# MODELLING THE EMISSION OF NOXIOUS COMPOUNDS OF MAIN ENGINE EXHAUST GASES IN THE GULF OF GDAŃSK REGION

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***Abstract***

*The development of marine diesel engines has so far been directed towards raising their power, reducing fuel consumption, burning fuels of the lowest possible quality and the extension of operation time. The rising pro-ecologic pressure has caused atmosphere pollution by exhaust gases of marine engines to be one of the main problems of environment protection of recent years. The Gulf of Gdansk 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 environment pollution and 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 conditions concerning the modelling of noxious compounds emission in the Gulf of Gdańsk region.*

## 1. Introduction

The emergence of regulations concerning the level of toxic compounds emission [1,2,3,4,5,6,7], made both engine manufacturers and shipowners undertake actions aimed at its reduction. Shipowners' activity in this scope is practically enforced by the requirements of local regulations concerning state coastal waters and ports. There is also the opinion that the MARPOL regulations in force will cover not only newly-built engines, but also those currently remaining in operation.

These changes are expected to affect the process of operation and ecologic supervision of marine engines. Apart from technical modification of marine engines and the construction of additional plants aimed at fulfilling the requirements of toxicity standards for exhaust gases, this will bring about the necessity of introducing new methods determining directly or indirectly the toxic compounds emission level in exhaust gases [8].

The above circumstances make it necessary to identify the effect of particular conditions of the engine work on the emission level of toxic compounds in exhaust gases. Whereas the effect of constructional and operational factors on engine work indexes is known and taken account of, their effect on emission indexes for toxic compounds is less known, at least with respect to marine engines. Such a state of things makes us undertake an analysis of this effect.

The Gulf of Gdańsk area (Fig.1), similarly to sea ports or coastal regions, is vulnerable to the effect of noxious compounds in vessels' exhaust gases, besides pollution coming from industrial and power plants or vehicles. This concerns vessels both in ports and in the roads. It should be pointed out that in spite of the small number of vessels in relation to, e.g., city traffic vehicles, emission values of noxious compounds from a marine engine are many times higher.

