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Modelling of Ecological Characteristics of Marine Main Propulsion Diesel Engines

Abstract: The work presents the procedure for modelling ecological characteristics of marine main propulsion diesel engines. The engine's ecological characteristics are related to its work condition and external conditions. A method has been given of determining this condition for various typical sailing conditions. The basis for determining the engine's ecological characteristics related to exhaust emission is provided by the hull's resistance characteristics in various sailing conditions. The engine's power characteristics were determined from them, and on their basis were determined the propeller characteristics of toxic compounds emission from exhausts and NO_x emission intensity. Vessel movement parameters were determined from data gathered by the AIS system.

Key words: *marine engines, ecological characteristics, modelling*

Modelowanie wyznaczania charakterystyk ekologicznych okrętowych silników spalinowych napędu głównego

Streszczenie: W pracy przedstawiono tok postępowaniu przy modelowaniu charakterystyk ekologicznych okrętowych silników spalinowych napędu głównego. Charakterystyki ekologiczne silnika związane są z jego stanem pracy oraz warunkami zewnętrznymi. Podano sposób określania tego stanu dla różnych, typowych warunków pływania okrętu. Podstawą wyznaczania charakterystyk ekologicznych silnika związanych z emisją spalin są charakterystyki oporowe kadłuba statku w różnych warunkach pływania. Z charakterystyk tych wyznaczono charakterystyki mocy silnika a na ich podstawie charakterystyki śrubowe emisji związków toksycznych zawartych w spalinach oraz natężenia emisji NO_x. Parametry ruchu statków określono z danych gromadzonych przez system AIS.

Słowa kluczowe: *silniki okrętowe, charakterystyki ekologiczne, modelowanie*

1. Introduction

In modelling characteristics of pollution emission by marine diesel engines, what is of key importance is the identification of true conditions of the vessel's operating and on this basis working out the characteristics of the ship's movement system, which as a rule are a set of functional connections of particular hull and propulsion system parameters [1].

The ecological characteristics of marine diesel engines as a rule concern the emission into the atmosphere of nitrogen oxides, carbon oxide and carbohydrates in ship's real sailing conditions. One among many forms of the marine engine's ecological characteristics is the dependence $E_{ZT} = P_e \cdot e_{ZT}$ in particular external conditions $Z = idem$, where E_{ZT} is the toxic compound emission intensity, P_e the engine's effective power, e_{ZT} toxic compound's unit emission.

The course of modelling the ecological characteristic of marine diesel engines has been presented in Fig. 1. The initial stage is the creation of a statistical data base concerning movement in normal operating conditions of the vessels analysed (nominal speed v_n and maximum v_{max}), basic hull dimensions (L, B, T), general data of installed main propulsion engines (number and type of engines – two-stroke, four-stroke, nominal and maximum power values and of the engine's rotational speed $P_{e(n)}$, n_n, $P_{e(max)}$, n_{max}). Among basic data there also the values of observed movement speed v in real external conditions of sailing (closer T_a, p_a, φ and farther SM, h, D, c_f).

The first step of the modelling considered is to determine a general resistance characteristic taking into account typical real external conditions (closer and farther), essentially affecting the work condition of the vessel's propulsion system and emission of toxic compounds contained in engine exhausts. The second step of modelling is to examine and determine a general propeller characteristic of main engine power related to the engine's rotational speed and the vessel's speed. In the third step, a general propeller characteristic of unit emission of basic toxic compounds takes place (e.g. nitrogen oxides NO_x, carbon oxide CO and hydrocarbons HC). This task requires rather extensive experimental research on the engine in laboratory and operational conditions.

In the last modelling step parameters of pollution emission are determined (in accordance with ISO 8178 standard), parameters of pollution emission depending on the work conditions of marine engines, in the shape of a complete ecological characteristic.

The last stage is the determination, in accordance with ISO 8178 standard, of parameters of pollution emission depending on the engines' operational conditions, in the shape of their complete ecological characteristic.

