Journal of POLISH CIMAC

Faculty of Ocean Engineering & Ship Technology
GDAŃSK UNIVERSITY OF TECHNOLOGY

MODELLING EXHAUST EMISSION FROM VESSELS IN THE GULF OF GDAŃSK AREA

Tomasz Kniaziewicz, Leszek Piaseczny

Polish Naval Academy
Smidowicza Street 69, 81-103 Gdynia, Poland
tel.: +48 58 6262851, 6262603
e-mail: tkniaziewicz@wp.pl, piaseczny@ptnss.pl

Abstract

The area of the Gulf of Gdańsk, just like port towns and coastal regions, is vulnerable to pollution contained in the exhaust gases of industrial plants, power plants, vehicles and harmful compounds contained in exhausts of vessels. In order to determine the share of vessels in polluting atmospheric air and to counteract the harmful effects of toxic compounds in marine engine exhausts it is necessary to know the values of those compounds' emission from particular vessels, which is possible by knowing the movement parameters of vessels, the values of concentrations of particular compounds for these parameters and the atmospheric conditions in the region of their occurrence.

The object of balancing emission of pollution contained in the exhausts from engines propelling vessels are the processes of global emission, averaged in a sufficiently long time period, which is determined first of all by the efficiency of averaging the variable conditions of the objects' operation. Due to the impossibility of making emission measurements on vessels in the region of research, it is necessary to work out suitable models of estimating emission of toxic compounds, based on proper measurement tests simulating navigational conditions in the Gulf of Gdańsk as well as mathematical models.

The work presents conditions related to modelling the emission of exhaust compounds from vessels engines in the region of the Gulf of Gdańsk, with particular consideration to estimating the values of toxic compounds concentration.

Keywords: *emission, dispersion, modelling, marine engines, exhausts*

1. Introduction

The problem of air pollution in ports and approaches to ports is important inasmuch as the ports are usually close to or on the territories of large cities, and their restricted area causes large concentration of vessels in a small area. Widely conceived operational conditions are not insignificant either, among them being the way of engine operation, the frequency of occurrence and character of non-stationary states, transitory processes characterised by considerably larger emission of toxic compounds than during sailing in open areas with constant engine load. The way of operation is also affected by external conditions, that is the effect of marine environment on the engine's work. Certainly the kinds of fuel and lubricating oil affect exhaust toxicity in no smaller degree.

The research currently carried out concerning atmosphere pollution caused by the emission of harmful compounds from traction engines (airplane and car engines) [1-3] provides very large contribution to the development of modelling of imission of harmful compounds emitted from diesel engines, but due to the difference in both topographic and hydrometeorologic conditions and the specificity of vessel operation, they cannot be applied for estimating imission in coastal areas [4].

Modelling emission of particular exhaust components from exhaust systems of marine engines during movement in a particular area constitutes one of the key problems of balancing and making input data for dispersion models.

The object of balancing emission of pollution contained in the exhausts from engines propelling vessels are the processes of global emission, averaged in a sufficiently long time period, which is determined first of all by the efficiency of averaging the variable conditions of the objects' operation.

The factors determining global emission of substances contained in marine engines exhausts have been classified and described in [4,5].

The process of modelling emission and dispersion of toxic compounds (ZT) in marine engine exhausts (which are the elements of modelling the imission of these compounds), is very complex and requires the knowledge of five basic parameter groups [5,6]:

- vessel parameters: length, breadth, draft, technical condition of propulsion system, kind of propulsion (including kind and number of engines), kind and number of propellers, etc.;
- vessel movement parameters: speed and course;
- external conditions: wind direction and force, air and water temperature, atmospheric pressure, air humidity, state of the sea;
- number of vessels, with consideration to category;
- topographic parameters of the area: terrain kind and profile (water, land).

Models of emission from land means of transport created in Europe, like HBEFA, COPERT, DVG and DRIVE-MODEM [7,8] endeavour first of all to take into account the largest possible number of parameters affecting emission, yet with such a large number of factors and the complex description of phenomena determining the emission process, simplifying assumptions cannot altogether be avoided.