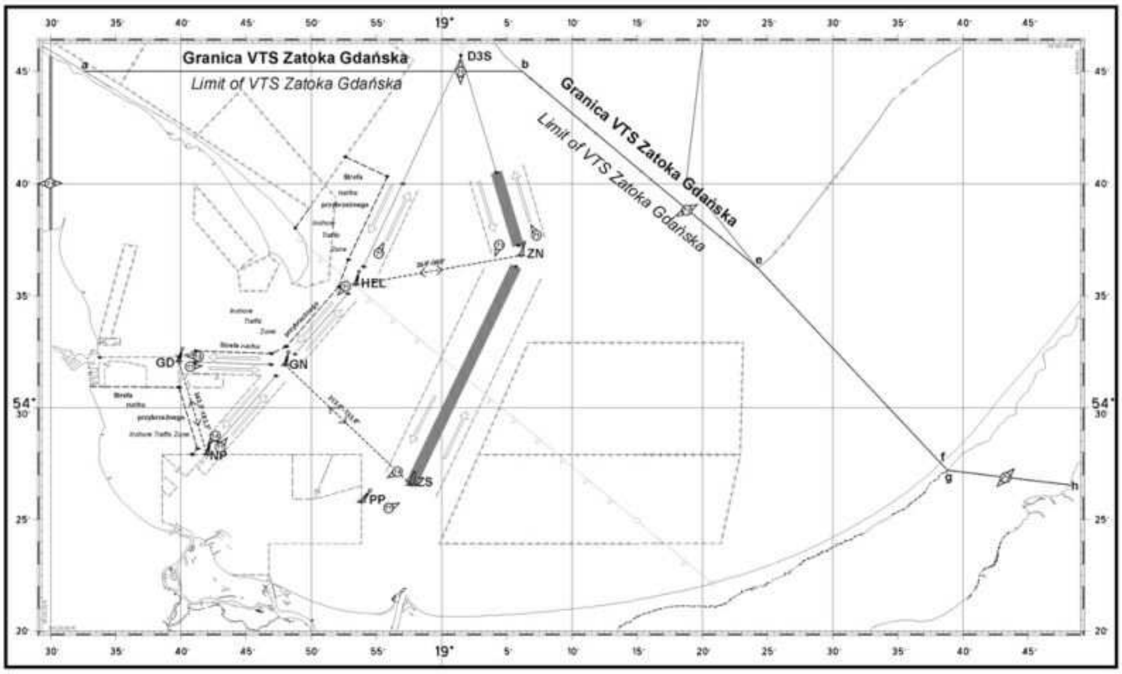


*Fig.1. Chart of Gulf of Gdańsk region with marked vessel traffic routes [9]*

The problem of air pollution in ports and approaches to ports is insomuch important, as the ports are in the area of large cities, and their limited area causes high concentration of vessels in a small space. Widely conceived operational conditions do not remain without significance, either. The following can be counted among the latter: the method of engine utilization, frequency and abruptness of non-stationary states, transitional processes characterised by higher emission of toxic compounds than when sailing in open areas with constant engine load, and the correctness and frequency of starting the engine. Of course, the toxicity of exhaust gases is no less affected by operational materials applied, that is kinds of fuel and oil.

## 2. The effect of vessel movement resistance and external conditions on the engine's load

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, like 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). 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:

$$e_n = f\,(M_o, n, J, Z, G, O) \qquad (1)$$

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:

$$E(t) = \frac{dm_t(t)}{dt} \tag{2}$$

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 like a vessel, in relation to road s covered by her

$$b_s = \frac{dm_s(s)}{ds} \tag{3}$$

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

$$m_s(S) = \int_0^S b_s(s)ds \tag{4}$$

and in time T

$$m_t(T) = \int_0^T b_t(t)v(t)dt \tag{5}$$

where v(t) vessel speed.
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 **J**(t), conditions of the surroundings **G**(t) and the changing vessel resistances **O**(t)

$$b_t = \wp[\, M_o(t), n(t), \mathbf{J}(t), \mathbf{G}(t), \mathbf{O}(t)] \tag{6}$$

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.

The power necessary for sailing on vessel with speed $v_s$ can be presented by means of equation:

$$P_o = \frac{V}{L}\frac{x}{\lambda}\sqrt{\psi}\,\frac{v_s^3}{C_p} = f\left(\frac{v_s^3}{C_p}\right) \tag{7}$$

where:

V – volume of the vessel's underwater part [m$^3$],
L – vessel length on the waterline [m],
$v_s$ – vessel speed [w],
$x$ – coefficient dependent on the number of shafts, taking into account the effect of protruding parts,
$\lambda$ – length correction factor calculated from the formula $\lambda = 0.7 + 0.3$ L/100,
$\psi$ – fineness ratio of the hull:

$$\psi = \frac{B}{L}\delta$$

B – vessel width [m],
$\delta$ – block coefficient of the hull,
$C_p$ – pressure resistance coefficient.

It should be remembered at the same time that engine power P is also affected by conditions of the surroundings different from exemplary ones, which is why it is necessary to correct the power value given by the engine manufacturer [11]. In the case of a four-stroke engine effective power $P_e$ equals [12]:

$$P_e \cong P_{eo}[k - 0.7(1 - k)(\eta_m^{-1} - 1)] \tag{8}$$

where:

$P_e$ – effective power for real external conditions [kW],
$P_{eo}$ – effective power for normal external conditions [kW],
$\eta_m$ – mechanical efficiency of the engine,
$k$ – coefficient taking into account a change of external conditions

$$k = \left(\frac{p_1 - a\varphi_1 p_{s1}}{p_0 - a\varphi_0 p_{s0}}\right)^m \left(\frac{T_0}{T_1}\right)^n \left(\frac{T_{c0}}{T_{c1}}\right)^q$$

where:

$p_o$, $p$ – barometric pressure of air sucked in, in normal and measurement conditions [hPa],
$p_{so}$, $p_s$ – vapour pressure in air sucked in, in normal and measurement conditions [hPa],
$\varphi_o$, $\varphi$ – relative humidity of the air in conditions as above [%],
$T_o$, $T$ – air temperature in conditions as above [K],
$T_{co}$, $T_c$ – cooling water temperature at the inlet of the supercharging air cooler in conditions as above [K].

Coefficient $a$ , index exponents $m$,$n$ and $q$ depend on engine type and are given in the standard [12].

