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MODELING OF EMISSIONS AND DISPERSION OF HARMFUL COMPOUNDS FROM MARINE MAIN PROPULSION DIESEL ENGINES OF VESSELS NAVIGATING IN SPECIFIED WATER BASINS

ABSTRACT

The article presents the results of the first nationwide study of a pro-ecological character, including the problem of the impact of shipping (in a particular basin) on the terrestrial human environment. Shipping in the waters of the Bay of Gdansk is taken as an example of the real system and a detailed identification of the operating conditions for the vessels has been undertaken. Data were obtained from the analysis of information gathered by surveillance systems of vessel traffic (such as Automatic Identification System — AIS) for the complete identification of parameters and characteristics of shipping traffic in the form of deterministic and statistical mathematical models. On the basis of these mathematical models of the emission of harmful exhaust emissions from marine engines have been developed. Models of the spread of exhaust gas are based on the models of Gauss, Euler and Lagrange. Their use has enabled a scientific tool to evaluate the contribution of immission of harmful compounds in the global immission of pollutants in the atmospheric air of the Tri-city agglomeration to be obtained.

Key words:
modeling, emission, ship, marine engines, real operating conditions.

INTRODUCTION

The current development of marine diesel engines was focused primarily on increasing capacity, reducing fuel consumption, combustion of fuels of the lowest

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quality and extending the service life. Increasing pro-ecological pressure has meant that atmospheric pollution caused by the exhaust gases of marine engines has become one of the main problems in the protection of the marine environment in recent years. In many countries, especially those developed along the banks of the infrastructure; there was a discussion on the legal regulation of the maximum amounts of harmful compounds emitted by ships and their energy efficiency. As a result, a number of standards and regulations at local and regional level have emerged.

The emergence of legislation on the level of toxic emissions has forced both engine manufacturers and ship owners to take action to reduce them. The operation of ship owners in this area is virtually forced by the requirements of local regulations regarding state coastal waters and ports.

It is expected that these changes will affect the process of the operation and the supervision of ecological marine engines. In addition to the technical modification of marine engines and construction of additional installations intended to meet the requirements of exhaust emissions standards, this will result in the need to introduce new methods of determining the properties of energy directly and indirectly, and emissions of harmful compounds in exhaust gases.

The above considerations lead to the need to identify the impact of various operating conditions on emissions of harmful substances in exhaust gases and its energetic properties.

The origins of examining emissions of toxic compounds contained in exhaust gases of marine engines at the Faculty of Mechanical and Electrical Engineering Naval Academy date back to 1996 with the initiative of Prof. Jerzy Merkisz, DSc., DEng. of the Poznan University of Technology who launched the first works in this scope with a team appointed by Prof. Leszek Piaseczny, DSc., DEng. The team consisted of Tadeusz Berger, DEng., Izydor Kafar, DEng., Ryszard Zadrąg, DEng., and the author of the article. These studies, carried out within the framework of statutory activity, resulted in the award by the KBN in respect of financing the research project at that time under the title *Methods of reducing toxic emissions of reciprocating internal combustion engines operating in the power plant of vessels* [12]. The project, implemented between 1997–2000, was aimed at selecting the most effective ways to reduce emissions of toxic compounds contained in exhaust gases to use them primarily for engines operating on vessels and ships. Studies in the scope of the project have involved defining test conditions of toxic emissions among others, the review of primary and secondary methods of its reduction, and mathematical modeling of energy processes occurring in the engine cylinder in related toxic emissions. Construction of a research station commenced based on the Sulzer 6AL 20/24 engine equipping it with a comprehensive computer system for measuring power parameters, flow rates of operating factors and the measurement of emitted exhaust components. A methodology for creating toxicity testing of exhaust gas engines other than automotive was also developed.

A further step in the activities of the team was the realization of a research project entitled: *Modelling emissions of toxic compounds under varying load conditions of a marine internal combustion engine with exhaust gas recirculation and water injection into the cylinders* (2000–2003) [11]. Project implementation commenced with the acquired theoretical and practical experience, and above all by having the original research station. The changing engine load conditions which reached the original characteristics of the influence of parameters of the emulsion of fuel and water associated with exhaust gas recirculation on the toxicity of exhaust gases were an important feature of the conducted studies. It was also used as organometallic catalyst additives which can be added on account of their solubility in water contained in the emulsion. The previously developed mathematical model of energy processes in the engine cylinder and toxic emissions in the exhaust was developed taking into account the provision of water into the engine cylinder, among others, as well as various degrees of EGR. Simulation tests of the model were verified by tests on a real object.

A patent on the method of obtaining water emulsion of fuel to power internal combustion engines with compression ignition (awarded in 2008) was also developed as a result of these activities. There was active co-operation with the Poznan University of Technology in the implementation of these and future projects and there were many publications as a result of this cooperation.

In subsequent years (2005–2008) a project on modeling was carried out in order to identify the technical condition of the engine based on the assessment of the emission of exhaust gas components. The original diagnostic models of the engine were obtained within the scope of the project with consideration of the parameters of the diagnostic indicators and characteristics of the emission of exhaust gas components.