2. Modelling emission of exhausts from marine engines

In work [9] there has been considered the trajectory of vessel movement as the realisation of a two-dimensional stochastic process $\{\mathbf{S}(t) = (X(t), Y(t)): \quad t \geq 0\}$, assuming that the process is of multidimensional distribution of continuous type and continuous realisations. The realisation of such a process is a two-dimensional trajectory dependent on time $\{\mathbf{s}(t) = (x(t), y(t)): \quad t \in T\}$.

The equation describing the mass of exhausts emitted can be presented as follows:

$$M = \int_{\alpha}^{\beta} f(\mathbf{s}(t)) \,|\, \mathbf{v}(t) \,|\, dt \,, \tag{1}$$

where:

v(t) length of vessel velocity vector.

Assuming that in the time intervals $[t_{i-1}, t_i], \quad i = 1,...,N$ the speed of the vessel is constant

$$|\, \mathbf{v}(t) \,| = v_i \,, \quad i = 1,...,N \quad , \tag{2}$$

and the intensity of exhaust emission is constant

$$f(x(t), y(t)) = \gamma_i \,, \quad t \in [t_{i-1}, t_i), \quad i = 1,...,N \,, \tag{3}$$

the lower estimation of emitted exhaust mass is obtained

$$M = \sum_{i=1}^{N} M_i \quad , \tag{4}$$

where:

$M_i = \gamma_i \, v_i \Delta t_i , \quad i = 1,2,...,N$.

The mass of emitted exhausts in particular area ***A*** in time interval $[t_{i-1}, t_i]$ is the sum of masses emitted by all vessels in this time interval in the area. If $W^{(k)}, \quad k = 1,...,K$ denotes the mass of exhausts emitted by the *k*-th vessel, then the total mass of exhausts emitted in area ***A*** in time interval $[t_{i-1}, t_i]$ is a random variable

$$\mathbf{W}_K = \sum_{k=1}^{K} W^{(k)} \quad , \tag{5}$$

Random variable $\mathbf{W}_K$ as the sum of independent random variables with normal distribution has normal distribution with expected value

$$E(\mathbf{W}_K) = \sum_{k=1}^{K} W^{(k)} = \sum_{k=1}^{K} [E(\Delta M^{(k)}) + M^{(k)}] = \sum_{k=1}^{K} [M^{(k)} + \varepsilon^{(k)} \sum_{i=1}^{N} \gamma_i^{(k)} \, \Delta s_i^{(k)}] \quad , \tag{6}$$

Standard deviation of these random variables is equal to

$$\sigma(\mathbf{W}_K) = \sqrt{\sum_{k=1}^{K} V[\Delta M^{(k)}]} = \sqrt{\sum_{k=1}^{K} \rho^{(k)} \sum_{i=1}^{N} [\gamma_i^{(k)} \, \Delta s_i^{(k)}]^2} \quad , \tag{7}$$

In this model the number of vessels *K* has been assumed to be constant. In reality the number of vessels varies randomly in time, so it is a stochastic process [10].

Work [11,12] presents a method of approximate identification of vessel movement model, and for estimating the parameters and characteristics of exhaust emission from vessels sailing in the Gulf of Gdańsk region it is necessary to know the number of vessels navigating in the region analysed, their distribution with regard to kind, size, speed, power and kind of main propulsion engines etc.

3. Modelling load of vessel main propulsion engines in order to estimate the value of toxic compounds emission in the exhausts

The amount of emitted harmful compounds in marine diesel engines depends on values describing the state of engine work like torque M_o, engine speed n, thermal state of the engine J, technical state of the engine Z (parameters of load exchange system, state of TPC system, technical state and proper regulation of injection apparatus), condition of environment G (e.g. ambient temperature, pressure, air humidity) and variable sailing resistance of vessel O (vessel resistance in shallow water, vessel resistance while moving in a canal, air resistance and waving effect). It can thus be written down that the emission of the n-th harmful compound in exhausts e_n will have the form:

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

To calculate the vessel's momentary power ***P**** there have been used methods of calculating the power necessary to sail with speed v_s based on calculations of resistance of sea-going vessels. There are a number of methods of calculating resistance of sea-going commercial vessels, among the most widespread being: Papmiel's, Ayre's, Lap's, Taylor's and Kabaczyński's. The first two permit the determination of total (towing power) resistance, the three other only residual resistance.

All methods (excluding Papmiel's and Ayre's) have vessel resistance comparable to resistance determined from model experiments, therefore additions have to be applied for them similar to those for resistance determined from model experiments. Only Papmiel's method, which in the range of smaller speeds gives results considerably higher than those obtained by other methods, supposedly takes account of those additions.