The effects of external conditions on the vessel's propulsion system and its functional interrelations have been presented in Fig. 2 [13].

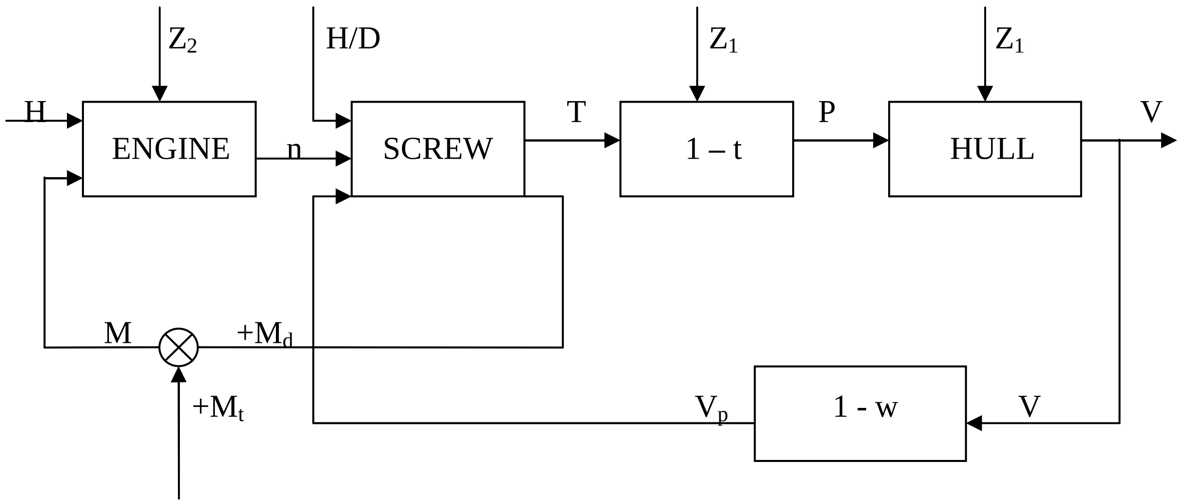


*Fig.2. Effect of external conditions on the vessel's propulsion system [13]*

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-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 with current methods of controlling propulsion systems it is practically impossible to accurately program and determine the engine's working point in real conditions, also when doing research on the toxicity of exhaust gases.

## 3. Possibilities of predicting work conditions of marine engines

Information identifying the vessel and determining her movement parameters can be obtained from VTS system (Vessel Traffic Service), which provides the operator with data in the following categories [14]:

a) hydrometeorological situation in the region,
b) status of navigational marking,
c) vessel positions, movement and intentions,
d) contact with the rescue centre,
e) possible other data indispensable for maintaining order and traffic safety in the responsibility area.

As can be seen, information categories mentioned in positions a) and c) are directly useful for estimating the effect of vessel traffic on air pollution with noxious compounds from exhaust gases. The information can be supplemented with information from an independent identification system - AIS. Information from these systems is combined in Maritime Safety Information Exchange System (SWIBŻ), which makes it possible to filter it according to numerous parameters (e.g. the vessel's name and data). The system has its merits and demerits. Its biggest demerit (from the point of view of the present writers' needs) is the necessity of gathering information of positional character, correlated in time, weather conditions and the vessel's type, engine and load, and the necessity of taking into consideration the loading state, speed and weather conditions. In work [14] at least partial elimination of these faults is suggested, as the system of automatic identification of ships (AIS) can be used more widely.

AIS system is a system of data transmission by radio waves. The data can be divided into three categories:

1) constant information,
2) information on travel,
3) variable information.

The first two categories are of alphanumeric character and are entered by the installer or operator. Variable information is taken from navigational apparatus cooperating with AIS. Information transmitted by AIS can be divided into static (MMSI number, name and call sign, IMO number, length and width, type, location of antenna in relation to hull geometry) and dynamic, determined in the normal course by external devices (vessel position and its accuracy index, UTC time of position determination, track angle over the bottom, speed over the bottom, ship's course, navigational status, angular velocity when making a turn). A separate group of information is constituted by information pertaining to travel (vessel's draft, dangerous cargo, port of destination and ETA, voyage plan).

