0^{\mathrm{T}} \mathrm{b_t(t)v(t)}d\mathrm{t}, \tag{7}$$

where v(t) - vessel speed.

If the length of the velocity vector is expressed by formula (3), and the vessel moves along $\{\mathbf{s}(t) = (x(t), y(t)): \quad t \in T\}$, then the equation describing the mass of emitted exhausts can be written down as follows:

$$M = \int_{\alpha}^{\beta} f(x(t), y(t)) \sqrt{[v_X(t)]^2 + [v_Y(t)]^2}\, dt \tag{8}$$

or:

$$M = \int_{\alpha}^{\beta} f(\mathbf{s}(t)) \,|\, \mathbf{v}(t) \,|\, dt\,, \tag{9}$$

Mass of emitted exhausts in a given area ***A*** at a time interval [α, β] is the sum of masses emitted by all the vessels operating in that time interval at that region. If $W^{(k)},\;\; k = 1,...,K$ constitutes the mass of exhausts emitted by z kt^h vessel, the total mass of emitted exhausts in area ***A*** in time interval [α, β] is random variable:

$$\mathbf{W}_K = \sum_{k=1}^{K} W^{(k)}\,,$$

Random variables $W^{(k)},\;\; k = 1,...,K$ are independent and have normal distributions of the expected value:

$$E(W^{(k)}) = E(\Delta M^{(k)}) + M^{(k)} = M^{(k)} + \sum_{i=1}^{N} \lambda_i^{(k)}\, d_i^{(k)} = M^{(k)} + \varepsilon \sum_{i=1}^{N} \lambda_i^{(k)}\, \Delta s_i^{(k)} \tag{10}$$

and standard deviation:

$$\sigma(W^{(k)}) = \sigma(\Delta M^{(k)}) = \sqrt{\sum_{i=1}^{N} [\lambda_i^{(k)}\, d_i^{(k)}]^2} = \rho \sqrt{\sum_{i=1}^{N} [\lambda_i^{(k)}\, \Delta s_i^{(k)}]^2}\,, \tag{11}$$

where: $\lambda_i = f(x(t), y(t)), t \in [t_{i-1}, t_i), i = 1,...,N$ - exhausts emission intensity,

ε coefficient of average road elongation,

ρ coefficient of standard error of road elongation.

On the majority of vessels the changes in values of engine load take place in accordance with the screw characteristic. The real screw characteristic of power of a main engine cooperating with a propulsion screw with given geometry (*H/D = const)* in particular external conditions of the vessel's movement *(WZ = const)* is described by the dependence [10]:

$$P_e = k_2\, n^m\; [W], \tag{12}$$

where: m ~ 3 for displacement hulls,

m = 1.8-2.2 for half-slide hulls,

m = 1.6-1.8 for slide hulls.

Relative screw characteristic of power for displacement hulls, averaged for normal operational conditions, is described by the polynomial:

$$P_{e\bullet} = -0.015 + 0.285 \cdot n_\bullet - 0.794 \cdot n_\bullet^2 + 1.523 \cdot n_\bullet^3, \tag{13}$$

where: $P_{e\bullet} = P_e/P_{e(n)}$,

$n_\bullet = n/n_n$.

From the dependences taking place between values characterising the work of the vessel's propulsion system, it follows that for a particular propulsion system solution and the way of its utilization (gear ratio, shafting efficiency, number of engines working per shaft), resistance characteristic of the hull and a particular vessel speed there strictly corresponds an engine load (power, rotational speed). This means that for a particular vessel, depending on the operational speed distribution, it is possible to predict the distribution of main engine loads.

In statistical determination of the marine vessels movement flow [11], there were considered the trajectories approaching the ports of Gdynia and Gdansk, as well as the trajectory splitting into those two trajectories. At those trajectories at particular places there were set perpendicularly some virtual „gates", which allowed to perform a statistical determination of the number of vessels passing through (in both directions) in the period of 11 months.

In the research, there were used some statistical data transmitted in the *Automatic Identification System*, registered by the AIS shore installation of R4 type (made by SAAB company), which traces the vessels movement in Gdansk Bay area.

To determine the toxic compounds emission in exhausts on the basis of data obtained via AIS [6, 7], there were formulated some statistical models describing the momentary power $\boldsymbol{P_e}$* for the momentary speed $\boldsymbol{v}$*, regarding the vessel size, its time spent in the area of research, and emission of toxic compounds. These values permit to estimate the emission intensity $\boldsymbol{E}_{\mathrm{NOx}}$ at that point at he level of (0.6 - 576) kg/h (Fig. 2).