In connection with the amount of information available concerning the vessels' dimensions and momentary speed ***v**** obtained from AIS system [13,14], two methods were accepted for calculating the value of momentary power P*: Papmiel's and the Admiralty's.

In Papmiel's method the power necessary for the vessel's sailing with speed v_s may be presented by means of the equation:

$$\mathrm{P_o} = \frac{\mathrm{V}}{\mathrm{L}} \frac{x}{\lambda} \sqrt{\psi} \frac{v_s^3}{\mathrm{C_p}} = f\left(\frac{v_s^3}{\mathrm{C_p}}\right) \quad , \tag{8}$$

where:
V – volume of the vessel's underwater part [m^3],
L – vessel's length on the waterline [m],
v_s - vessel's speed [k],
x – coefficient dependent on the number of shafts, taking account of protruding parts,
λ - length allowance coefficient calculated from the formula $\lambda = 0.7 + 0.3\ L/100$,
ψ - hull fineness coefficient.

In the case of Admiralty's method the equation describing the power necessary for the vessel to sail with speed v_s is significantly simplified and has the following form:

$$P_o = \frac{v_s^3 D^{2/3}}{C_0} \quad , \tag{9}$$

where:

P_o – power required (towing power bound with hull resistance),
C_0 – Admiralty's coefficient for towed power,
v_s – vessel speed [k],
D – vessel's displacement [m^3].

On the basis of formulae (8) and (9) there were calculated the values of momentary power P*, whose distributions have been presented in Figs 1 and 2.

On the basis of results analysed it can be stated that the differences in calculated values of momentary power determined by Papmiel's and Admiralty's methods are significant. Therefore, particular attention should be paid to the means of determining momentary power, as successively the value of toxic emission for particular vessels is calculated on its basis, which entails further simplifications and errors.

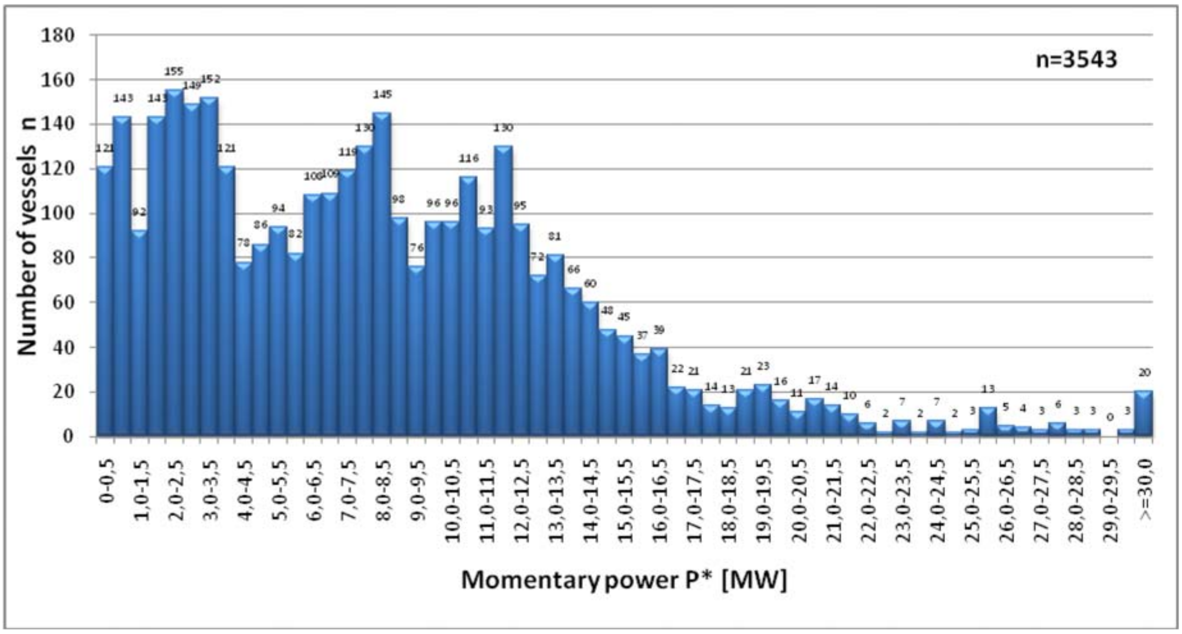

Fig. 1 Distribution of momentary power P [MW] calculated by Papmiel's method for vessel group tested [9]*

