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PROGRAM FOR THE EMISSION SIMULATION OF TOXIC COMPOUNDS IN THE MAIN ENGINE EXHAUST OF VESSELS OPERATING IN A SPECIFIED WATER REGION

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Abstract

The current worldwide research on air pollution caused by the emission of harmful compounds from ships' engines is based on a simplified input. The existing databases of harmful compound emissions in the exhaust of vessels operating in various parts of the world cannot be used to estimate emissions in meso- and microscale, e.g. in the Baltic Sea or the Gulf of Gdansk, because this would lead to excessive generalization of emission factors, mainly due to the lack of the required detail concerning vessel motion characteristics.

The first issue tackled within the framework of the project, one of whose effects is to create a research tool in the form of a computer program which simulates toxic compound emissions in the exhaust of the main engines of vessels operating on a specific water body, was to create a vessel traffic database in a selected marine region (e.g. the Gulf of Gdansk). The data was obtained from the marine Automatic Identification System (AIS).

In addition to the parameters of vessel traffic in the analyzed region of the sea, the database created, is a collection of the available construction and operational data of those vessels, such as their size, displacement, power rating of the main propulsion engines, etc. Those data, after the appropriate processing, produced the so-called generalized resistance characteristics of the ships which became the basis for the determination of the maximum demand required by the screw propeller under given operating conditions. Information of the motive power (instantaneous) is necessary to determine the emission characteristics of harmful exhaust gases.

The extensive research resulted in the development of an original computer program, MEFSAS (Model of Emission From Ships At Sea), which allows to determine the power ratings of the screw propulsion engines (and on their basis the emissions characteristics) depending on the aforementioned variables of the operating conditions in the static and dynamic. states.

***Key words**: emissions of toxic compounds, marine engines, emission models, simulation*

1. Introduction

The problem of air pollution in harbors and harbor approach areas is all the more important because of the fact that harbors are typically located near or in large cities, and their limited area causes a large concentration of vessels in a small area. Not without significance are also the broadly understood operating conditions. The latter include the manner in which engines are operated, the incidence and nature of steady and transient load states, as well as the external conditions affecting the engine operation. Toxicity of the exhaust gases is also influenced by the types of fuel and lubricating oil used.

Factors determining the global emissions of substances contained in exhaust gases of marine engines are classified and described in detail in [1, 2].

The process of modeling the emission of toxic compounds in the exhaust of a marine engine is very complex, and it requires the input data that can be divided into four fundamental groups [9]:

- vessel parameters – length, breadth, draft, technical condition of the propulsion system, propulsion type (including the type and number of engines), type and number of screw propellers, etc.;
- vessel motion parameters – velocity and heading;
- external conditions – wind force and direction, air and water temperature, atmospheric pressure, humidity, sea state;
- number of vessels, taking into account their categories.

Models of emissions from land transport, which are made in Europe, cannot be used to assess emissions from ships. due to the difference of both hydro-meteorological conditions and the specifics of the ship operation.

The model of toxic emissions in the exhaust gases of marine engines, STEAM (*Ship Traffic Emission Assessment Model*), which is presented in [3], is based on data transmitted by AIS, which is a basis of the calculations for determining emissions factors related to the emissions of harmful compounds in exhaust gases. In this model, however, simplifying assumptions were not avoided either, which may result in the fact that the determined emissions factors do not reflect the real emissions value.

2. Theoretical foundations for determining the ship's resistance and the power of the main propulsion system

In order to give a vessel a certain velocity, the main propulsion engine has to provide adequate power to the propeller, which is necessary to overcome the resistance to the motion of the ship, and the energy loss of the propeller, shafting, gears, and couplings. A general motion equation of a ship may be presented as follows [4,5]:

$$-(m + m_{11}) \cdot \frac{dV}{dt} - R - \Delta T + T = 0 \qquad (1)$$

where:

m – weight of the ship, propellers and rudder,
m_{11} - weight of accompanying water,
R – ship's total resistance,
T – propeller thrust
ΔT – thrust deduction..

The total resistance R of the vessel depends on the size of the vessel, its velocity, and the shape of its hull. The resistance is also affected by external factors such as waves of the sea, hull fouling, draft variations, etc.