It follows from the description of AIS system functions that it is viable to make use of the system data for determining models of vessel movement and the attendant models of emission of noxious compounds contained in exhaust gases.

## 4. Possibilities of modelling noxious compounds emission from main engine exhaust gases in the region of the Gulf of Gdańsk

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

$$P_e = k_2 \cdot n^m \ \ [W] \tag{9}$$

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:

$$P_{e\bullet} = -0.015 + 0.285 \cdot n_{\bullet} - 0.794 \cdot n_{\bullet}^2 + 1.523 \cdot n_{\bullet}^3 \tag{10}$$

where:

$P_{e\bullet} = P_e/P_{e(n)}$
$n_{\bullet} = n/n_n$

For each marine engine of the main propulsion it is possible to determine the screw characteristics of concentrations or emission of particular noxious compounds in exhaust gases. Within the framework of research conducted at the Naval Academy at Gdynia there were determined toxicity characteristics and quality models describing concentration values of particular compounds as function of the engine's speed [15]

Fig. 3 presents the screw characteristic of torque and the concentrations of nitrogen oxides in the exhaust gases of Sulzer engine type 6AL20/24, and an equation describing the value of nitrogen oxides $c_{NOx}$ concentration as function of the engine's speed.

Determining this type of characteristics for a larger number of engines of the same type or kind would permit, after suitable statistic treatment, the preparation of universal characteristics and models for a given group of engines.

At present, due to lack of universal models, it is possible to determine approximate emission on the basis of average emission for a particular kind of engine. The value of such emission can be calculated on the basis of equations:

$$e_{in} = P_e \cdot \bar{e}_{in} \cdot r \ \ [g/(kW{\cdot}h)] \qquad or \qquad e_{in} = B_e \cdot t \cdot \bar{e}_{in} \cdot r \ \ [kg/t_{pal}] \tag{11}$$

where:

$e_{in}$ – emission value of the n[th] compound,
$P_e$ – effective power for real external conditions [kW],
$B_e$ – fuel consumption per hour [t/h],
t – mean time of the vessel's stay in the researched region [h],
*r* – coefficient taking into account the effect of external conditions on additional resistance (vessel resistance in shallow waters, air resistance, wave-caused resistance),
$\bar{e}_{in}$ – value of average emission of the n[th] compound for the kind of engine (based on MAN-B&W and Wartsila catalogues):

medium-speed engines:

- $\bar{e}_{NOx}$ =13.8 g/(kW·h) or 59 kg/$t_{pal}$
- $\bar{e}_{CO}$ – 1.8 g/(kW·h) or 8 kg/$t_{pal}$
- $\bar{e}_{HC}$ – 0.6 g/(kW·h or 2.7 kg/$t_{pal}$
- $\bar{e}_{CO2}$ – 3250 kg/$t_{pal}$

slow-speed engines:

- $\bar{e}_{NOx}$ – 18 g/(kW·h) or 84 kg/$t_{pal}$
- $\bar{e}_{CO}$ – 2 g/(kW·h) or 9 kg/$t_{pal}$
- $\bar{e}_{HC}$ – 0.6 g/(kW·h) or 2.5 kg/$t_{pal}$
- $\bar{e}_{CO2}$ – 3150 kg/$t_{pal}$