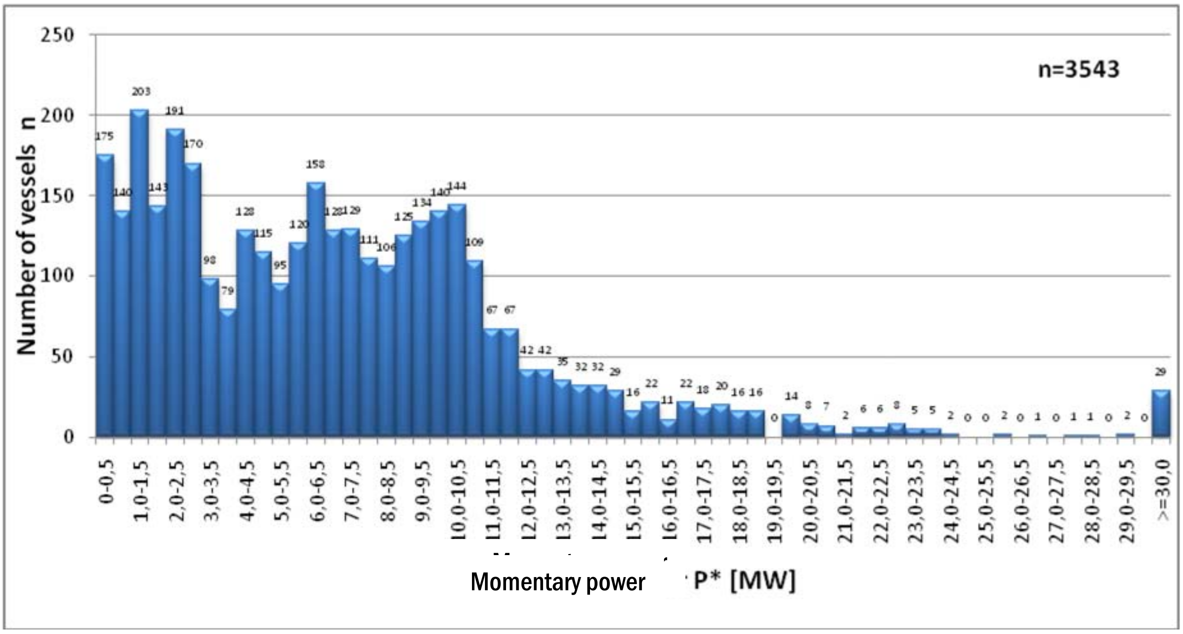

Fig. 2. Distribution of momentary power P [MW] calculated by Admiralty's method for vessel group tested [9]*

For a more accurate assessment of the emission value of particular toxic compounds there were worked out tests for examining the concentration of toxic compounds in the exhausts of main engines of vessels sailing in the Gulf of Gdańsk. For this purpose, out of the group of vessels sailing in the examined area in a period embracing 11 months 63 vessels were picked out with the highest incidence index, which gave 3543 observations [15].

On the basis of momentary power values of vessels tested $P^* = P_e/P_n$ 4 and 10-phase tests of exhaust toxicity were prepared. Seeing that most of the considered vessels sail according to typical propeller characteristic, modified test E3 acc. to ISO 8170 part 4 was accepted as initial test. The modification consisted in altering the values of weight coefficients, which in the original test characterise the whole range of the engine's operation, and in the case considered are to present conditions of engine work on the Gulf of Gdańsk fairways. Particular values of four-phase tests have been presented in Table 1[16].

In Fig. 3 there have been compared the emission values of nitrogen oxide calculated by means of E3 test according to ISO 8170-4 and prepared 4-phase test A (required power P_0 determined by Admiralty method) and 4-phase test P (required power P_0 determined by Papmiel method).

The difference between results of NO_x emission results obtained on the basis of E3 tests according to ISO8178-4 and 4-phase tests A and P seem to be insignificant (from 0.1 to 0.47 g/(kW·h)). Yet if the typical powers of vessels sailing in the Gulf of Gdańsk are taken into consideration, e.g. ferry "Stena Nornica" sailing from Gdynia (114 observations within 1 year, engines power 39600kW), then such slight differences in tests give NO_x emission intensity respectively from 3.96 to 18,61 kg/h. In relation to NO_x emission values from vehicles these are significant values and should not be ignored.

