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# Method of Creating Dynamic Characteristics of Pollution Emission by Marine Diesel Engines

*Abstract: In the report thy dynamic work conditions of marine diesel engines have been identified. The identification was based on the changes of ship movement parameters, engine steering by the operator and his work conditions. There have been considered the dynamic processes of engine pollution emission being the result of the transient work of the ship's propulsion system. These processes are difficult to determine experimentally, therefore it was decided to describe them by ship movement equations determined in a simplified way based on data obtained from AIS ship movement identification system, as well as the results of own research.*

*The research results may provide the basis for original tests for determining dynamic characteristics of pollution emission.*

Key words: *emission, harmful compounds, marine engines, dynamic characteristics*

## Metoda tworzenia charakterystyk dynamicznych emisji zanieczyszczeń przez okrętowe silniki spalinowe

*Streszczenie: W referacie dokonano identyfikacji dynamicznych warunków pracy okrętowych silników spalinowych. Identyfikacja ta została wykonana na podstawie zmian parametrów ruchu statków, sterowania silnikiem przez operatora i warunków jego pracy. Rozpatrzono dynamiczne procesy emisji zanieczyszczeń silnika, będące następstwem nieustalonej pracy okrętowego układu napędowego. Procesy te są trudne do określenia eksperymentalnego i dlatego zdecydowano opisać je równaniami ruchu okrętu wyznaczonych w sposób uproszczony na podstawie danych uzyskanych z systemu identyfikacji ruchu statków (AIS), a także wyników realizowanych badań własnych.*

*Uzyskane wyniki badań mogą być podstawą do opracowania propozycji oryginalnych testów do określenia dynamicznych charakterystyk emisji zanieczyszczeń.*

Słowa kluczowe: *emisja, związki szkodliwe, silniki okrętowe, charakterystyki dynamiczne*

## 1. Introduction

The transitory processes accompanying transient states are of dynamic nature both in relation to frequency and the values of changes in the load of propulsion system subassemblies, first of all piston diesel engines of the ship's propulsion sensitive to these changes. In practice the division and classification of the current state are difficult and depend on the accuracy of analysis and assumed division criteria of the ship's sailing conditions; for the movement of the vessel at a fixed mean velocity is actually characterised by a certain dynamics of changes resulting from the changing external sailing conditions essentially affecting changes in the resistance characteristics, thereby requiring changes in the propulsion force (main engine power) at a given sailing speed. At the same time it is known that the increased hull resistance is significantly affected by worse external conditions, namely sailing in shallow waters, channels (canals), with strong water currents, in storms, and also due to increased draft (e.g. in result of increased amount of cargo, ballasting of empty tanks and cargo spaces, or decreased water density), increase of protruding parts and hull roughness due to its germination and corrosion.

Because of the specificity and kind of tasks performed, determining the changing work conditions of the ship's main engines, it is purposeful in modelling characteristics to distinguish vessels basically operated at a fixed sailing speed (usually assuring economical exploitation). Changes in the load level occur in consequence of local navigational restrictions, in roads water areas and port approaches. It can thus be assumed that in normal hydrometeorological conditions the dynamic work of the ship's propulsion system and hull elements takes place above all in roads and port approaches and the share of this kind of load may be essentially significant in the total pollution emission by main propulsion engines

Among these vessels there should be singled out special vessels, in the case of which, apart from leaving the port, sea passage to the place of performing basic tasks and back to, port, there occur specific conditions of utilising propulsion systems with exceptionally high share of work conditions of dynamic character. Among typical vessels of this type there should be counted for instance fishing vessels operating on fishing grounds, where independently of the effect of changes in external conditions and sailing speed there also occur changes in the resistance characteristics. Even more complex dynamic conditions can occur while operating men-of-war during performing various combat tasks (e.g. in the case of minesweepers or chasers). Fig. 1 includes examples of changes in the density of carbon oxide and nitrogen oxides in the exhaust gas of the warship's main engine during free sailing [1,2].