A project dedicated to dynamic dosing of emulsion fuel and water with different water content using a specially designed rotary device to produce the emulsion was carried out in subsequent years, together with the University of Warsaw and Krakow. This device still remains with the Faculty and is used in research activities.

Between 2006–2009, the original project was undertaken on modeling imissions of toxic compounds coming from the exhaust of marine diesel engines in the atmospheric air of the Tri-city agglomeration [14]. This project was completed with the development of original simulation immission models in certain marine waters (e.g. Bay of Gdansk), originating from the emissions from the engines of ships sailing in the area. At that time, the team was joined by Miroslaw Walkowski, DEng., and Malgorzata Pawlak, DEng.

The last project carried out by a team led by Prof. Leszek Piaseczny was a research project entitled: *Methods for determining the static and dynamic characteristics of toxic emissions from internal combustion engines of marine vessels; whose aim was to develop the dynamic characteristics of toxic fumes emissions of marine vessel diesel engines* [13]. It was the first such work in the country and abroad and it is extremely fragmentary and includes measurements rather than a formalized mathematical description. Original results obtained allow for the knowledge of toxic emissions in the exhaust gases of marine diesel engines to be expanded.

As a result of this work, three members of the team received a doctoral degree in technical sciences [3, 10, 15], and one a habilitated doctor [4]. Between 1997–2014, the research team published more than 200 articles and papers in the country and abroad.

FACTORS DETERMINING EXHAUST GAS EMISSIONS

The processes of global emissions are the subject of balancing the emission of pollutants contained in the exhaust gas engines powering vehicles and vessels, averaged over a sufficiently long time [1]. This time primarily determines the efficiency of averaging variable operating conditions on the objects.

The movement of vessels may be classified according to several criteria, but are fundamentally related to the evaluation of the dynamic properties of change processes of the load and engine speed as well as with the average speed of sailing.

Factors that determine the global emissions of substances contained in exhaust gases of marine engines can be classified as follows [4, 7, 9]:

- the structure of ships (considering the size and purpose of vessels), the size and type of the engine, the number of different types of engines on the vessel (main and auxiliary engines), due to the technical condition of the vessel taking into account the technical solutions and the condition of the hull and consumption propulsion of components of the vessel and their multiplicity;
- the intensity of the operation of vessels;
- traffic movement models of vessels;
- ambient conditions: weather conditions (waving and strong winds, icing), navigation of water basins (ports, straits, canals and other dangerous and difficult areas for navigation and open waters), sailing in ice;
- economical characteristics of vessels due to fuel consumption supplies;
- ecological characteristics of engines used on vessels;
- fuel properties (due to the type of fuel, the composition and content of impurities, among others).

The structure of vessels plays an important role in global emission models. The degree of expansion of the structure determines the accuracy of the modeling of global emissions on one hand and the possibility of efficient use of models due to problems with the delivery of reliable data regarding the number of floating vessels and the intensity of their use on the other hand. It is the latter limitation that constitutes the most serious criterion for accepting the structure of vessels.

The number of vessels and the intensity of their use are extensive values of global emissions. The number and length of routes traveled by vessels in the period of emission balancing is understood as being through the concept of the intensity of the operation of vessels in models of global emissions.

Ambient conditions affect engine operating conditions (due to the resistance and nature of the movement of vessels), and the environmental performance of engines [4, 5, 7, 9]. For the purpose of analyzing the impact of environmental conditions on the engine and the further emission of harmful compounds in the exhaust gas vessels, environmental conditions can be divided into:

- closer ambient conditions — temperature, humidity and air pressure in the power plant;
- further ambient conditions (external conditions):
  - atmospheric conditions: air temperature and humidity, atmospheric pressure, temperature and condition of the sea ice, ocean currents, wind strength and direction,
  - ambient conditions: weather conditions (waving and strong winds, icing), navigation of water basins (ports, straits, canals and other dangerous and difficult areas for navigation and open waters), sailing in ice.

Fuel properties have an effect on emissions due to the nature of operation of the engine and the contents of components with different physical and chemical properties, and also because of the content of impurities. The impact of fuel properties on exhaust emissions is primarily associated with [4]:

- the contents of fuel contaminants, sulfur and phosphorous;
- the contents of the fuel hydrocarbon ring, and their derivatives (in benzene among others), influencing the increase in emissions of polycyclic aromatic hydrocarbons (PAH);
- the contents of the fuel organic compounds of oxygen affecting the increase in the emission of aldehydes and nitrogen oxides and reducing emissions of carbon monoxide and hydrocarbons;
- the contents of the fuel additives modifying the properties of the fuel, e.g. reducing the deposition of carbon deposits;
- structure of fractional fuels, such as the significant effect of heavy fuels on particulate emissions.

From the above considerations, it appears that the process of modeling the emission of harmful compounds in the exhaust gas marine engine is very complex; it requires knowledge of described groups of parameters describing the characteristic parameters of the vessel, the parameters of movement of vessels, external conditions and ecological and economical properties of marine engines. These parameters should be considered as variables or interference in the created mathematical models of marine diesel engine emissions for main propulsion in real conditions of their operation.