Tab.1. Proposition of 4-phase exhaust toxicity tests of vessels sailing in the Gulf of Gdańsk acc. to propeller characteristic taking consideration of the method of engine power determination

Engine speed [% n_n]	100	91	80	63
Load [% P_n]	100	75	50	25
Weight coefficient P[1)]	0.20	0.38	0.40	0.02
Weight coefficient A[2)]	0.22	0.20	0.41	0.17
Weight coefficient of E3 test acc. to ISO 8178-4	0.20	0.50	0.15	0.15

[1)] weight coefficient P - required power P_0 determined by Papmiel's method,
[2)] weight coefficient A - required power P_0 determined by Admiralty's method.

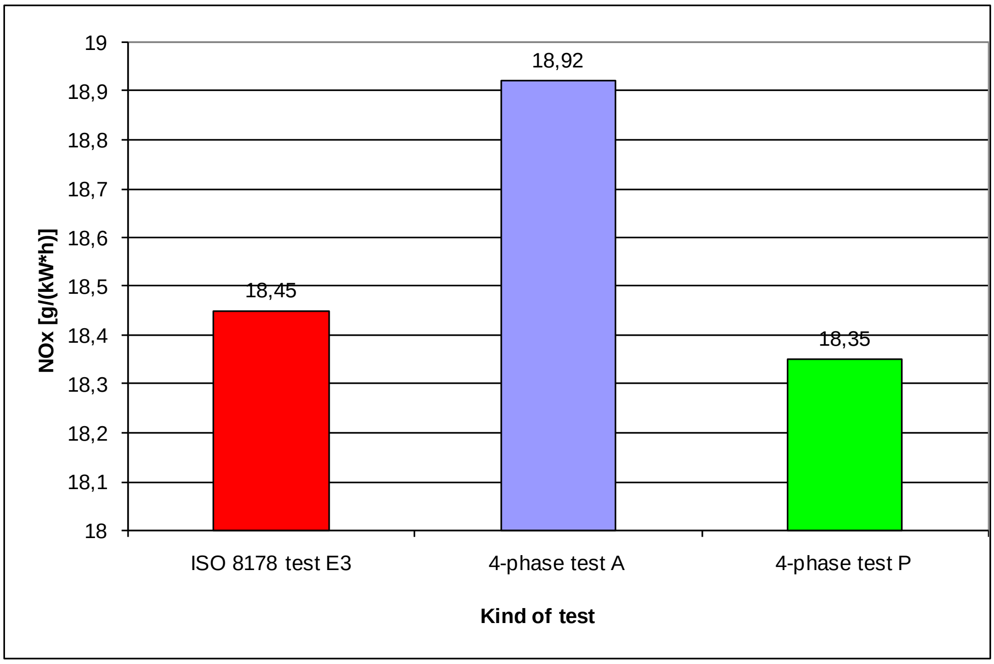

Fig.3. Comparison of NO_x emission values [g/(kW·h)] calculated by E3 test acc. to ISO 8170-4, 4-phase test A (required power P_0 determined by Admiralty's method) and 4-phase test P (required power P_0 determined by Papmiel's method)

Recapitulation

The modelling of emission of harmful compounds is a very important problem and a complex one at the same time. The scientific research work conducted at present devoted to pollution spreading concerns pollution in atmospheric air of stationary origin (power and industrial plants), motorisation and recently also airplanes. Current studies which concern first of all motorisation, because of, among other things, the size of marine engines, cannot find application for modelling emission of toxic compounds from marine engines, as the model structure depends not only on its destination but largely also on the amount and quality of input data.

The possibility of obtaining data from AIS system like ship's name, length, breadth and type, universal time bound with the vessel's passing through the „gate", course and velocity over the ground (COG, VTG) and the ship's draft permit the creation of innovative models describing vessel traffic in the area researched and the emission of harmful compounds in exhausts both for one vessel and the whole researched area.