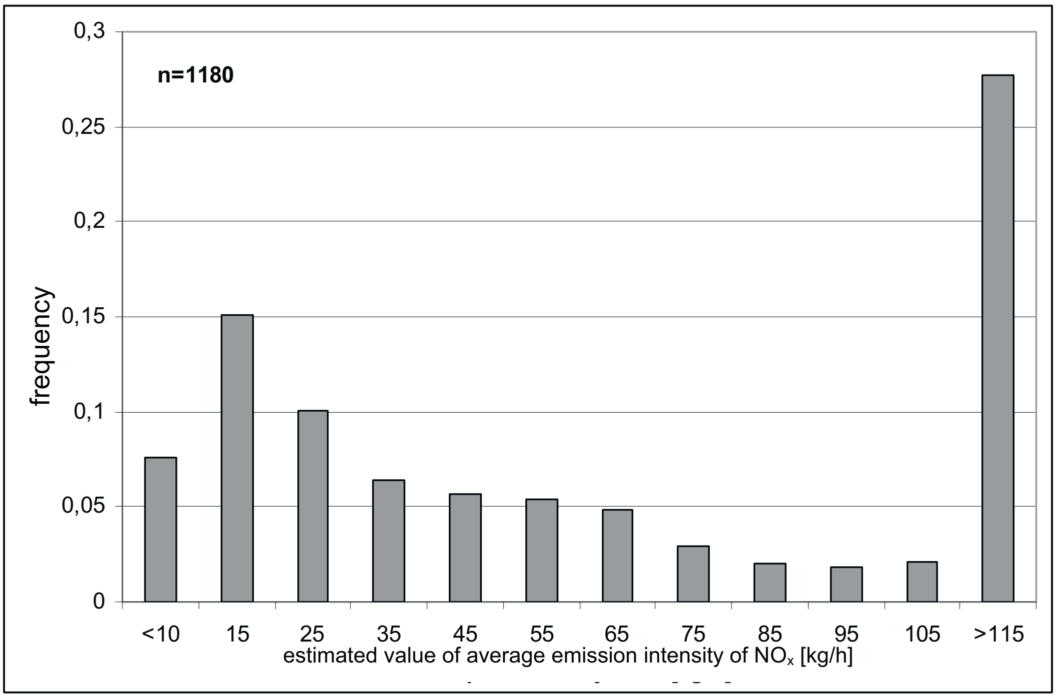

Fig. 2. Distribution of estimated emission intensity E_{NOx} [kg/h] for vessels passing through „gate" a Gdynia ($\overline{\boldsymbol{CD}}$)

A considerable number of vessels of emission intensity $\boldsymbol{E}_{\mathrm{NOx}}$ above 115 kg/h results from the fact that the above range of emission intensity relates to the engines of momentary power $\boldsymbol{P_e}$* above 8.3 MW.

However, it should be noticed that time a vessel spends in the gate area is a few minutes, whereas absolute time a vessel requires for covering the distance Hel - Gdynia (gates $\overline{\boldsymbol{AB}}$ - $\overline{\boldsymbol{CD}}$), depending on the vessels speed, accounts for 20 - 144 minutes. Thus, determining the value of emission intensity $\boldsymbol{E}_{\mathrm{NOx}}$ in kilograms per nautical mile [kg/Mm] seems to be more expedient in this case (Fig. 3).

3. Conclusion

Modelling emission, and then dispersion and imission of toxic compounds in marine engines' exhausts constitutes a very important and very complex issue. Currently conducted research, devoted to the pollutants dispersion, refer to air pollutants of stationary origin (electric power stations, industrial plants), of motorization origin, and recently also of aircraft origin.

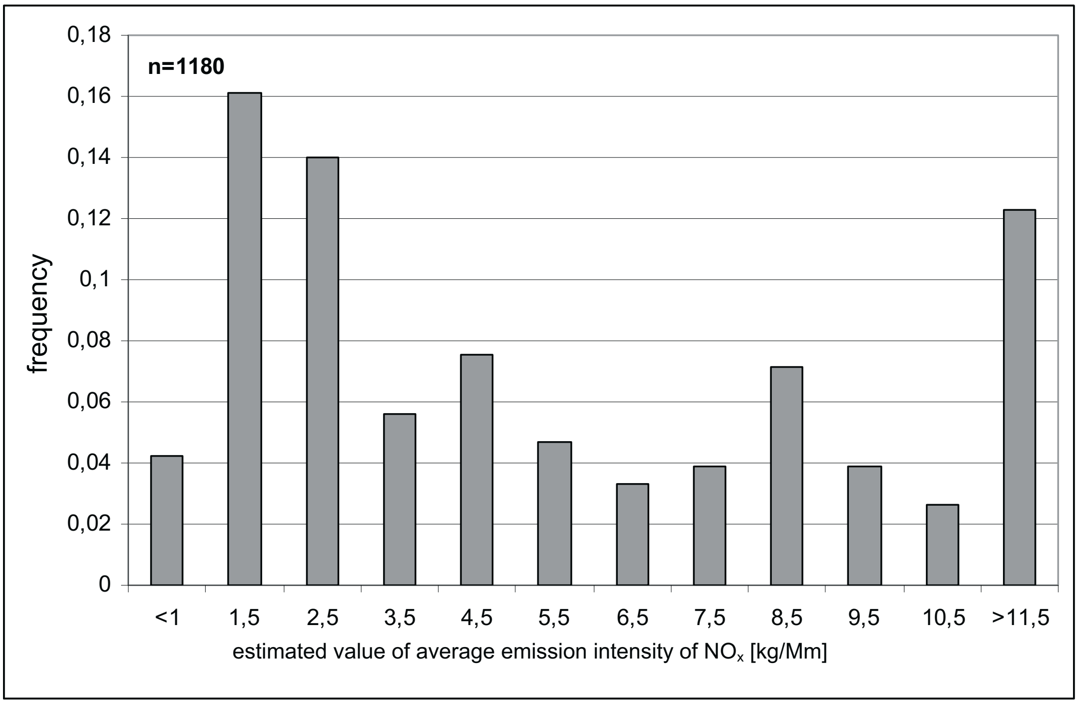

Fig. 3. Distribution of estimated value of average emission intensity E_{NOx} [kg/Mm] for vessels operating in the approach area of Hel - Gdynia (gates $\overline{\boldsymbol{AB}}$ - $\overline{\boldsymbol{CD}}$)

Scientific papers, mainly referring to motorization, because of the size of marine engines, cannot be applied in modelling the emission of toxic compounds from marine engines, as the model structure depends not only on its destination, but also on the quantity and quality of input data.

Additionally, apart from the problems appearing when modelling the toxic compounds emission from road vehicles, in case of marine vessels, among the parameters disturbing the appropriate determination of particular compounds emission (due to the lack of data or its changeability) are also technical state of engine, and especially of fuel apparatus, as well as atmospheric conditions (mainly wind power and direction).

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