ECOLOGICAL CHARACTERISTICS OF MARINE ENGINES

In the description of the problems associated with process modeling emissions of internal combustion engines in terms of traction [4], it was assumed that the characteristics of a description of the property is a compound of selected physical quantities ($\mathbf{w}$) selected as a test for the object of cognition. This compound can be stored in the form of operators, which is a generalization of functional dependence

$$\mathcal{L}[\mathbf{w}] = 0. \tag{1}$$

The number of elements in the **w** vector is reduced by 1 and constitutes a row or dimensional characteristics. The elements forming characteristics are physical quantities describing the tested object of knowledge. The basic extensive size is characterized by air pollution by harmful compounds contained in exhaust gases of marine engines is the m mass of pollutants emitted.

Values are intensive, concentrations of the components in the exhaust gas — mass and volume characterize the emissions. It is possible to create four combinations under consideration as a measure of the amount of exhaust gas and a constituent substance in the form of weight and volume.

The intensity of the emission E is derived from the emission as a function of time $m_t(t)$ from a particular source over time t

$$E = \frac{\mathrm{d}m_t(t)}{\mathrm{d}t}. \tag{2}$$

Route emission can be defined as that which is derived from the emissions of the vessel as a function of the route $m_s(s)$, in relation to the s route which it sailed through

$$b_s = \frac{\mathrm{d}m_s(s)}{\mathrm{d}s}, \tag{3}$$

whereby $m_s(s) = m_t(\varphi(s))$, wherein $\varphi(s)$ is the inverse function to $s = s(t)$.

Route emissions as a function of time can be stored as

$$b_t(t) = b_s\big(s(t)\big). \tag{4}$$

The value of average route emissions is therefore

$$b_{s_{śr}} = \frac{1}{S} \int_0^S b_s(s)\mathrm{d}s = \frac{m_s(S)}{S}. \tag{5}$$

Since the speed of the vessel V is a derivative of the route with respect to time, the average emissions of the route can be represented as

$$b_{s_{śr}} = \frac{1}{S} \int_0^T b_t(t)V(t)\mathrm{d}t, \tag{6}$$

where:

$T = \int_0^S \frac{1}{V(\varphi(s))} \, \mathrm{d}s.$

For constant speed V the value of route emissions can be recorded

$$b_s = \frac{\mathrm{d}m_s(s)}{\mathrm{d}s} = \frac{\mathrm{d}m_t\left(\frac{s}{V}\right)}{\mathrm{d}s} = \frac{E(t)}{V}. \tag{7}$$

Specific emission e is defined as the ratio of the emission m from the engine within a specified time T in any work done by the engine L

$$e = \frac{m}{L}. \tag{8}$$

Since the work done by engine can be expressed as the product of the average output and working time

$$L = P_{e_{śr}} \cdot T \tag{9}$$

and the average emission intensity $E_{śr} = m/T$, the average specific emission can be expressed as

$$e_{śr} = \frac{E_{śr}}{P_{e_{śr}}}. \tag{10}$$

Engine power output P_e can be presented as

$$P_e = \frac{1}{\eta} \, [R]^+ \, V, \tag{11}$$

where:

η — the overall efficiency of the propulsion of the vessel;

R — the total resistance of the vessel.

Function $[R]^+$ positivity argument is indicated according to the relation

$$[R]^+ = \begin{cases} R, & \text{when } R > 0 \\ 0, & \text{when } R \le 0 \end{cases}. \tag{12}$$

The total resistance of the ship R is the sum of the resistance force: friction R_F, viscosity resistance of pressure (shape) RVP, of the waveform R_W and the additional R_d

$$R = \sum_i R_{(i)} = R_F + R_{VP} + \mathrm{R_W} + \mathrm{R_D} = \mathcal{F}\,(V, a, \mathbf{M}, \mathbf{A}, \mathbf{G}, \mathbf{O}) = \Phi\,(V, \mathbf{M}, \mathbf{A}, \mathbf{G}, \mathbf{O}). \quad (13)$$

This force can be represented as a function of $\mathcal{F}$: momentary speed of the ship V, acceleration a, vector **M**, characterized inertia of the ship, a vector **A**, containing information about the variable resistance movement of the ship, connected with the sailing water basin (water depth, the width of the water basin (canals), etc.), vector **G**, describing the environmental conditions (e.g. pressure and ambient temperature) and the vector **O**, describing the conditions of navigation (wind strength and direction, wave height and length, etc.). Since acceleration is derived from velocity in relation to time, generally functions of resistance of the ship can be represented as dependency operators Φ the ship's speed and vectors **M**, **A**, **G** and **O** [4, 9].