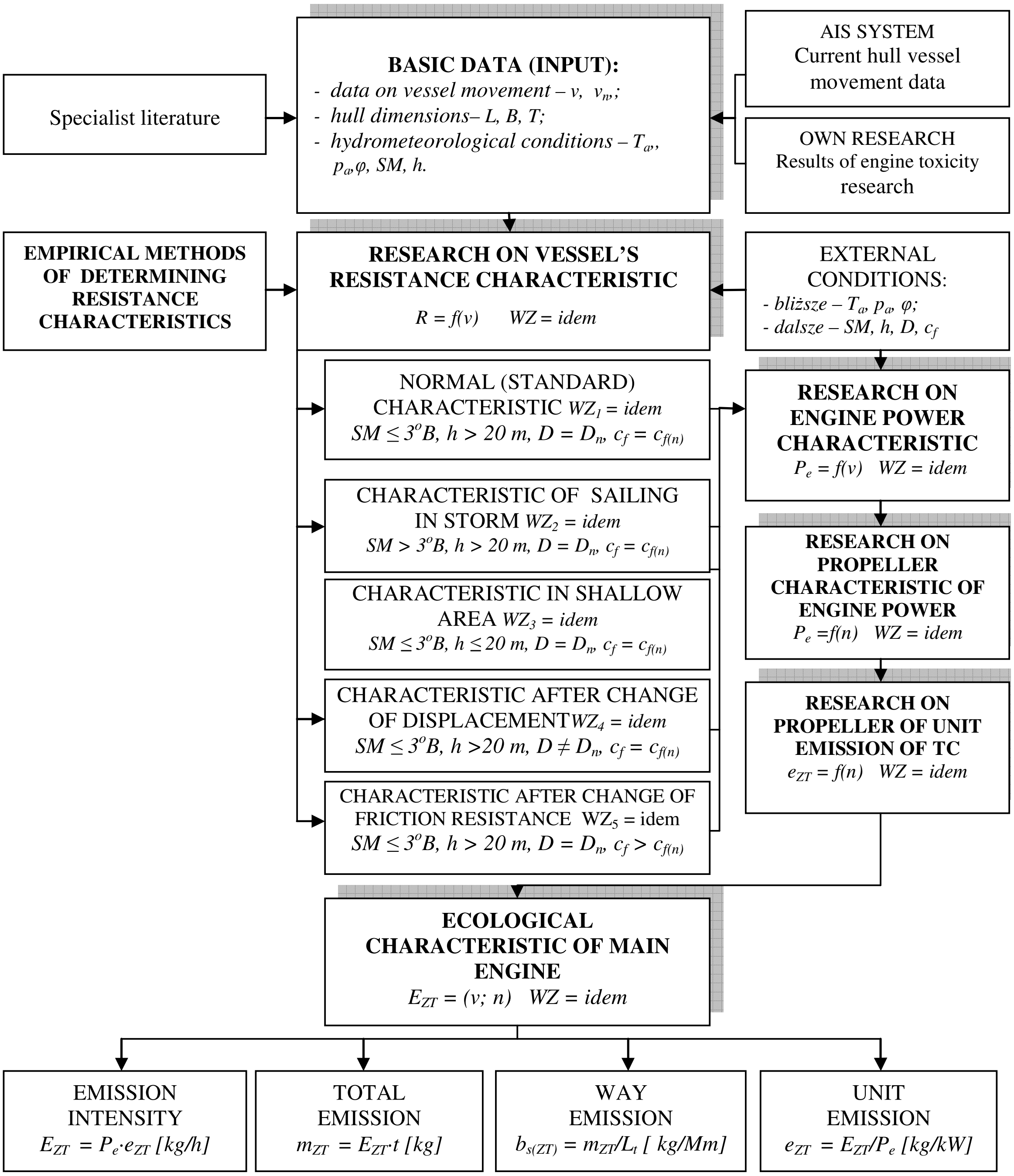

Fig. 1. Course of modelling the ecological characteristic of marine main propulsion diesel engine
SM – state of sea; WZ – external conditions; AIS – system of automatic identification of vessel traffic; L,B,T – length, breadth, draft of vessel's hull; E_{ZT} – intensity of toxic compound emission; v – ship's speed; T_a, p_a, φ – temperature, pressure, relative humidity of atmospheric air; 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)

2. Resistance characteristic

The movement of vessels at sea in principle takes place on designated routes. Ships' communication route is composed of m waterway sections, of length described by the vector $\bar{r} = (r_1, r_2, \dots, r_m)$. At the same time, particular sections of the way differ as to values of sailing area parameters $\bar{p_i} = (p_{i_1}, p_{i_2}, \dots)$, which essentially affect the work of the ship's propulsion system. This means that the basic value characterising the ship's movement system, that is hull resistance $R_i(v_i, \bar{p_i})$ on the i-th fairway section of length r_i depends on parameters $\bar{p_i}$ and the vessel's speed v_i.