It can therefore be concluded that the value of the maximum demand required depends primarily on the dimensions of the ship and its instantaneous velocity.

The value of the propeller thrust depends on the diameter of the propeller, its geometrical shape, speed, and the velocity of the vessel. The propeller thrust created must equalize the total resistance of the ship R and the thrust deduction ΔT, acting on the hull in the direction opposite to its motion.

For steady movement (*dv/dt*=0) equation (1) becomes:

$$R + \Delta T = T \tag{2}$$

The total resistance of the ship is the sum of the resistance components

$$R = \sum_i R_{(i)} = R_F + R_{VP} + \mathrm{R_W} + \mathrm{R_D} = S\frac{\rho\cdot v^2}{2}\left(c_F + c_{VP} + c_W\right) + R_D = k\cdot c_T\frac{\rho\cdot v^2}{2} \tag{3}$$

where:
R_F – frictional resistance,
R_{VP} – viscous pressure resistance (form resistance)
R_W – wave resistance,
R_D – additional resistance,
S – wetted surface [m^2],
ρ – water density [$kg\cdot m^{-3}$],
v – flow velocity around the hull. [$m\cdot s^{-1}$],
c_F– frictional resistance coefficient,
c_{VP} – viscous pressure resistance (form resistance) coefficient,
c_W – wave resistance coefficient,
k – additional resistance coefficient (assumed k = 1,1 ÷ 1,2),
c_T – total resistance coefficient.

Frictional resistance is related to the tangential stresses that are induced on the wetted surface of the hull due to the viscosity. Frictional resistance coefficients c_F thus depends primarily on the Reynolds number, expressed as

$$Rn = \frac{VL}{\upsilon} \tag{4}$$

where:
V – velocity of the vessel,
L – length of the vessel,
υ – kinematic viscosity coefficient of water.

Wave resistance is related to the wave pattern generated by a moving ship on the water surface without viscosity (ideal fluid), i.e. on the phenomena whose existence is conditioned by gravity. Therefore, wave resistance coefficient c_W depends primarily on the Froude number.

$$Fn = \frac{V}{\sqrt{gL}} \tag{5}$$

Viscous pressure resistance is related to the effects of viscosity on the pressure distribution and hence to form of the the waves pattern. Viscous pressure resistance coefficient thus depends both on the Reynolds and Froude numbers.

Additional; resistance R_D is primarily composed of appendage resistance R_{AP} and air resistance R_{AA}.

Appendages affecting the total resistance of the ship are such components as bilge keels, shaft brackets, shafts, propeller screws, rudders and shaft bossings on the hull.

Air resistance around the emersed part of the ship is of viscous character. The components of air resistance are frictional resistance and viscous pressure resistance. Air resistance results from both the relative motion of the ship in still air, and from the absolute motion of the air, i.e. the wind. Air resistance is strongly dependent on the size and shape of the the emersed part of the ship (especially its superstructures), and the volume and direction of the relative speed of the air. The formula for air resistance takes the form:

$$R_{AA} = c_{AA} \frac{\rho_A}{2} V_{WR}^2 A_T \tag{6}$$

where:
ρ_A – air density,
V_{WR} – relative air velocity,
A_T – midship cross section area of the emersed part of the ship,
c_{AA} – air resistance coefficient,

The total resistance of the ship R is the sum of the following resistance components: frictional R_F, form R_{FV}, wave R_W and additional R_D

$$R = R_F + \mathrm{R_{VP}} + \mathrm{R_W} + \mathrm{R_D} = \Psi\,(\nu, \mathrm{L}, \rho, \upsilon, \mathrm{M}, \mathrm{A}, \mathrm{G}, \mathrm{O}) \tag{7}$$

This force can be presented as a function of Ψ: instantaneous speed of the ship ν, hull length ***L***, water density ρ, kinematic viscosity coefficient of water **υ,** vector **M,** characterizing the inertia of the ship, vector **A** , containing information about the variable motion resistances of the ship associated with a given water region (water depth, width of the fairway (channels), etc.), vector **G**, describing the ambient conditions (e.g. ambient pressure and temperature), and vector O, describing the navigational conditions (wind force and direction, wave height and length, etc.)[2].