The average power output $P_{e_{śr}}$ performed by the motor (engine) main propulsion will amount to

$$P_{e_{śr}} = \frac{1}{T}\int_0^T P_{e_{śr}} \mathrm{d}t = \frac{1}{T}\int_0^T [\Phi]^+ V \mathrm{d}t. \quad (14)$$

There is the issue of dependency between the average emission and the specific emission

$$\frac{b_{s_{śr}}}{e} = \frac{T P_{e_{śr}}}{S} = \frac{P_{e_{śr}}}{V_{śr}}. \quad (15)$$

The average power output $P_{e_{śr}}$used on board, in a general case is obtained by multiplying the average of the positive resistance of the vessel and the average velocity divided by the overall efficiency of propulsion. The ratio of these values can be recorded as

$$\frac{P_{e_{śr}}}{\frac{1}{\eta}[R_{śr}]^+ V_{śr}} = \frac{\frac{1}{\eta}\frac{1}{T}\int_0^T [R]^+ V \mathrm{d}t}{\frac{1}{\eta}\frac{1}{T}\int_0^T [R]^+ \mathrm{d}t \frac{1}{T}\int_0^T V \mathrm{d}t}; \quad (16)$$

$$\frac{P_{e_{śr}}}{\frac{1}{\eta}[R_{śr}]^+ V_{śr}} = \frac{T\int_0^T [R]^+ V \mathrm{d}t}{\int_0^T [R]^+ \mathrm{d}t \int_0^T V \mathrm{d}t}. \quad (17)$$

Since in static conditions $\mathrm{d}V/\mathrm{d}t = 0$, and $\mathrm{d}R/\mathrm{d}t = 0$ is

$$[R]^+ = R; \quad (18)$$

$$P_{e_{śr}} = P_e = \frac{1}{\eta} R \cdot V. \quad (19)$$

The ratio of the average emissions of the specific route emission is

$$\frac{b_{śr}}{e} = \frac{R}{\eta}. \qquad (20)$$

A compound in size, characterized by environmental pollution by harmful compounds contained in the exhaust gas of marine engines in real operating conditions, is under certain operating conditions of the ship, is treated as a condition for sailing, ecological characteristics of the marine vessel engine main drive.

PROGRAM FOR THE SIMULATION OF EMISSIONS OF TOXIC COMPOUNDS IN THE EXHAUST GASES FROM MAIN ENGINES OF VESSELS NAVIGATING ON SPECIFIED WATER BASINS

In order to carry out simulations of vessel traffic on the analyzed area and the estimation of emissions of harmful substances in exhaust gases of the main engines at specified time intervals, a calculation program was created by the ***MEFSAS*** computer (*__M__odel of __E__mission __F__rom __S__hips __A__t __S__ea)* [4].

Figure 1 shows an example of a 'window' to the input parameters of the model (hydro meteorological conditions), and figure 2 — a 'window' of toxic emissions in the exhaust by individual days of the week for the first category of ships (bulk carriers) [8]. Figures 1 and 2 are for illustration only, which presents a graphic program, hence the content inside the sample 'window' was not presented in English.

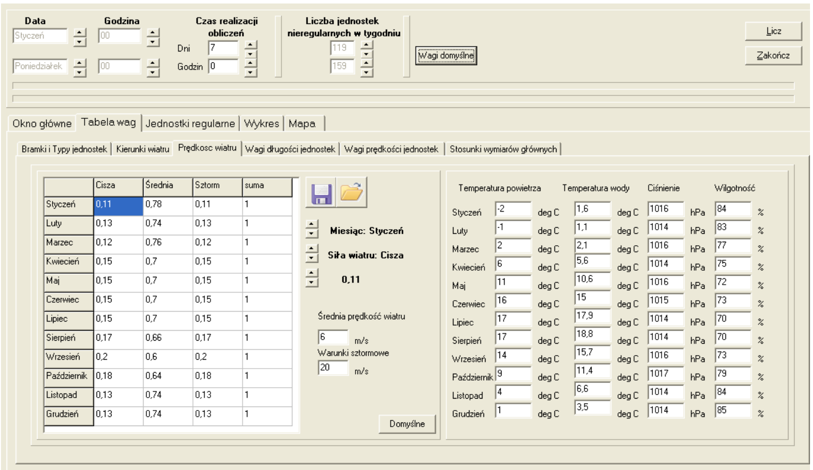

Fig. 1. Example 'window' to the input parameters of a mathematical model to estimate the emissions of harmful substances in exhaust gases of the main engines of ships — MEFSAS (hydro-meteorological conditions) [8]

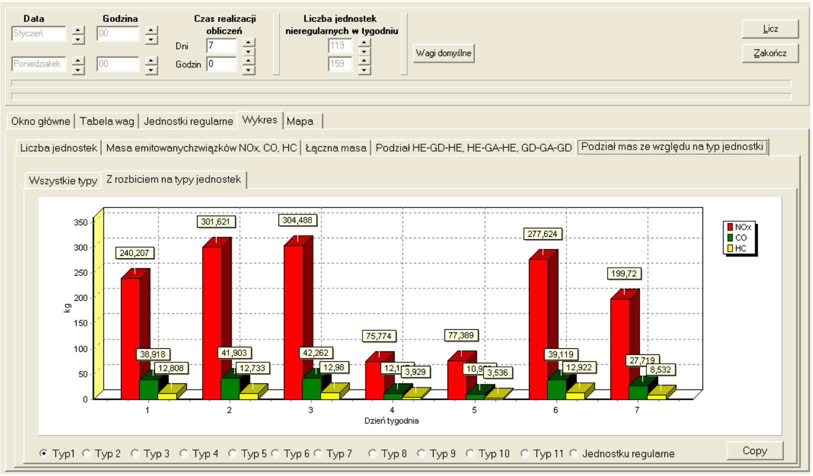

Fig. 2. An example of a 'window' showing estimates of the emissions of harmful substances in exhaust gases of the main engines of ships — MEFSAS calculated using a mathematical model, emission values of toxic compounds in exhaust gases for individual days of the week for the first category of ships (bulk carriers) [8]

The 'MEFSAS' computer program, beyond the presentation of simulation results in tabular form, allows them to be visualized using bar graphs, which significantly facilitates their analysis.