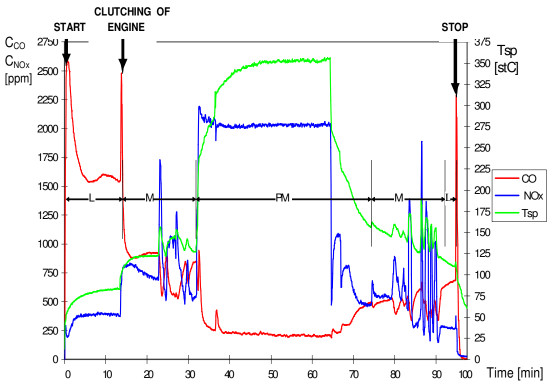


Fig. 1. Densities of carbon oxide and nitrogen dioxides and temperature of exhaust gas during the vessel's passage from the port of Hel to the port of Gdynia from the moment of starting the engine (cold start-up) to switching off the engine. L –idle run, M – manoeuvres in port, PM – sea passage

In considerations pertaining to the first of the mentioned vessel groups the following assumptions were made:

- consideration was taken of external steerable functions (setting forth, accelerating and braking the vessel), which cause the steadily dynamic work of propulsion system elements;
- external non-steerable functions (restrictions of sailing water area, storm, change in displacement, change in hull roughness) affect first of all the change of static resistance characteristics and in particular time intervals the propulsion system elements work in established conditions at the changed load level;
- in the modelling of simplified dynamic characteristics, due to negligible duration time (too short e.g. during sudden change of water depth, or too long e.g. during change of wind force, hull roughness), no consideration is taken of dynamic transient processes occurring during real change of external sailing conditions.

In the method of creating characteristics the vessel's movement identification and data are of essential significance. In own research use was made of data obtained by means of the current AIS system, proving information related to the vessel's type and name, its main dimensions (*L, B, T, H*), position, true course and speed of movement over the water and over the ground.

## 2. Vessel movement equations

In the dynamics of vessel movement it is assumed that it is a stiff body, having a longitudinal plane of shape symmetry, which is at the same time the symmetry plane of hull mass distribution. The complex movement of a stiff body can be described by the superposition of translatory motion of a selected body point (pole *G*) and rotary motion of the solid around the momentary rotation axis passing through the pole. It follows therefrom that the equations of the ship's free movement can be written down in the *xyz* coordinate system bound with the ship, as the inertia moments and deviation moments are constant then. At the same time, the Cartesian coordinate system *xyz* is so situated that the axes *x* and *z* lie in the ship's symmetry plane, and pole *G* is at the same time the centre of the vessel's mass.

The general vessel movement equations [3,4,5] result thus from the general principles of preserving the momentum and the angular momentum of a stiff body, which in the *xyz* system have the shape

$$\frac{d\vec{P}}{dt} + \vec{\omega} \times \vec{P} = \vec{F} \tag{1}$$

$$\frac{d\vec{K}}{dt} + \vec{\omega} \times \vec{K} + \vec{v} \times \vec{P} = \vec{M} \tag{2}$$

where: $\vec{P}$ – *ship's momentum;*
$\vec{K}$ – *ship's moment of momentum;*
$\vec{v}$ – *ship's absolute velocity;*
$\vec{\omega}$ – *ship's angular velocity;*
$\vec{F}$ – *external resultant force;*
$\vec{M}$ –*resultant moment of external forces*.

At the same time the ship's momentum and moment of momentum can be expressed as kinetic energy gradients

$$\vec{P} = grad_v E_k, \tag{3}$$

$$\vec{K} = grad_\omega E_k, \tag{4}$$

and kinetic energy by means of the dependence

$$E_k = \frac{1}{2}mv^2 + m\begin{vmatrix} \omega_x & \omega_y & \omega_z \\ \bar{x}_G & \bar{y}_G & \bar{z}_G \\ v_x & v_y & v_z \end{vmatrix} +$$

$$+\tfrac{1}{2}\left(I_{xx}\omega_x^2 + I_{yy}\omega_y^2 + I_{zz}\omega_z^2 - 2I_{yz}\omega_y\omega_z - \right.$$
$$\left. -2Izx\omega z\omega x - 2Ixy\omega x\omega y \right. \qquad (5)$$

where: $I_{ii}$ – *moments of inertia of mass in relation to respective axes (i = x, y, z);*
$I_{ij}$ – *moments of deviation of mass in relation to respective axes when* $i \neq J$.