Since the resistance coefficients c_F, $c_{VP} = f\,(Rn)$ and c_W, $c_{VP} = f\,(Fn)$, it was assumed for modeling purposes that the values necessary to perform the calculations for a given category of a tramp vessel are the generated values of the vessel's length L and its instantaneous speed ν.

The total hull resistance $\tilde{R}$ is presented by the equation:

$$\tilde{R} = \tilde{S} \frac{\rho \cdot \tilde{v}^2}{2} (c_F + c_W) + \tilde{R}_{AA} \tag{8}$$

where:
$\tilde{S} = \frac{\sum_{i=1}^{i=n} S_i}{n}$ for i=1,2, ...,n – average wetted area, computed using n relationships,
$\tilde{v}$ – vessel speed generated on the basis of statistical data,
$\tilde{R}_{AA}$ – air resistance generated on the basis of statistical data,

Frictional resistance coefficient was computed using the ITTC formula [5].

$$c_{F_{ITTC}} = \frac{0{,}075}{(log Rn - 2)^2} \tag{9}$$

Since the outer surface of the hull (even with high-quality coatings), cannot be considered hydrodynamically smooth, the calculations took into consideration also the hull roughness expressed as an additive hull roughness coefficient Δc_F using the formula [5,6]:

$$\Delta c_F = \left[105 \left(\frac{k_s}{L}\right)^{1/3} - 0{,}64\right] \cdot 10^{-3} \tag{10}$$

The coefficient of friction was calculated from

$$c_F = c_{F_{ITTC}} + \Delta c_F \tag{11}$$

Wave resistance cannot be determined analytically. Theoretical methods of determining the ship's wave resistance are based on the following assumptions [5,7]:

– water is considered to be non-viscous liquid,

– flow around the hull is considered to be potential, non-cyclic.

The above assumptions lead to a nonlinear boundary value problem for Laplace's equation in three dimensions. This problem can hardly be solved by the adoption of further simplification consisting in the linearization of the boundary conditions.

For the calculated vessel the towing capacity will be

$$\tilde{P}_H = \tilde{R} \cdot \tilde{v} \tag{12}$$

Instantaneous effective power of the propulsion engine $\tilde{P}_e$ will then have the value expressed by the equation:

$$\tilde{P}_e = \frac{\tilde{P}_H}{\eta_0 \cdot \eta_S \cdot \eta_G \cdot \eta_B} \tag{13}$$

For the calculation of coefficients, efficiencies were adopted on the basis of the literature [4,5].

3. Program for the emission simulation of toxic compounds in he main engine exhaust of vessels operating in a specified water region

In order to perform simulations of vessel traffic in the analyzed area, and the estimation of emissions of harmful substances in the main engine exhaust gases at specified intervals of time, a computer calculation program was developed, known as ***MEFSAS*** (***M****odel of* ***E****mission* ***F****rom* ***S****hips* ***A****t* ***S****ea)* [2].

Fig. 1 shows a sample window of a model input parameters (hydrometeorological conditions), and Fig. 2 a window of toxic emissions in the exhaust on particular days of the week for the first category of vessels (bulk carriers) [2].