The method of calculating power required for vessel propulsion has significant influence on the final results of determining values of toxic compounds emission in the exhausts of vessels. During analysis of data obtained from AIS system and simulated loads of main engines it was found that vessels mostly sail in the Gulf of Gdańsk with a load of $0.4 \div 0.6\ P_n$ and $0.9 \div 1.0\ P_n$. Yet due to the lack of hull resistance characteristics of vessels considered it seems pointless to make tests in the function of vessel velocity.

It should be added here that apart from problems that motorisation experts are coping with when modelling the emission of toxic compounds, in the case of vessels among the parameters disturbing the accurate determination of emission of particular compounds (due to lack of information or its variability) there should be additionally counted the engine's technical condition, fuel apparatus in particular, and atmospheric conditions (particularly wind direction and force).

References

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

[2] Brzozowska, L., Brzozowski, K., *Komputerowe modelowanie emisji i rozprzestrzeniania się zanieczyszczeń samochodowych,*. Wydawnictwo Naukowe „Śląsk" , Katowice – Warszawa 2003.

[3] Kotlarz, W., *Turbinowe zespoły napędowe źródłem skażeń powietrza na lotniskach wojskowych*, Wyższa Szkoła Oficerska Sił Powietrznych, Katedra Płatowca i Silnika, Dęblin 2003.

[4] Kniaziewicz, T., *Problemy modelowania imisji szkodliwych składników spalin z silników okrętowych w rejonach miejskich aglomeracji nadmorskich,* Zeszyty Naukowe Politechniki Częstochowskiej 162, MECHANIKA 26, Częstochowa 2006.

[5] Kniaziewicz, T., Piaseczny, L., *Model of NO_x Emission by Sea-going Vessels Navigating in the Gulf of Gdansk Region*, Silniki Spalinowe PTNSS – 2007-SC3. Poznań 2007.

[6] Kniaziewicz, T., *Problems of Modeling NO_x Emission from Marine Diesel Engines,* Journal of KONES Powertrain and Transport, vol.15, No.4, p. 227-234, Warszawa, 2008.

[7] Drąg, Ł, *Modelowanie emisji i rozprzestrzeniania się zanieczyszczeń ze środków transportu drogowego*, Archiwum Motoryzacji nr 1/2007.

[8] Joumard, R., *Methods of Estimation of Atmospheric Emission from Transport: European Scientific State of the Art,* Action COST319 final report, LTE 9901 report**,** 1999.

[9] Pawlak, M., Piaseczny, L., *Modelowanie ruchu jednostek morskich dla określania emisji związków toksycznych spalin.* Czasopismo Techniczne „Mechanika" z. 7-M/2008, str. 319-334, Kraków, 2008.

[10] Kniaziewicz, T., Piaseczny, L., Merkisz, J., *Stochastic Models of Emission of Toxic Compounds in Marine Engines Exhaust*, Journal of POLISH CIMAC. Vol. 3, No. 1, p. 129-138, Gdańsk, 2008.
[11] Pawlak M., Piaseczny L., *Model ruchu jednostek morskich dla określenia emisji związżów szkodliwych spalin.* Materiały Konferencji Explo-Diesel & Gas Turbine, Międzyzdroje, kwiecień 2009.
[12] Grabski, F., *Stochastyczne modele ruchu jednostek pływających*, Fragment sprawozdania z realizacji projektu badawczego Nr 502 009 31/1187. AMW Gdynia 2008.
[13] Felski, A., Piaseczny, L., *Monitoring of the movement of the objects on the Gdansk bay in order to recognize the characteristics of their main propulsion systems*, Combustion Engines, No. 2007-SC1, p. 377 – 382. Poznań 2007.
[14] Kniaziewicz, T., Piaseczny, L., *Możliwość wykorzystania informacji z systemu AIS w modelowaniu emisji składników spalin z silników statków w rejonie Zatoki Gdańskiej*, Zeszyty Naukowe AMW Nr 4, Gdynia 2008.
[15] Kniaziewicz, T., Piaseczny, L., *Modelling the Emission of Toxic Compounds in Marine Engine Exhaust Gas*, Czasopismo Techniczne „Mechanika” z. 7-M/2008, str. 239-249, Kraków, 2008.
[16] Pawlak, M., *Testy badania stężenia związków toksycznych w spalinach silników głównych statków pływających po obszarze Zatoki Gdańskiej*, Fragment sprawozdania z realizacji projektu badawczego Nr 502 009 31/1187. AMW Gdynia 2008.