As axes $x$ and $z$ lie in the symmetry plane and the pole $G$ is at the same time the mass centre, then $x_G = y_G = z_G = 0$ and $I_{yz} = I_{xy} = 0$, and the expression for the ship's kinetic energy will be simplified to the form

$$E_k = \frac{1}{2}mv^2 + \frac{1}{2}\left(I_{xx}\omega_x^2 + I_{yy}\omega_y^2 + I_{zz}\omega_z^2 - 2I_{zx}\omega_z\omega_x\right) \qquad (6)$$

The following simplifying assumptions have been introduced:
- the hypothesis of quasi-stationariness of hull, engine and propeller characteristics has been assumed;
- the value of the torque produced by the propulsion engine depends only on the position of the fuel linkage of the injection pump;
- sailing area is unrestricted (deep with large width);
- external sailing conditions are constant;
- vessel of constant displacement moves on undisturbed sea surface, which means that there occur only component sailing velocities $v_x$ and $v_y$, and the component $v_z = 0$;
- the propulsion system is composed of $k$ sets independent of each other, in which each engine propels a separate propelling screw.

For the above-mentioned assumptions and after substituting the above-mentioned dependencies into the initial equations, there is obtained a system of differential scalar equations containing functions describing the vessel's movement [6,7]

$$\begin{aligned} &(m + \Delta m_x)\frac{dv_x}{dt} - (m - \Delta m_y)\omega_z v_y = F_x \\ &(m + \Delta m_y)\frac{dv_y}{dt} + (m + \Delta m_x)\omega_z v_x = F_y \qquad (7) \\ &(I_{oz} + \Delta I_z)\frac{d\omega_z}{dt} - (\Delta m_x - \Delta m_y)v_x v_y = M_z \\ &\frac{d}{dt}(I_i\omega_i) = M_i \qquad i = 1, 2, \ldots, k \end{aligned}$$

where: $m$ [kg] – *ship's mass* $m = D/g$;
$\Delta I_z$ [kg·m²] – *inertia moment of water accompanying movement*
$D$ [N] - *ship's displacement;*
$g$ [m/s²] – *gravitational acceleration;*
$\Delta m_x$ [kg] – *mass of water accompanying the ship's translatory motion towards longitudinal axis (axis X);*
$\Delta m_y$ [kg] – *mass of water accompanying the ship's translatory motion in a direction perpendicular to its symmetry plane (axis Y);*
$v_x$ [m/s] – *component of ship's current (momentary) speed parallel to its symmetry plane;*
$v_y$ [m/s] – *component of ship's momentary speed perpendicular to its symmetry plane;*
$t$ [s] – *time;*
$\omega_z$ [rad/s] – *ship's rotational speed in horizontal plane (in relation to vertical axis Z);*
$F$ [N – *resultant of external forces reacting on the ship;*
$F_x$, $F_y$ -*projection of external forces resultant onto axes X and Y;*
$I_{oz}$ [kg·m²] – *ship's moment of inertia in rotational motion in relation to axis Z;*
$\Delta I_z$ [kg·m²] – *inertia's moment of water accompanying the ship's rotation motion;*
$M_z$ [N·m] – *resultant moment of external forces acting on the ship in horizontal plane;*
$I_i$ [kg·m²] – *total moment of inertia of i-th propulsion set of the propulsion engine's moving parts, main engine shafting, gear and screw taking consideration of mass of water rotated by the screw* $I_i = I_{si} \cdot i_{ri}^2 + I_{pi}$;
$I_{si}$ [kg·m²] – *moment of inertia of moving masses of i-th propulsion engine reduced on the main engine shafting axis;*
$i_r$ – *reduction gear ratio;*
$I_{pi}$ [kg·m²] – *moment of inertia of i-th propeller with propeller shaft and accompanying water;*
$\omega_i$ [rad/s] – *angular speed of i-th propeller (propeller screw);*
$M_i$ [N·m] – *resultant moment of forces acting on i-th propeller;*
$k$ – *number of ship's power units.*