Basic options for the presentation of simulation results include:

- bar graphs are divided into vessel types (fig. 2);
- bar charts of toxic emissions for specific types of vessels as a function of time, presented separately for CO, HC and NO_x (fig. 3).

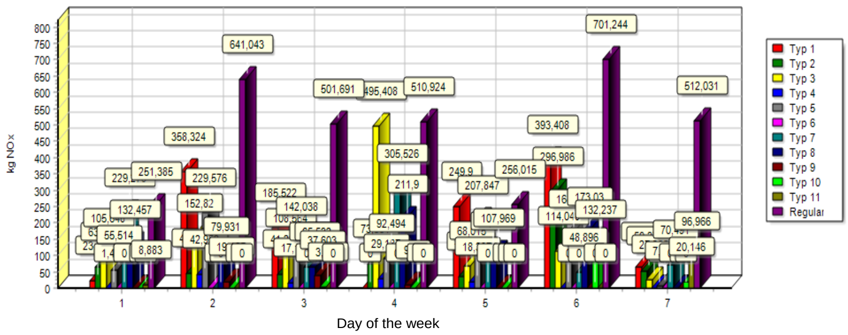

Fig. 3. Graph showing the relationship of NO_x emissions for specific types of vessels as a function of the day of the week [8]

All the results carried out using the MEFSAS program simulation can be saved to a text file, which can be subjected to statistical analysis (to the extent not provided for in the time of writing the program) with almost any tool such as Statistica, Excel, etc.

Figure 4 shows an algorithm based on which calculations are carried out by the MEFSAS program.