On particular waterway sections vessel speed is described by vector $\bar{v} = (v_1, v_2, \dots, v_m)$, which at the same time depends on the values of way and hull parameters $\bar{p_i} = (p_{i_1}, p_{i_2}, \dots)$. So vector $\bar{p_i}$ describes the parameters of particular waterway sections taking consideration of external sailing conditions and hull and propulsion system parameters of the ship. Thus it was assumed in the description $\bar{p_i} = (p_{i_1}, p_{i_2}, p_{i_3})$, where:

- $p_{i1} = h_i/T$ – *relation of depth of i-th waterway section to the vessel's draft;*
- $p_{i3} = v_{wi}$ – *wind velocity on i-th fairway section;*
- $p_{i3} = c_f$ – *hull roughness.*

There are also distinguished constant parameters characterising vessels sailing on particular fairway sections, emitted by the AIS system and catalogue data corresponding to them, as well as assumed values of selected parameters that have been included in the data base. Among this type parameters there are:

- $p_4 = L$ – *hull length;*
- $p_5 = B$ – *hull breadth;*
- $p_6 = T$ – *hull draft;*
- $p_7 = \delta$ – *hull block coefficient;*
- $p_8 = P_{e(n)}$ – *installed (nominal) effective power in the propulsion system;*
- $p_9 = v_n$ – *vessel's nominal speed.*

Standard (normal) characteristic

On the basis of state of knowledge so far two kinds of works can be distinguished of utilitarian character, pertaining to the modelling of ship resistance, among which purely theoretical works are prominent based mainly on known hydrodynamic laws and works based on empirical data and data of mathematical statistics. Theoretical works mainly concern the subject matter of designing vessels, and it results from analyses included in literature (e.g. studies [2 ÷ 4]) that they aim at:

- working out methods useful in the process hull shape resistance optimisation;
- working out parametric methods indispensable in initial designing;
- working out methods of accurate resistance prognostication, based on non-linear calculation methods, aimed at replacing experimental model research by suitable computer calculations.

On the basis of previous attainments in the area of theoretical modelling it can be assumed that the vessel's theoretical total resistance can be expressed by means of the approximate relation

$$R_t = R_w + R_v + R_p = \frac{1}{2}[C_w(\bar{K}, Fr) + C_v(\bar{K}, Rn) + C_p] \cdot \rho \cdot v^2 \cdot \Omega(\bar{K}) \qquad (1)$$

where: $R_w = C_w(\bar{K}, Fr) \cdot \rho \cdot v^2 \cdot \Omega(\bar{K})$ – *ship's wave resistance;*

C_w – *non-dimensional resistance coefficient is a function dependent on the hull's shape expressed by a set of shape parameters* $K = (p_1, p_2, \dots, p_n)$ *and by Froud* number $Fn = \frac{v}{\sqrt{L \cdot g}}$;

$R_v = C_v(\bar{K}, Rn) \cdot \rho \cdot v^2 \cdot \Omega(\bar{K})$ – *viscosity resistance*

C_v – *non=dimensional resistance coefficient dependent on hull shape and Reynolds* number $Rn = \frac{v \cdot L}{\mu/\rho}$;

v – *vessel's velocity;*

L – *hull length;*

μ - *coefficient of dynamic water viscosity;*

ρ – *water density;*

Ω – *hull's moistened surface;*

R_p, C_p – *resistance and coefficient of additional components (e.g. aerodynamic resistance, resistance after change of roughness etc.).*