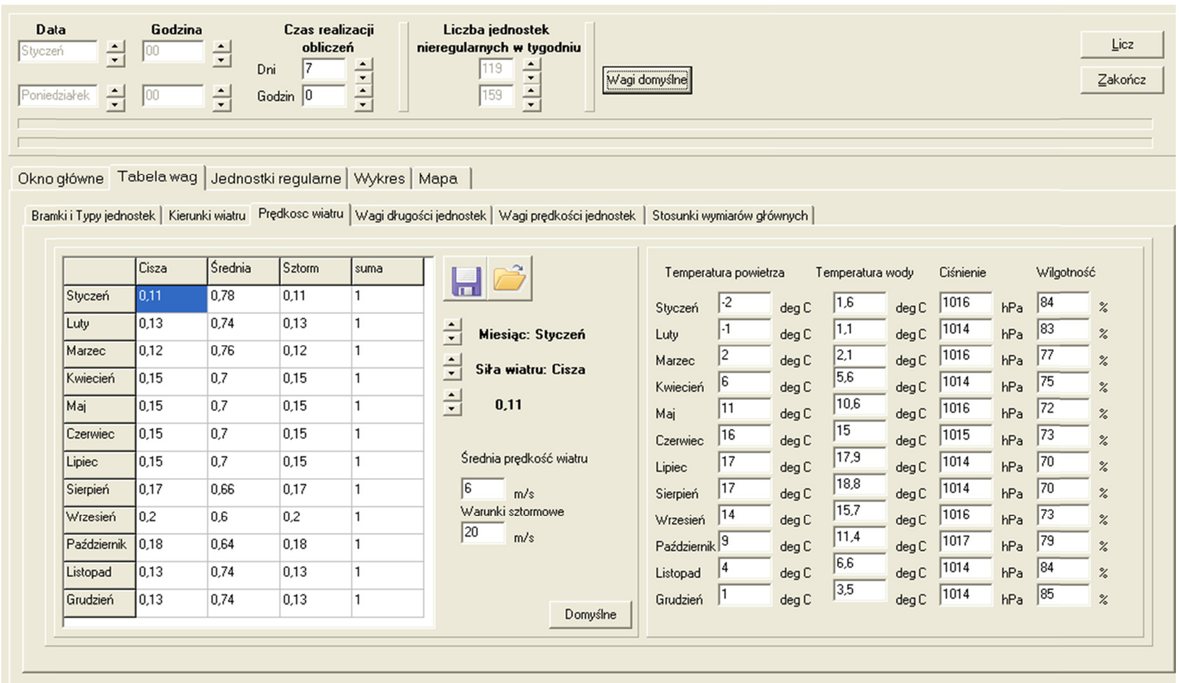

Fig.1. Sample window of input parameters for a mathematical model used to estimate the emissions of harmful substances in the exhaust gases of the marine main engines – MEFSAS (hydrometeorological conditions) [2]

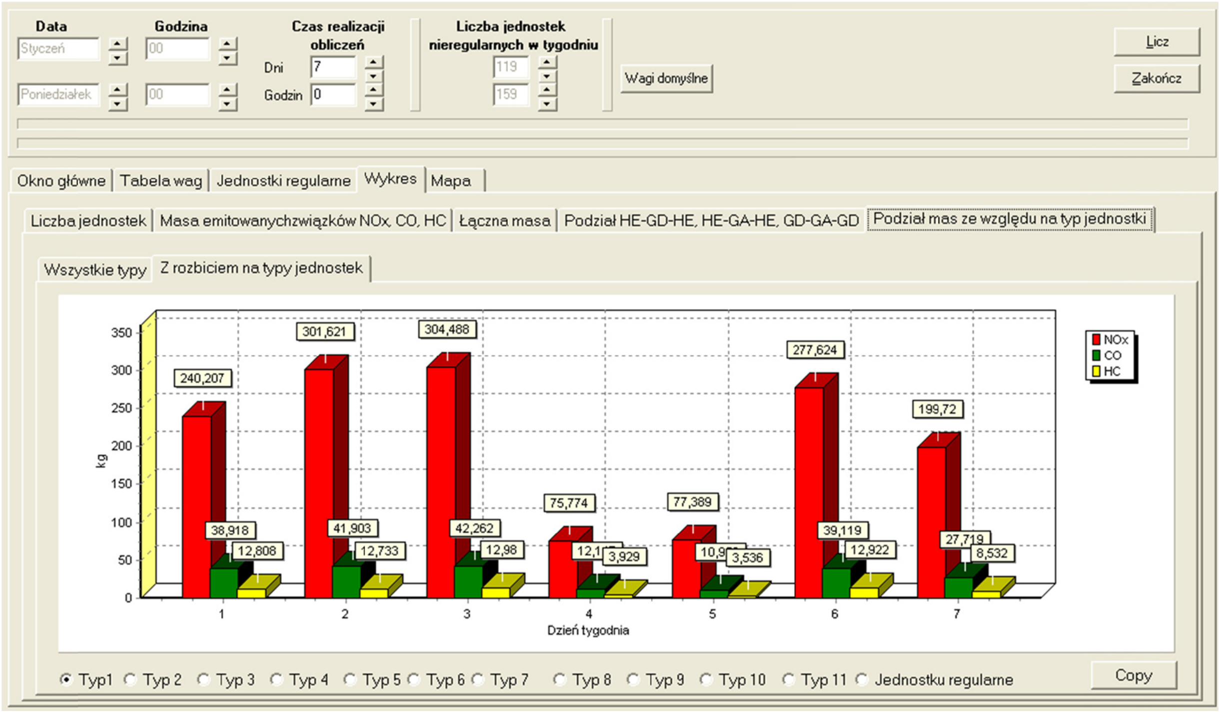

Fig. 2 Sample window showing the estimates – calculated using a mathematical model – of the emissions of harmful substances in the exhaust gases of the marine main engines –MEFSAS – on particular days of the week for the first category of vessels (bulk carriers) [2]