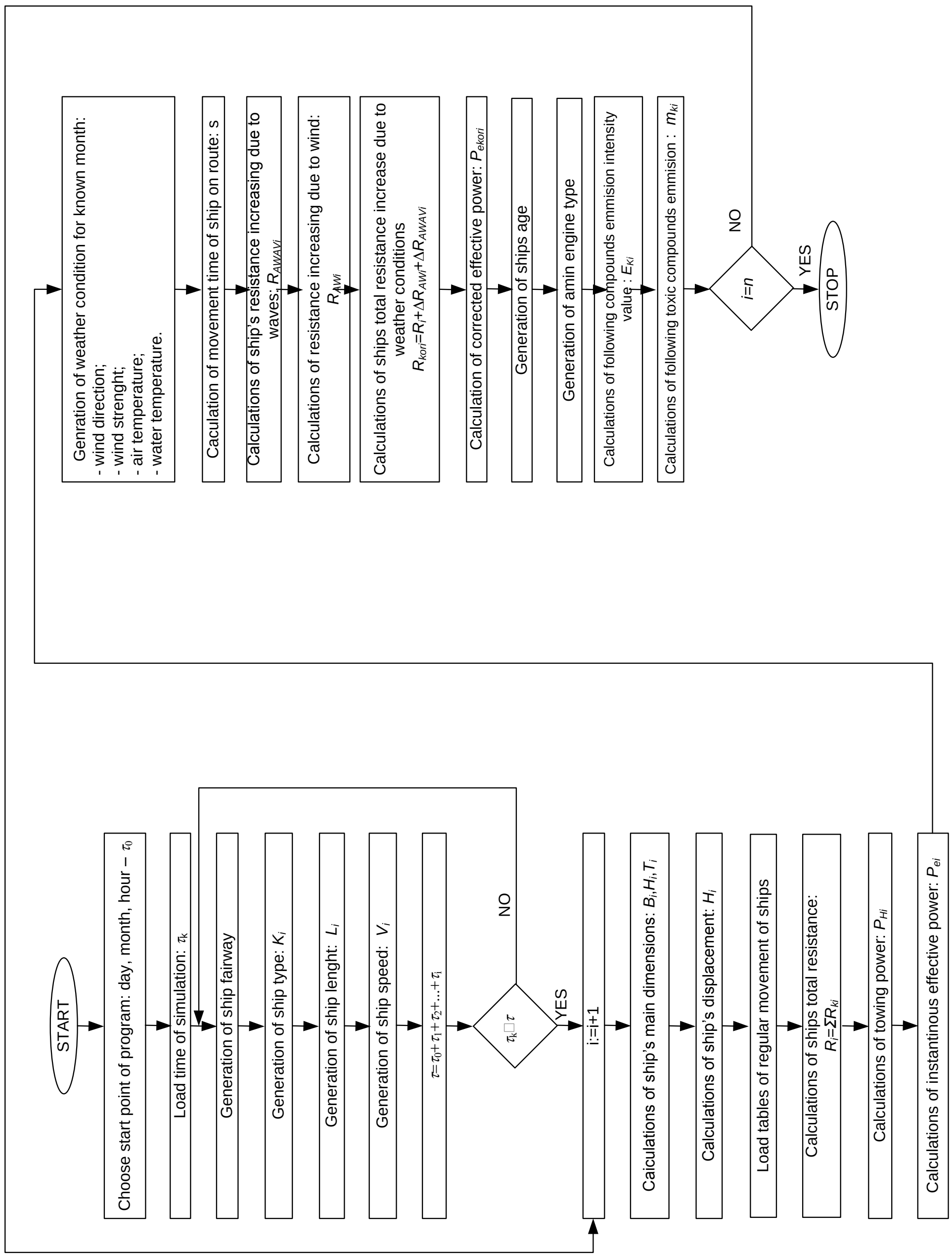

Fig. 4. The algorithm, based on the MEFS program for which calculations are carried out [8]

THE SIMULATION MODEL OF SPREADING ATMOSPHERIC POLLUTION FROM FLOATING VESSELS NEAR THE BAY OF GDANSK

Among the large number of mathematical models describing the spread of pollutants in the atmosphere, it is dominated by models which use Markov processes of diffusion [3]. Using the simplified diffusion equation, O. G. Sutton received the formula for the concentration of pollutants emitted continuously from the stationary emission point of sources located on height *h*. This pattern is in the form [2, 14]:

$$S(x,y,z)=\frac{D}{\pi C_y C_z v_x x^{2-n}}\exp\left[-\frac{y^2}{C_y^2 x^{2-n}}\right]\left\{\exp\left[\frac{-(z-h)^2}{C_z^2 x^{2-n}}\right]+\exp\left[\frac{-(z+h)^2}{C_z^2 x^{2-n}}\right]\right\}, \quad (21)$$

where:

x, y, z — Cartesian coordinates *A,* wherein *ox* axis is directed in the direction of the wind, *oy* axis is horizontally perpendicular to the wind direction, *oz* axis is perpendicular to the plane defined by the axes *ox, oy;* the source of emission is at a point *(0, 0, h)*;

S(x, y, z) — the density of impurities at point *A = (x, y, z)*;

C_x, C_y, C_z — atmospheric diffusion coefficients in the direction *x, y, z*;

D — the amount of pollutants emitted per unit of time;

n — meteorological exponent.

It should be emphasized that formula (21) relates to a solid point source emissions of atmospheric pollutants. Nevertheless, this formula can be used for mobile emission sources, which are floating objects. In a short period of time [t_e, $t_e + \Delta t_e$) the emission source can be treated as stationary. The 'quantum' exhaust gas emitted reaches the measuring point A = (u_A, w_A, z_A) time *θ*, mainly it depends on the wind speed and distance of the point from the emission source *d*. If in the predetermined time *t* emission source (chimney outlet of floating object) is point *E*= (u_E, w_E, *h*), the distance *d* is expressed by the formula [14]:

$$d=\sqrt{(u_A-u_E)^2+(w_A-w_E)^2+(z_A-h)^2}\,. \quad (22)$$

If the average wind speed is a vector

$$\mathbf{v}=[v_u, v_w, v_z] \quad (23)$$

the length of this vector, which is a scalar measure of the average wind speed is given by

$$|\mathbf{v}| = \sqrt{v_u^2 + v_w^2 + v_z^2}\ .$$

The average time to reach the exhaust gas can be calculated from the formula

$$\bar{\theta} = \frac{d}{|\mathbf{v}|_{EA}}, \tag{24}$$

where:

$$|\mathbf{v}|_{EA} = |\mathbf{v}|\cos\alpha = \frac{(u_A - u_E)v_u + (w_A - w_E)\,v_w + (z_A - h)v_z}{\sqrt{(u_A - u_E)^2 + (w_A - w_E)^2 + (z_A - h)^2}} \tag{25}$$

the average wind speed is a vector $\mathbf{v}$ on vector EA. Using the formulas (24) and (25) we obtain

$$\bar{\theta} = \frac{(u_A - u_E)^2 + (w_A - w_E)^2 + (z_A - h)^2}{(u_A - u_E)v_u + (w_A - w_E)\,v_w + (z_A - h)v_z}. \tag{26}$$

Therefore, the emission source of the floating object is always at point (0, 0, h), and therefore the coordinate system which can use the formula (21) is a moving structure with respect to a fixed measuring point A. Let $ouwz$ be a 'fixed' Cartesian coordinate system. Since the area is considered relatively small, therefore the first two coordinates of the point in the system can be accepted as the geographical coordinates. The third coordinate in both systems is the same. Performing calculations which result in a density of pollutants from the emissions of floating objects requires the use of isometric transformation, which is a superposition of displacement and rotation on the plane. This conversion is defined by the general formula [14]:

$$\begin{aligned} x &= a_{11}u + a_{12}w + a_{13} \\ y &= a_{21}u + a_{22}w + a_{23} \end{aligned}. \tag{27}$$