The form of expression presented above, however, has a definition character of resistance and does not ensure calculations of the vessel's resistance characteristic. Therefore, the modelling of hull resistance in dependence on vessel velocity is based exclusively on empirical met. Out of a number of methods, because of a simple algorithmic structure and usefulness in encoding numerical computer algorithms, a known method described in work [5] deserves attention:

$$R = g\left\{0{,}17 \cdot \Omega \cdot v^{1{,}825} + 1{,}45\left(24 - \frac{L}{B}\right)\delta^{\frac{5}{2}}\frac{D}{L^2}v^4\right\} \qquad (2)$$

where: g *[m/s²]* – *gravitational acceleration;*

Ω *[m²]* –*area of hull's moistened surface;* v *[m/s]* – *vessel velocity;* B, L *[m]* – *hull's breadth and length of designed waterline (DWL);* δ – *hull's block coefficient* $\delta = \frac{V}{L \cdot B \cdot T}$; D *[t]* – *vessel's displacement.*

Fig. 2 presents a generalised average standard resistance characteristic, determined on the basis of dependence (2) and data obtained by AIS system (about 3500 commercial vessels were analysed of various intended use in the Gulf of Gdańsk area). The curve shown on the Figure and the respective approximating polynomial may be used in considerations concerning vessel resistance with displacement hulls on confidence level $\alpha = 0.95$ in conventionally accepted standard conditions of their operation ($SM \leq 3^oB$, $h > 20$ m, $D = D_n$, $c_f = c_{f(n)}$).

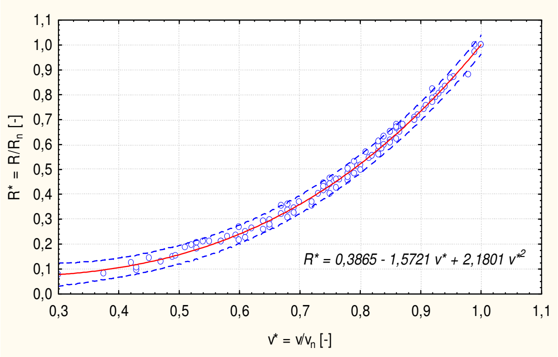

Fig. 2. General resistance characteristic of vessels with displacement hulls

Resistance characteristic during storm

The components of static resistance characteristic of a vessel sailing in storm are:

- standard resistance characteristic corresponding to standard operational conditions of a vessel $R = f(v)$;
- distribution of additional resistance from wind $R_p = f(v)$;
- distribution of additional resistance from wave $R_F = f(v)$.

Additional resistance from wind can be calculated from the dependence

$$R_p = c_o \cdot \rho \cdot A_p \cdot \cos\varphi \,(v_w^2 + v^2 + 2v_w \cdot v \cos\varphi) \qquad (3)$$

where: ρ [kg/m^3] – air density $\rho = 0,2928$;
A_p [m^2] – area of lateral surface of hull's of hull's upperworks projection; φ [^{o}] – angle between wind direction and ship's course; v [m/s] – vessel velocity; v_w [m/s] – wind velocity; c_o [-] – air resistance coefficient = characterises the resistance of hull's upperworks development.

On the basis of dependence (3) there were determined universal dependencies of relative resistance increase from wind velocity and vessel's speed in storm, which have been presented and described by approximating polynomials as ion Fig. 3 and Fig. 4.

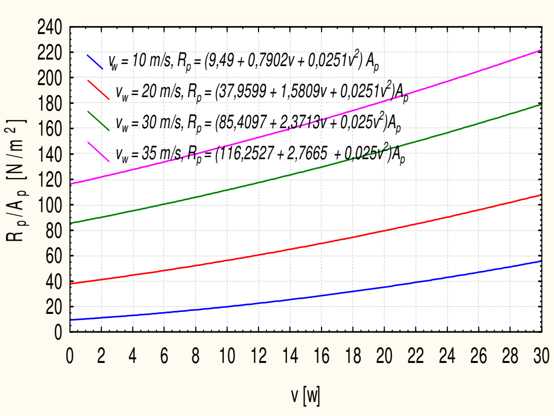

Fig. 3. Relative additional resistance from air depending on wind velocity and vessel's speed in storm