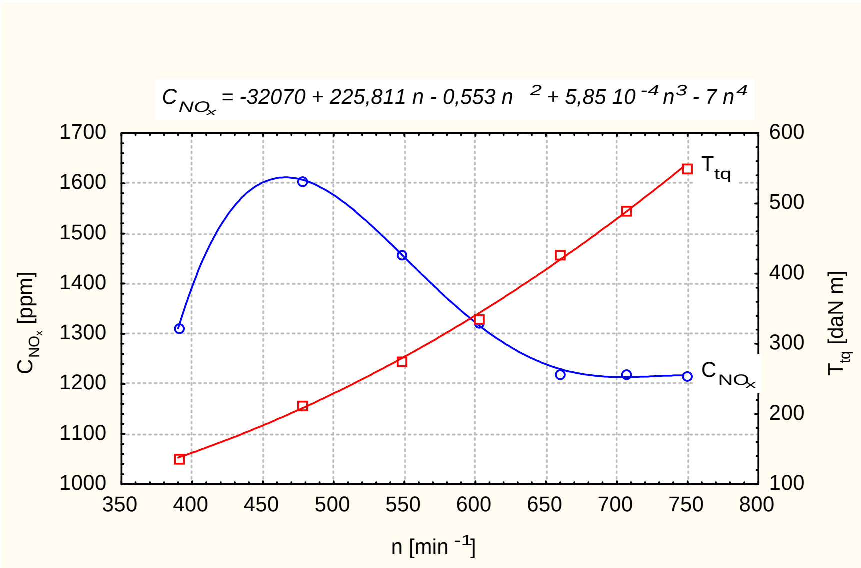


*Fig. 3. Screw characteristic of torque and nitrogen oxide concentration in the exhaust gases of Sulzer type 6AL20/24 engine*

## 5. Conclusions

1. With known value of the vessel's speed, and the type and characteristic of the engine, it is possible to determine engine power, and consequently to calculate unit emission of particular noxious compounds in the exhaust gases of marine engine.
2. Determining this type of characteristics for a larger number of engines of the same type or kind would permit, after suitable statistic treatment, the preparation of universal characteristics and models for a given group of engines.
3. Among parameters disturbing the accurate determination of emission of particular compounds (due to lack of information or their changeability) there can be counted the effect

of surface roughness of the hull (unevenness of hull plates and their joints, unevenness of paint layers, and unevenness caused by hull corrosion and overgrowing), technical condition of the engine, fuel apparatus in particular, and atmospheric conditions (especially wind direction and force).

4. In case of lack of the above data, it is possible to determine the approximate emission of noxious compounds on the basis of average emission values.

**References**


[1] Dietrich, W.R., *Experience with the Germany Clean Air Act of stationary internal-combustion engines*, MTZ 49/1988.

[2] Emission Standards Reference Guide for Heavy-Duty and Nonroad Engines. EPA 420-F-97-014, September 1997.

[3] Euromot Working Group Euromot Proposal on Exhaust Emission Standards for Marine the Prevention of Pollution from Ships (MARPOL 73/78), Annex VI “Regulations for the Prevention of Air Pollution From Ships” - London 26.09.1997

[4] International Maritime Organization - Protocol of 1997 to the International Convention for the Prevention of Pollution from Ships (MARPOL 73/78), AneksVI “Regulation for the Prevention of Air Pollution From Ships” – London 26.09.1997.

[5] Leigh-Jones, C., *Worldwide Developments in Exhaust Emission Legislation for Marine Sources*, Ricardo Consulting Engineers Ltd, West Sussex, 18 April 1994.

[6] The Marine Engineering Society in Japan: Recent trends in the control of emissions from ships, Martch 1996.

[7] Ustawa o zapobieganiu zanieczyszczaniu morza przez statki. Dziennik Ustaw RP Nr 47, Warszawa 09 maja 1995.

[8] Vollenweider, J., *Exhaust Emission Control of Sulzer Marine Diesel Engines*, Marine Engine Symposium, Szczecin, Gdynia/Gdańsk, czerwiec 1994.

[9] www.umgdy.gov.pl

[10] Chłopek, Z., *Modelowanie procesów emisji spalin w warunkach eksploatacji trakcyjnych silników spalinowych*, PN Politechniki Warszawskiej , Mechanika, z.173, Warszawa 1999

[11] Wojnowski, W., *Okrętowe siłownie spalinowe, cz. III Projektowanie siłowni okrętowych*, Wydawnictwo Politechniki Gdańskiej, Gdańsk 1992

[12] Norma ISO 3406/I-1975/E

[13] Berger, T., *Zastosowanie systemów diagnostycznych w użytkowaniu urządzeń okrętowych.*, Zeszyty Naukowe AMW Nr 4/88, Gdynia 1988.

[14] Felski, A., *Implementation of AIS in air pollution investigations*, Materials of European Navigation Conference Global Navigation Satellite Systems. Geneva 2007.

[15] Kniaziewicz, T., Piaseczny, L., Merkisz, J., *Charakterystyki śrubowe stężeń* $NO_x$, *CO, HC w spalinach silnika SULZER typu 6AL20/24*, Czasopismo Techniczne MECHANIKA, zeszyt 6, str. 333-340, Politechnika Krakowska 2004