The coefficients of this transformation change with the position of the floating object, and therefore are functions of time

$$\begin{aligned} a_{11} &= a_{11}(t), \quad a_{12} = a_{12}(t), \quad a_{13} = a_{13}(t) \\ a_{21} &= a_{21}(t), \quad a_{22} = a_{22}(t), \quad a_{23} = a_{23}(t) \end{aligned}. \tag{28}$$

The values of these coefficients can be found by solving appropriate system of linear equations with six unknowns. If the predetermined time in the ouw

'geographical' coordinate system, source of pollution emission (floating object) has the coordinates (u_E, w_E), whereas the measuring point A has the two first coordinates (u_A, w_A)

$$\begin{aligned} 0 &= a_{11}u_E + a_{12}w_E + a_{13} \\ 0 &= a_{21}u_E + a_{22}w_E + a_{23} \\ x_A &= a_{11}u_A + a_{12}w_A + a_{13} \\ y_A &= a_{21}u_A + a_{22}w_A + a_{23} \end{aligned} , \tag{29}$$

whereby $x_A = x$, $y_A = y$ are the coordinates of the flat measuring point. The other two equations are obtained using the assumption that the direction of the axis ox is identical with the expected wind direction at a given time. If the expected value of the wind velocity in the horizontal plane ouw is the vector $\boldsymbol{v} = [v_x, v_y]$, then the vector unit direction of the wind has the coordinates

$$a = \frac{v_x}{\sqrt{v_x^2 + v_y^2}}, \quad b = \frac{v_y}{\sqrt{v_x^2 + v_y^2}} . \tag{30}$$

Thus, the other two equations take the form

$$\begin{aligned} 1 &= a_{11}a + a_{12}b + a_{13} \\ 0 &= a_{21}a + a_{22}b + a_{23} \end{aligned} . \tag{31}$$

Finally, a system of linear equations on the six unknowns are obtained [14]

$$a_{11}, \quad a_{12}, \quad a_{13}, \quad a_{21}, \quad a_{22}, \quad a_{23}.$$

$$\begin{aligned} u_E a_{11} + w_E a_{12} + a_{13} &= 0 \\ u_A a_{11} + w_A a_{12} + a_{13} &= x_A \\ a\, a_{11} + b\, a_{12} + a_{13} &= 1 \\ u_E a_{21} + w_E a_{22} + a_{13} &= 0 \\ u_A a_{21} + w_A a_{22} + a_{13} &= y_A \\ a\, a_{21} + b\, a_{22} + a_{23} &= 0 \end{aligned} . \tag{32}$$

It is easy to note that the system is reduced to two independent equations of which each is a system of three equations with three unknowns. Thus, when $t \in [t_e + \overline{\theta}, t_e + \Delta t_e + \overline{\theta}]$ the density of pollutants (exhaust gases)in point A originating from one object is expressed by the formula [14]

$$S(x,y,z,t)=\frac{D}{\pi C_y C_z v_x x^{2-n}}\exp\left[-\frac{y^2}{C_y^2 x^{2-n}}\right]\left\{\exp\left[\frac{-(z-h)^2}{C_z^2 x^{2-n}}\right]+\exp\left[\frac{-(z+h)^2}{C_z^2 x^{2-n}}\right]\right\}, \quad (33)$$

where:

$$x = x_A = a_{11}u_A + a_{12}w_A + a_{13}$$
$$y = y_A = a_{21}u_A + a_{22}w_A + a_{23}.$$

Knowing the coordinates of the location and the type of facility in the moments of emission

$$t=\tilde{t}_k = t_e + (k-\tfrac{1}{2})\Delta t_e, \quad k=1,2,\ldots,K,$$

by repeating the calculation procedure, the approximate value of the density of pollutants in moments of 'observation' is obtained

$$t=\bar{t}_k = t_e + (k-\tfrac{1}{2})\Delta t_e + \bar{\theta}_k, \quad k=1,2,\ldots,K.$$

In this way, for the fixed 'measuring' point $A = (u_A, w_A, z_A)$, the density of pollutants in discrete moments coming from a moving floating object are obtained for one floating object. By repeating the calculation for all the objects that are sailing in the bay, the approximate density of pollution coming from these objects is obtained. The sum of these functions gives the total density of pollutants at the point $A = (u_A, w_A, z_A)$. Figure 5 shows graphs of approximate density of pollutants from two objects [14].

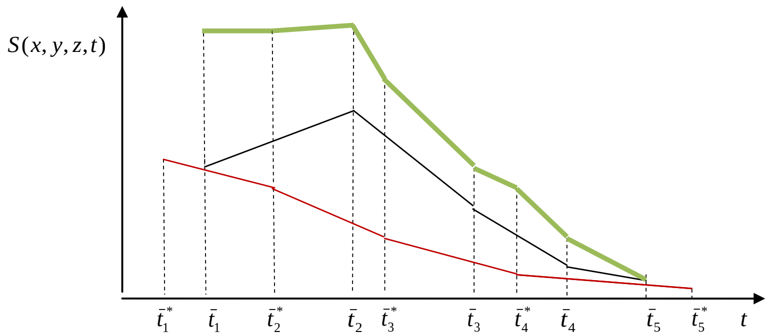

Fig. 5. Graphs of approximate density of pollutants from two floating objects and the total approximate density (green) of pollutants in the fixed point $A = (u_A, w_A, z_A)$ [14]

The same calculations can be performed for the multiple fixed 'data points' at a fixed time t. The values of the summary density of pollutants in these sections allow for a 'map' of pollution density of a certain area to be specified (fig. 6) [14].