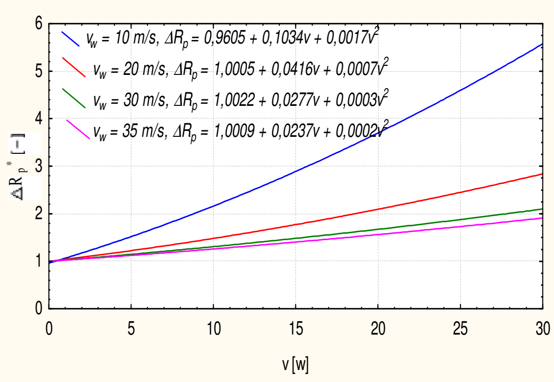

Fig. 4. Relative additional resistance increase from air depending on wind velocity and vessel's speed in storm

Additional resistance from waving

Additional resistance from waving R_F [N] can be calculated from the dependence

$$R_F = \frac{\rho(v + v_f)^2}{2} \cdot \frac{B \cdot h_f}{\pi}(1 - \cos\psi_d) \qquad (4)$$

where: $\rho = 1026$ kg/m^3 – water density;
v_f [m/s] – wave movement velocity; λ [m] – wave length; B [m]- vessel's breadth at waterline; ψ_d [^{o}] – half an angle of hull bow's becoming more acute at waterline.

Calculations results of additional resistance from water waving depending on vessel's velocity have been presented in Figs 5 and 6.

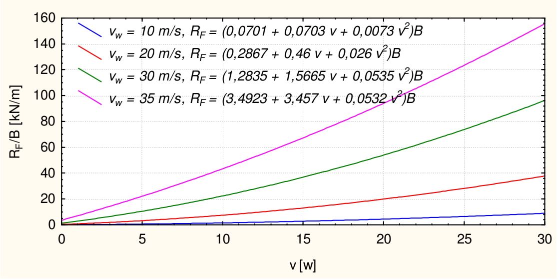

Fig. 5. Additional unit resistance from water waving during sailing in storm

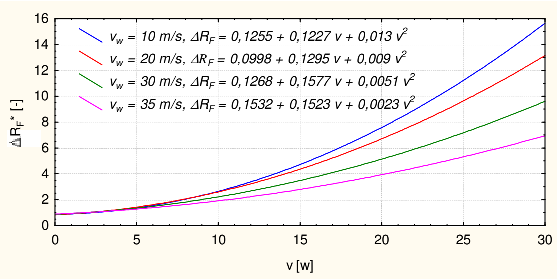

Fig. 6. Relative increase of additional resistance from water waving depending on wind velocity and vessel sailing in storm

Resistance characteristic in restricted waters

In area of restricted depth the basic changes concern wave resistance, which reaches maximum value at critical velocity described by the dependence

$$\upsilon_{kr} = \sqrt{g \cdot h} \tag{5}$$

where: g *[m/s²] is gravitational acceleration.*

It follows from observation that at sailing velocity smaller than $\upsilon_h = 0.4 \cdot \upsilon_{kr}$ the hull's flow-around practically does not differ from flow-around in deep water and hence it can be assumed that also the resistance value of a given ship in shallow water at these velocities does not essentially differ from resistance in deep water. At velocities in intervals $0.4 \cdot \upsilon_{kr} < \upsilon_h \leq 0.75 \cdot \upsilon_{kr}$ the characteristic of the waving system changes considerably (the angle of quartering seas propagation increases), the amplitudes of diagonal and transverse waves increase, and the resistance increases in comparison deep water resistance. At velocities in the interval $0.75 \cdot \upsilon_{kr} < \upsilon_h \leq \upsilon_{kr}$ almost all the waving system is concentrated in two swollen transverse waves, having the nature of isolated waves, generated close to the hull's stern and bows. In this velocity range the vessel's resistance reaches maximum value. At velocities $\upsilon_h > \upsilon_{kr}$ the waves, unable to keep up with the vessel, lag behind the ship, only tiny diagonal waves are generated, and the ship sails with significant share of hydrodynamic lift.