It can be noticed that the left side of the equations contains generalised mass forces dependent on identified generalised masses of the ship; the right side, on the other hand, contains generalised external forces acting on the ship. With established main dimension parameters and established loading state, the generalised masses of a particular vessel can thus be considered as constant values. So, for predicting sea properties, including those pertaining to the speed of a vessel's movement, characteristics are indispensable expressing the dependence of generalised masses on its main construction parameters (*L, B, T, H, …)*

Research on many ships' dynamics in real conditions both at the time of setting forth and accelerating, as well as reverting to the opposite direction, shows that the introduced simplifying assumptions are admissible. In general, the processes taking place during the vessel's sailing dynamics are approximated fairly faithfully.

The method assumed is characterised by an essential simplification pertaining, for instance, to the omission of certain features of contemporary solutions of the steering system with feeding the engine with fuel by means of the currently applied rotary speed governors. Currently applied governors, apart from controlling rotational speed, fulfil the function of, for instance, restricting fuel setting depending on the value of supercharging pressure, as well as restricting the torque depending on the rotational speed setting. This signifies that the engine's performance field is considerably restricted, practically to a not very wide belt (field) adjacent from top to the static propeller characteristic. The device restricting fuel settings depending on supercharging air pressure considerably lengthens the process of loading the engine to maximum power, irrespectively of the fact if the load setting (fuel dose) is given once, or gradually increased to maximum value. This is due to a certain delay in the incrementation of supercharging pressure (rotational speed of the turbocharger). The additionally applied governor functions protect the engine against long-lasting overload (work on the moment's restricting characteristic) and against high losses (restricting the engine's work with low internal efficiency $\eta_i$ with high smokiness of exhausts and emission of carbon oxide and carbohydrates). In general it is recognised that a new or repaired governor is properly set if the time from the process's start to attaining full (nominal) load equals about one minute.

After transformations and introducing dependencies from the area of theoretical basics of marine power plants, the following forms of equations are obtained, determining time *t* and way *S* of the transient processes:

- while increasing ship's speed from $v_1$ to $v_2$

$$t = (m + \Delta m) \int_{v_1}^{v_2} \frac{v \cdot dv}{\xi_{o_x} \cdot P_e - P_h} \qquad (8)$$

$$S = (m + \Delta m) \int_{v_1}^{v_2} \frac{v^2 \cdot dv}{\xi_{o_x} \cdot P_e - P_h} \qquad (9)$$

- while setting forth and accelerating the ship to the set speed $v$

$$t = (m + \Delta m) \int_{0}^{v} \frac{v \cdot dv}{\xi_{o_x} \cdot P_e - P_h} \qquad (10)$$

$$S = (m + \Delta m) \int_{0}^{v} \frac{v^2 \cdot dv}{\xi_{o_x} \cdot P_e - P_h} \qquad (11)$$

- while actively braking the ship from the speed corresponding to switching on engine $v_r$

$$t = -(m + \Delta m) \int_{v_r}^{0} \frac{v \cdot dv}{\xi_{o_x} \cdot P_w + P_h} \qquad (12)$$

$$S = -(m + \Delta m) \int_{v_r}^{0} \frac{v^2 \cdot dv}{\xi_{o_x} \cdot P_w + P_h} \qquad (13)$$

where: $P_e$ *[kW] –installed effective horse power of the engine;* $P_w$ *[kW] - admissible effective horse power of the propulsion engine back running;* $\xi_{ox}$ *[-] – propulsive efficiency of the propeller (*$\xi_{ox} = \xi_o$ *= idem,* $\xi_o = 0.65$ *for system with low-speed engine,* $\xi_o = 0.55$ *for high-speed engine);* $v_r$ *[m/s] – vessel speed corresponding to the moment of switching the engine to back running;* $P_h = R \cdot v$ *[kW] – towing power of the ship with resistance R in stable external conditions.*