Apart from the presentation of simulation results in a tabular form, the MEFSAS program may be used to visualize the results using bar graphs, which significantly simplifies their analysis.

The basic options for presenting the simulation results include:

- Bar graphs broken down by the vessel type (Fig. 2).
- Bar graphs of toxic emissions for different vessel types as a function of time, presented separately for CO, HC i NO_x (Fig.. 3),

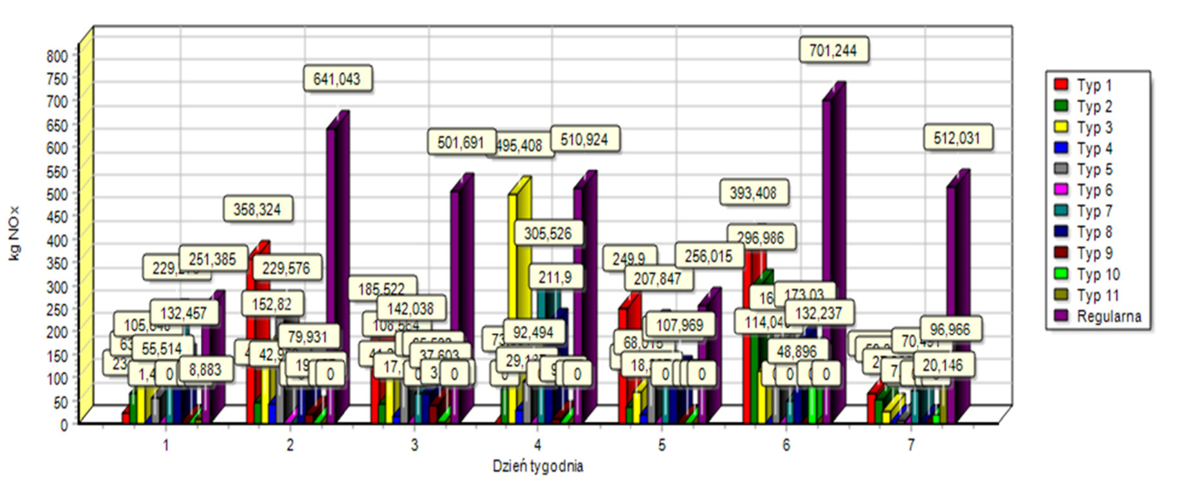

Fig. 3 Graph showing the dependence of NO_x emissions for different vessel types, as a function of day of the week [8]

All the simulation results obtained using the MEFSAS program can be saved to a text file, which can be subjected to statistical analysis (the scope of which was not defined at the time of writing the program) using practically any tool, such as: Statistica, Excel, etc. (rys.4).