The above data indicate that for the determination of the ship's resistance in areas with restricted depths a method can be applied consisting in comparing resistance values at deep water at a given sailing velocity v with resistance in shallow water with another equivalent movement velocity υ_h. Therefore it was assumed that hull resistance in deep water at speed v is equal to resistance in shallow water with velocity

$$\upsilon_h = \upsilon \cdot \sqrt{tgh \frac{g \cdot h}{\upsilon^2}} \tag{6}$$

The calculations were conducted for a number of assumed water depths, and the results have been presented graphically in Fig. 7. Standard curve $R_g^* = f(v^*)$, corresponding to unrestricted sailing conditions, has also been placed on this Figure.

It can also be observed that essential changes of resistance and engine power occur with diminished water depth to $h \leq 20$ *m* (they are increasingly larger along with diminished water depth). Therefore the character of curves also changes from second-degree polynomial through third-degree polynomial to exponential curves.

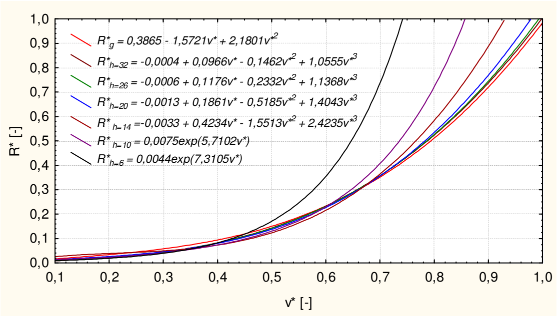

Fig. 7. Averaged relative resistance characteristic in real sailing conditions in areas of various water depths

Resistance characteristic after change of hull displacement

In accordance with admiralty dependence the change of resistance due to changed loading state of a given vessel can be related to the real value of hull draft T

$$\frac{R_n}{R} = \left(\frac{T_n}{T}\right)^{\frac{2}{3}} \tag{7}$$

where: R_n *– hull resistance at standard hull loading;* R *– hull resistance at current loading (draft);* T_n *– draft corresponding to standard loading;* T *– draft at current hull loading.*

Fig. 8 includes a graph and dependence for calculating allowance for sailing resistance at current hull draft *T*.

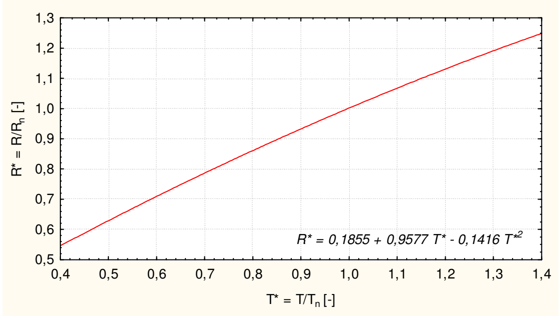

Fig. 8. Dependence of relative resistance on hull's draft change of a vessel

The change of resistance, and thereby of sailing velocity at a particular engine power can be caused by commonly occurring changes of hull plating roughness and the elements of its underwater equipment, caused mainly by growth of marine organisms, corrosion, cavitation of plating and erosion of protective and maintenance paint layer. The friction resistance of a vessel moving at a particular speed depends thus on the dimensions and shape of moistened hull surface and its roughness

$$R_f = c_f \frac{\rho \cdot v^2}{2} \Omega \qquad (8)$$

where: *R_f [N] – hull friction resistance;*
c_f [-] – friction resistance coefficient;
v [m/s] - vessel's velocity;
Ω [m^2] – moistened surface area of hull

The value of friction resistance coefficient for clean hull (after repair and maintenance) can be determined from empirical dependence like ITTC (*International Towing Conference)*

$$c_f = \frac{0{,}075}{(log Rn - 2)^2} \qquad (9)$$

where: $Rn = \frac{v \cdot L}{\nu}$ *- transformed Reynolds number; v[m/s] – vessel velocity; L [m] – vessel's length; ν[m^2/s] – kinematic viscosity of sea mater (for T= 288 K viscosity $\nu = 1{,}18 \cdot 10^{-6}$ m^2/s).*