## 3. Practical assumptions simplifying the dynamic model of the ship's movement

From the analysis conducted there follows the general necessity of applying approximated calculation methods of the parameters of processes taking place in transient conditions of operating the ship. Identification data emitted by the AIS system are also decisive about this solution.

It follows from theoretical bases and empirical research that for calculating approximated resistance characteristics of displacement hulls in established normal sailing conditions there can be used the dependence

$$\frac{R}{R_n} \simeq \left(\frac{v}{v_n}\right)^2 \qquad (14)$$

where: *R – current resistance for the ship's particular sailing speed* $v$*;* $R_n$ *– nominal at the ship's nominal sailing speed* $v_n$*.*

Hence, the ship's resistance distribution under the effect of external sailing conditions will change in accordance with the dependence [8]

$$R \simeq k \cdot R_n \left(\frac{v}{v_n}\right)^2 = \frac{k \cdot R_n}{v_n^2} v^2 = b \cdot v^2 \qquad (15)$$

where: *k – non-dimensional coefficient of sailing resistance changes; b [kg/m] – constant coefficient; v [m/s] - vessel's speed.*

Then, towing power $P_h = R \cdot v$ after change of the ship's sailing resistance

$$P_h \simeq b \cdot v^3 \qquad (16)$$

Dependencies (15) and (16) make it possible to determine basic parameters of the movement system, also in changed external conditions of the vessel's sailing.

## 4. Simplified ways of calculating parameters of transient processes

Increasing the vessel's speed

The parameters of increasing the vessel's speed from value $v_1$ to $v_2$, taking consideration of simplifications pertaining to the ship's braking power $(P_h \simeq b \cdot v^3)$ and the efficiency of engine shafting $(\eta_{LW} \simeq 1)$, are described by equations (8) and (9) transformed into

$$t = \frac{m+\Delta m}{3\sqrt[3]{\xi_o \cdot P_e \cdot b^2}} \left\{ \frac{1}{2} ln \frac{(\xi_o \cdot P_e - b \cdot v_2^3)(\sqrt[3]{\xi_o \cdot P_e} - \sqrt[3]{b} \cdot v_1)^3}{(\sqrt[3]{\xi_o \cdot P_e} - \sqrt[3]{b} \cdot v_2)^3 \cdot (\xi_o \cdot P_e - b \cdot v_1^3)} + \right.$$

*13arctg23b·v2+3ξo·Pe3·3ξ0·Pe−arctg23b·v1+3ξo·Pe3·3ξ0·Pe* (17)

$$S = \frac{m+\Delta m}{3 \cdot b} ln \frac{\xi_o \cdot P_e - b \cdot v_1^3}{\xi_o \cdot P_e - b v_2^3} \qquad (18)$$

The ship's setting forth

According to the assumption that the process of the ship's setting forth and reaching assumed movement speed $v_1$ takes its course basically with the approximately established value of rotational speed, the parameters of the process can be calculated from equations (10) and (11) transformed to

$$t = (m+\Delta m) \int_0^{v_1} \frac{v \cdot dv}{\xi_o \cdot P_e - b \cdot v^3} =$$

$$= \frac{m+\Delta m}{3\sqrt[3]{\xi_o \cdot P_e \cdot b^2}} \left[ \frac{1}{2} ln \frac{\xi_o \cdot P_e - b \cdot v_1^3}{(\sqrt[3]{\xi_o \cdot P_e} - \sqrt[3]{b} \cdot v_1)^3} + \right.$$