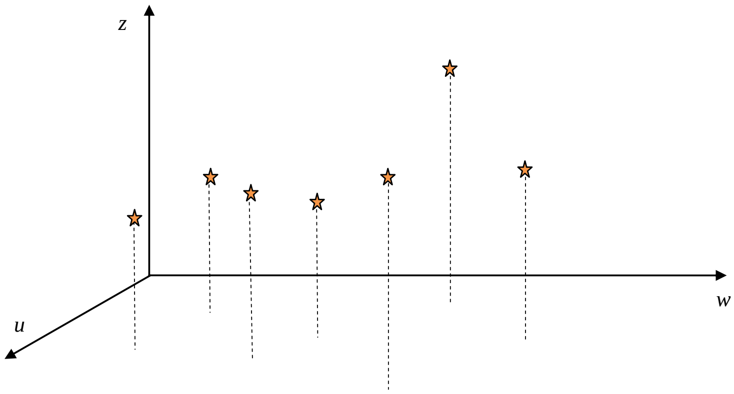

Fig. 6. The values of the summary density of atmospheric pollution at different points in a given time *t* coming from all floating objects that are currently in the study area [14]

CONCLUSIONS

Worldwide research, currently being conducted, on the pollution of atmospheric air caused by the emission of harmful substances from marine vessel engines, based on simplified data input cannot be used to estimate emissions on a scale, e.g. Baltic Sea or the Bay of Gdansk, since it leads to a significant underestimation of emission factors, mainly due to the insufficient detail on the characteristics of vessel traffic. Besides, the known models of emissions of harmful substances in exhaust gases of marine vessel engines, used primarily to support local and regional model tests on air quality, are deterministic models with varying degrees of accuracy, which depends on the spatial resolution of allocation of emissions at a specific time and place. In addition, the accuracy of the model depends also largely on the quantity and quality of input data, determinate financial resources earmarked for the creation, implementation and calibration of the model [4].

The mathematical model of toxic emissions proposed in [4], based on stochastic processes, with the use of Monte Carlo, allows for a fast analysis of vessel traffic in a particular area and the calculation of the emission intensity of each of harmful compounds, with considerable accuracy, and their weight in relation both to an individual vessel and in vessels staying in the area for a specified period of time. What's more, the developed model, as a first, is a fully predictive model, and the developed computer simulation program allows to analyze the traffic of vessels and the intensity of emission at a selected point of time, taking into account the corresponding point of hydro-meteorological conditions.

A computer program was created on the basis of a mathematical model that allows solving the equations. The results of the program can be saved to a file compatible with Microsoft Excel, which allows for their analysis irrespective of the developed software model. In addition, visualization of simulation results is possible in the form of clear charts showing the number of vessels contained in the analyzed waters during the day, with the option of division into types of vessels, the issuance of individual toxic compounds per day and total emission of individual compounds on the types of vessels, from all vessels in each day of the simulation. Another feature of the program is to illustrate the movement of simulated vessels in the area of the basin analyzed on the basis of the results of the simulation. This function is based on a motion animation of vessels plotted on a map of the basin.

The developed simulation program is open to all modifications related to the specifics of the analyzed issues and besides, its versatility enables its implementation to any area of the operation of vessels very quickly after entering the new input data.

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MODELOWANIE EMISJI I DYSPERSJI ZWIĄZKÓW SZKODLIWYCH POCHODZĄCYCH ZE SPALIN SILNIKÓW NAPĘDU GŁÓWNEGO JEDNOSTEK PŁYWAJĄCYCH PO OKREŚLONYM AKWENIE

STRESZCZENIE

W artykule przedstawiono wyniki pierwszych w skali kraju badań o charakterze proekologicznym obejmujących problem oddziaływania żeglugi morskiej (w określonym akwenie) na lądowe środowisko człowieka. Żeglugę na wodach Zatoki Gdańskiej przyjęto jako przykład systemu rzeczywistego i dokonano szczegółowej identyfikacji warunków użytkowania na niej jednostek pływających. Z analizy informacji gromadzonych przez systemy nadzoru ruchu statków (m.in. AIS) uzyskano dane do pełnej identyfikacji parametrów i charakterystyk ruchu statków w postaci deterministycznych i statystycznych modeli matematycznych. Na ich podstawie opracowano modele matematyczne emisji związków szkodliwych spalin silników ze statków. Modele rozprzestrzeniania się spalin oparto na modelach Gaussa, Lagrange'a i Eulera, co pozwoliło uzyskać naukowe narzędzie do oceny udziału imisji związków szkodliwych w globalnej imisji tych zanieczyszczeń w powietrzu atmosferycznym aglomeracji Trójmiasta.

Słowa kluczowe:
modelowanie, emisja, jednostki pływające, silniki okrętowe, rzeczywiste warunki pracy.