3. Characteristic of propelling engine power

For the propulsion of a vessel at speed v_i on a particular sea way section r_i the required effective power of main propulsion engine $P_{e(i)}$ can be expressed in the form of general relation

$$P_{e_{(i)}} = \frac{R(v_i,\bar{p}_i) \cdot v_i}{\xi_0(v_i,\bar{p}_i)} = \frac{R(v_i,\bar{p}_i) \cdot v_i}{\eta_p(v_i,\bar{p}_i) \cdot \xi_k(v_i,\bar{p}_i) \cdot \xi_r(v_i,\bar{p}_i)} \; [W] \quad (10)$$

Assuming that propulsion efficiency ξ_0 in the variability range of velocity vectors $\bar{v}$ and waterway and hull parameters $\bar{p}$ assumes constant values, and neither do the particular fairway parameters on a particular section differ essentially, dependence (10) is simplified to the form

$$P_e \simeq \frac{R(v_{śr},p_{śr}) \cdot v_{śr}}{\xi_{o_{śr}}} \; [W] \qquad (11)$$

where*: $v_{śr} = v = (v_1 + v_2)/2$- average vessel velocity on a particular fairway section; $p_{śr} = (p_1 + p_2)/2$ – average parameter value of fairway section; $\xi_{ośr} = 0.65$ for power plant with low-speed engines; $\xi_{ośr} = 0.55$ for power plant with high-speed engines*

Fig. 9 contains a standard graph and approximating polynomial of main engine power curve (towing power) in dependence on vessel velocity in standard operational external conditions.

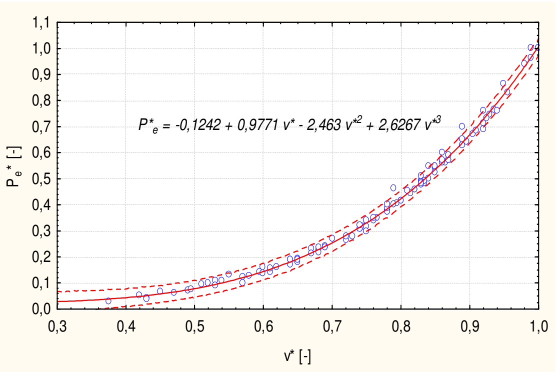

Fig. 9. Standard averaged dependence of main propulsion engine power on the sailing velocity of a vessel with displacement hull

It should be stressed that in the method presented there is lack of a general propeller characteristic of emission of toxic compounds from main propulsion diesel engines. Its determination is possible on the basis of experimental research of engines, both in laboratory and in the place of fixed mounting in vessels' propulsion systems. The report contains only an example concerning a contemporary marine engine with governor of rotational speed, equipped with an automatic torque-restricting system depending on the supercharging pressure.

In the creation of an ecological characteristic indispensable are also an averaged propeller characteristic, which has been place in Fig. 10 and a load characteristic of the main engine, placed in Fig. 11.

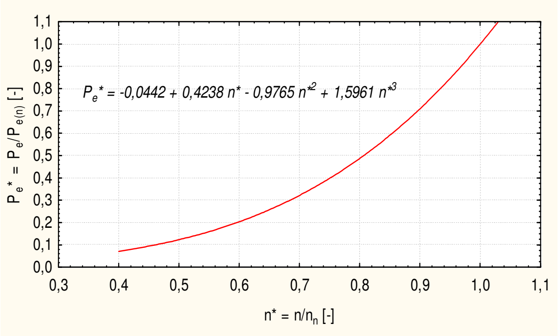

Fig. 10. Standard averaged propeller characteristic of main propulsion engine of a vessel with displacement hull