*+13arctg23b·v13+3ξo·Pe3·3ξ0·Pe−13lnξo·Pe−π63*

$$S \simeq (m+\Delta m) \int_0^{v_1} \frac{v^2 \cdot dv}{\xi_o \cdot P_e - b \cdot v^3} = \frac{m+\Delta m}{3 \cdot b} ln \frac{\xi_o \cdot P_e}{\xi_o \cdot P_e - b \cdot v_1^3} \qquad (19)$$

Braking and halting the vessel

After taking into considerations the simplifications capable of being mathematically written down, the equations describing stage III of the active braking process of the ship (12) and (13),will be transformed to

$$t_{III} = (m+\Delta m) \int_{v_r}^{0} \frac{v \cdot dv}{\xi_o \cdot P_e + b \cdot v^3} =$$

$$= \frac{m+\Delta m}{3\sqrt[3]{\xi_o \cdot P_e \cdot b^2}} \left\{ \frac{\pi}{6} + ln \frac{v_r + \sqrt[3]{\frac{\xi_o \cdot P_e}{b}}}{\sqrt{v_r^2 - \sqrt[3]{\frac{\xi_o \cdot P_e}{b}} v_r + \left(\sqrt[3]{\frac{\xi_o \cdot P_e}{b}}\right)^2}} - \right.$$

*−3arctg2vr33ξo·Peb−33*

$$S_{III} = (m+\Delta m) \int_{v_r}^{0} \frac{v^2 \cdot dv}{\xi_o \cdot P_e + b \cdot v^3} = \frac{m+\Delta m}{3 \cdot b} ln \frac{\xi_o \cdot P_e}{\xi_o \cdot P_e + b \cdot v_r^3} \qquad (20)$$

where: *$v_r$ [m/s] – ship's speed at which the engine was started working $v_r \simeq 0.30 \cdot v_n$;*
*$P_e = P_{ew}$ [kW] – admissible engine power on back running $P_{ew} = 0.30 \cdot P_{en}$*

## 5. Method of determining dynamic parameters of pollution emission characteristics by transport ship's main engines

Fig. 2 presents a diagram of determining the basic parameters of dynamic characteristics of pollution emission by ships' main engine operated in typical kinds of vessels performing sailing tasks of communication and transport nature.

## 6. An example of determining indexes of toxic compounds emission

The example concerns an engine of rated power $P_{e(n)}$ = 9000 kW mounted on a vessel *(L = 129 m, B = 22 m, $T \neq T_n$ = 6.1m)* of rated speed $v_n$ = 15 k, which sails with a speed established from AIS system data AIS $v_{śr} = v_E$ = 13.6 k.

The example concerns the total emission of toxic compounds of a vessel operated in the Gulf of Gdańsk at nominal loading state of $D = D_n$ $(T = T_n)$ and state of the sea $SM < 3^oB$ and true depth of sailing area. The particular four stages of the way covered represent the conditions of operating and toxic compounds emission of each vessel sailing in the direction of Gulf ports and its putting to sea. The results of calculation conducted in accordance with the dependencies given above, have been presented in Table 1 and in Figs 3 – 5.

The data included here document, in accordance with the diagram in Fig. 2, the suggested method of determining the parameters of dynamic characteristics of pollution emission by main propulsion engines during operation of vessels in a given area.