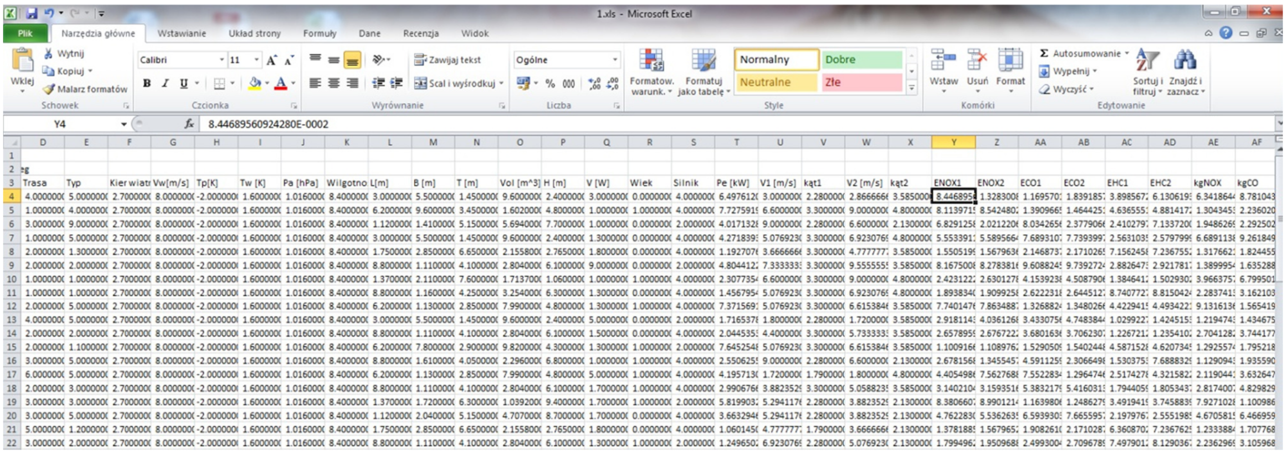

Fig. 4 View of the table containing data obtained using the MEFSAS computer simulation program

The following data is saved to the file:

- day of the vessel's entry into the water region,
- minute of the event (in relation to day),
- tramp or liner vessel information,
- vessel type
- wind direction,
- wind speed,
- air temperature,
- water temperature,
- atmospheric pressure
- air humidity
- vessel's length,
- vessel's breadth,
- vessel's draft,
- immersed hull volume
- vessel's height
- vessel's velocity
- vessel's age,
- main propulsion type (two- or four-stroke engine)
- maximum demand required of the main engines
- wind speed relative to the vessel's hull,
- wind direction relative to the vessel's hull,
- specific NOx emissions for a given engine type,
- specific CO emissions for a given engine type,
- specific HC emissions for a given engine type,
- NOx emissions for a given engine type,
- CO emissions for a given engine type,
- HC emissions for a given engine type,

Figure 5 shows an algorithm which is the basis for calculations performed by the MEFSAS program.