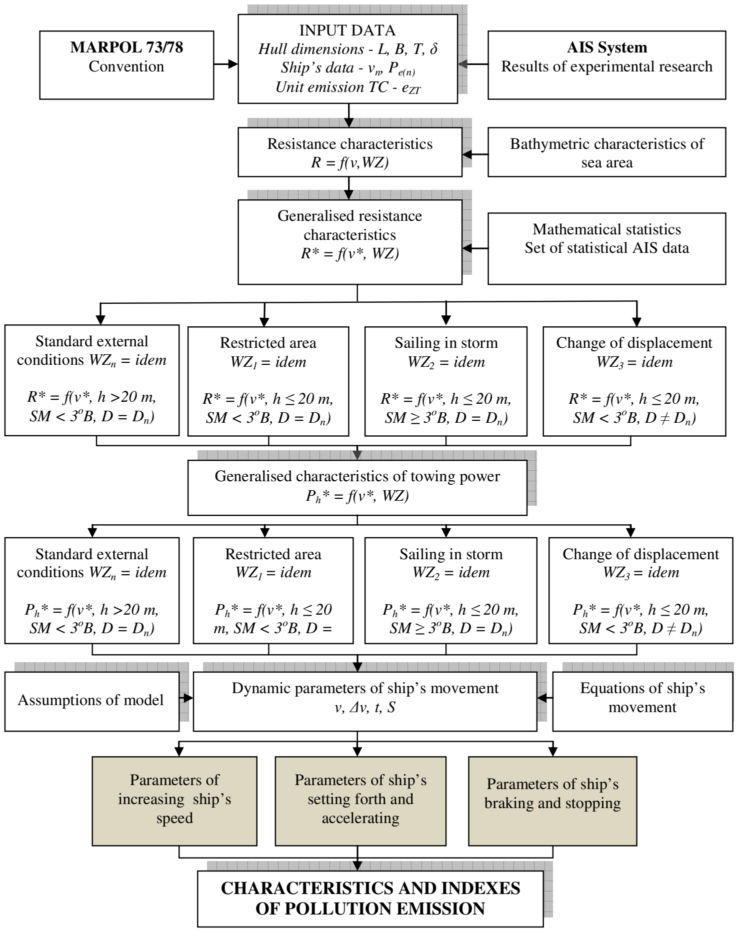


Fig. 2. Diagram of determining parameters of dynamic characteristics of ship's main propulsion engine in various external operating conditions of a vessel; SM – state of sea; WZ – external conditions; AIS – system of automatic identification of vessel traffic; L,B,T – length, breadth, draft of vessel's hull; $P_h$ – towing power; v – ship's speed; h – depth of sea, $P_e$ – engine's effective power; D – ship's displacement $c_f$ – friction coefficient of hull against water, (indexes: n – nominal, max – maximum, *denotes relative depths)

Table 1. Estimated (test) values of toxic compounds emission of a vessel realising typical stages of sailing (of a voyage) in the Gulf of Gdańsk

*Ship's data: $P_{e(n)}$) = 9000 kW; $v_n$ = 15 k; $v_{śr}$ = $v_E$ = 13.6 k.*

| Emission index | Toxic compound | | | Voyage direction and stages | | | | Σ |
|---|---|---|---|---|---|---|---|---|
| | name | marking | measuring unit | port of Gdynia | | putting to sea | | |
| | | | | free sailing | braking | accelerating | free sailing | |
| Emission intensity | nitrogen oxides | $E_{NOx}$ | kg/h | 106.60 | 45.90 | 153.0 | 106.60 | - |
| | sulphur oxides | $E_{SOx}$ | | 18.81 | 8.10 | 27.0 | 18.81 | - |
| | carbon oxide | $E_{CO}$ | | 11.90 | 5.10 | 17.1 | 11.90 | - |
| | carbohydrates | $E_{HC}$ | | 3.80 | 1.60 | 5.4 | 3.80 | - |
| Way emission | nitrogen oxides | $b_{s(NO_x)}$ | kg/Mm | 7.84 | 60.77 | 279.12 | 7.84 | - |
| | sulphur oxides | $b_{s(SO_x)}$ | | 1.38 | 10.75 | 49.26 | 1.38 | - |
| | carbon oxide | $b_{s(CO)}$ | | 0.88 | 6.77 | 31.20 | 0.88 | - |
| | carbohydrates | $b_{s(HC)}$ | | 0.28 | 2.2 | 9.85 | 0.28 | - |
| Total emission | nitrogen oxides | $m_{NOx}$ | kg | 56.75 | 13.77 | 82.62 | 56.75 | **209.90** |
| | sulphur oxides | $m_{SOx}$ | | 9.97 | 2.43 | 14.58 | 9.97 | **36.95** |
| | carbon oxide | $m_{CO}$ | | 6.34 | 1.53 | 9.23 | 6.34 | **23.44** |
| | carbohydrates | $m_{HC}$ | | 2.02 | 0.48 | 2.92 | 2.02 | **7.44** |

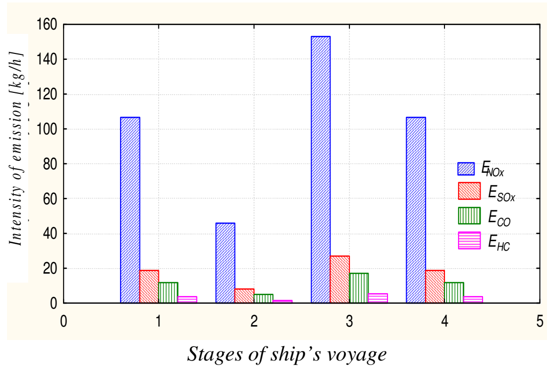


Fig. 3. Distribution of pollution emission intensity at distinguished typical stages of a vessel's voyage in the Gulf of Gdańsk area

*Stage 1 – free sailing at speed* $v_E$ *= idem;*
*Stage 2 – ship's braking to v = 0;*
*Stage 3 – setting forth and accelerating to* $v_E$ *= 13.6 k;*
*Stage 4 – free sailing at speed* $v_E$ *= idem*

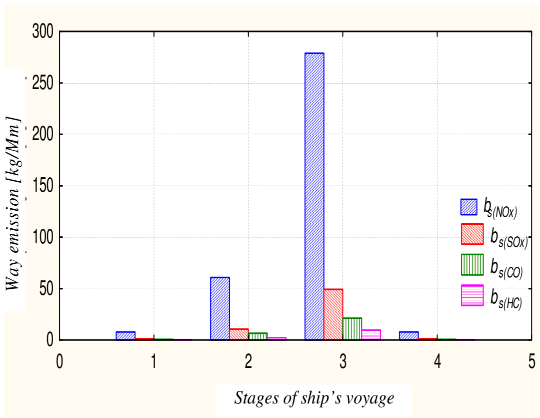


Fig. 4. Way pollution emission at distinguished stages of a typical ship's voyage in the Gulf of Gdańsk area

*Stage 1 – free sailing at speed* $v_E$ *= idem;*
*Stage 2 – ship's braking to v = 0;*
*Stage 3 –setting forth and accelerating to* $v_E$ *= 13.6 k; Stage 4 – free sailing at speed* $v_E$ *= idem*

## Recapitulation

The presented method and test of the toxicity of ship's main propulsion engines operated in a particular sea area should be considered as initial ones, requiring further research aimed at obtaining a more accurate mapping of reality. Due to the necessity of assuming many simplifications and also to incomplete verified data from AIS system, the determined general characteristics and dependencies may be characterised by limited universality and some discrepancies with real data.

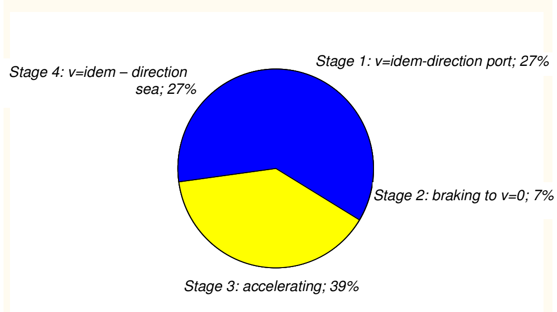


Fig. 5. Percentage shares of pollution emission in successive stages of a typical ship's voyage in Gulf of Gdańsk area

In the estimation procedures of the toxicity of engine exhausts a simplification was also assumed consisting in the use of averaged constant values of unit emissions of toxic compounds recommended by Marpol 73/78 Convention or determined on the basis of literature data and results of own research conducted for a number of years.

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