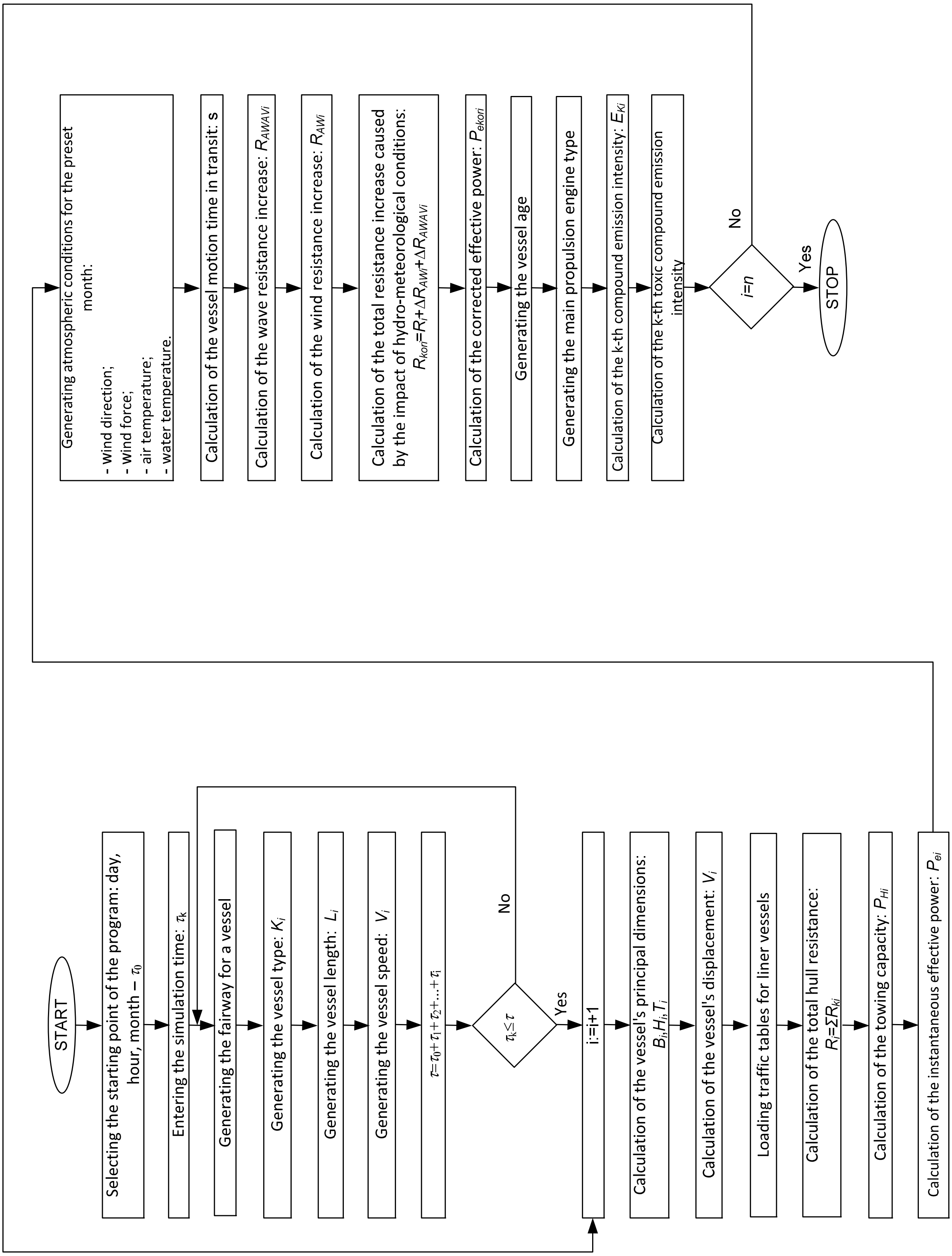

Fig. 5 Algorithm being the basis for calculations performed by the MEFSAS program.

4. Conclusions

Continuous development of maritime transport, with the ever increasing demands on environmental protection, high costs, and problems associated with the measurement of emissions of harmful compounds in the exhaust of ships in transit, as well as the lack of sufficiently accurate methods for the determination of indirect emissions, were the main reason for undertaking research studies on modeling the emissions processes of marine diesel main propulsion engines under the marine operating conditions [2].

The current worldwide research on atmospheric air pollution caused by the emission of harmful compounds from ships' engines, based on a simplified input data cannot be used to estimate emissions within e.g. the Baltic Sea or the Gulf of Gdansk, since they lead to a significant underestimation of emissions, mainly because of insufficient detail of the marine traffic characteristics. Besides, the known models of the harmful compound emissions in exhaust gases of marine engines, which are used primarily to support local and regional model studies concerning air quality, are deterministic models with varying degrees of accuracy which depends on the resolution of the spatial allocation of emissions at a particular location and time. Moreover, the accuracy of a given model depends to a large extent on the amount and quality of input data, determined by financial resources earmarked for the creation, implementation, and calibration of the model [2].

The mathematical model of toxic emissions proposed in [2], which is based on stochastic processes using Monte Carlo methods, allows for a rapid analysis of marine traffic in a particular area, and for calculation with considerable accuracy of the emission intensity of each harmful compound, and their weight in relation to both a single vessel, and to vessels remaining in the area for a specified period of time. Furthermore, the model developed is the first fully predictive model, and the accompanying computer simulation program allows the analysis of marine traffic, and emission intensity at the selected point of time, taking into account hydro-meteorological conditions corresponding to that point.

The mathematical model was the basis for the development of a computer program that allows to solve the model's equations. The results generated by the program can be saved to a file compatible with Microsoft Excel, which allows for their analysis independent of the software used by the model. Additionally. it is possible to visualize the simulation results in the form of easily readable charts showing: the number of vessels in the analyzed water area during the day, with the option of splitting the vessels by their type, the emissions of various toxic compounds by the day and vessel type, as well as the total emissions of individual compounds from all vessels on each of the days of the simulation. Another feature of the program is the is the possibility to visualize the motion of the simulated vessels in the analyzed water region on the basis of the simulation results. This feature is based on the animation showing the vessels plotted on the chart of the relevant area.

The simulation program developed is open to any modifications related to the specifics of the analyzed issue, and, what is more, because of its versatility, it may be implemented into any area of marine operations very quickly after the introduction of a new set of input data.

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