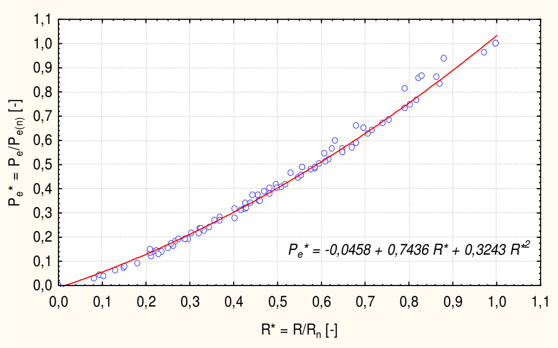

Fig. 11. Load characteristic of main propulsion engine

4. Propeller characteristic of unit emission of toxic compounds

The conditions of producing toxic compounds in main propulsion marine diesel engine are determined by the values of load parameters (effective towing power P_e, vessel's movement speed v), thermal state parameters (exhaust temperature T_{sp}, water in the cooling system T_w, oil in the lubrication system T_o) and parameters of air surrounding the engine (temperature T_a, pressure p_a, relative humidity of air φ) $\bar{p}_j = (P_e, v, T_{sp}, T_w, T_o, T_a, p_a, \varphi)$. Parameters of load and thermal state also depend on external conditions described in set $\bar{p}_i$. Therefore, a programme on experimental research on toxic compounds unit emission should correspond to the power propulsion characteristic of technically efficient main engines, equipped on a modern level with typical steering mechanisms of rotational speed governors, in standard and changed external conditions of the vessel's operation. At the same time the determined characteristic should be reduced to normal surrounding conditions, which may be expressed by the relation

$$e_{ZT_j} = \frac{E_{ZT}(\bar{p}_i, \bar{p}_j)}{T_{tq}(\bar{p}_i, \bar{p}_j) \cdot \omega} \quad \left[\frac{g}{kWh}\right] \qquad (12)$$

Fig. 12 contains an example of laboratory research results on unit emission of nitrogen oxides of a marine engine equipped with a regulator with torque-restricting system depending on the supercharging pressure [6].

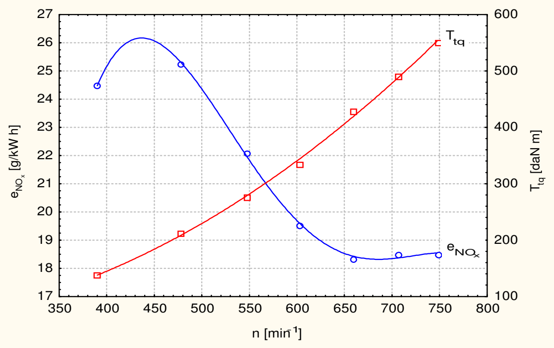

Fig. 12. Propeller characteristic of unit emission of nitrogen oxides and torque of Sulzer 6AL20/24 engine in conditions of established load

5. Ecological characteristic of main engine

On the basis of current regulations in the subject matter considered, the following indexes have been assumed characterising the toxicity level of marine engines [7]:

- unit emission of toxic compound e_{ZT} *[kg/kW h]*
- emission intensity $E_{ZT} \simeq P_e \cdot e_{ZT}$ *[kg/h]*;

- total emission $m_{ZT} = E_{ZT} \cdot t \ \ [kg]$;

- way emission $b_{s_{ZT}} = \frac{m_{ZT}}{L_t} \left[\frac{kg}{Mm}\right]$.

Fig. 13 contains an example of ecological characteristic of nitrogen oxide emission intensity of a main propulsion diesel engine.

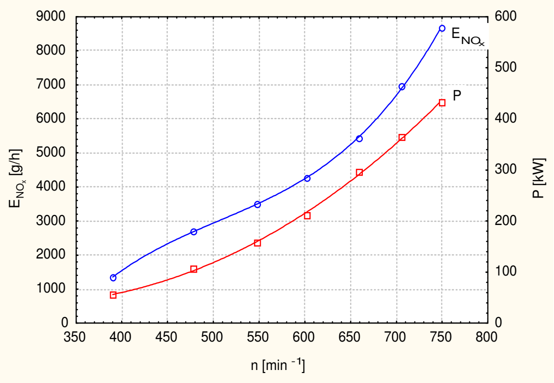

Fig. 13. Propeller characteristic of nitrogen oxides emission intensity and power of Sulzer 6AL20/24 engine in conditions of fixed load

Recapitulation

The prepared modelling procedure defines the method and indispensable data for determining an approximate ecological characteristic of main propulsion piston engines in basic real operational conditions of vessels with displacement hulls. The prepared characteristics describing the work conditions of these engines have features of universal dependencies, capable of being applied in the process of determining tests and ecological characteristics of similar vessels.

In the suggested method of modelling an ecological characteristic it was assumed that in the identification and description of operational conditions of main propulsion marine diesel engines, the basic dependence was the standard resistance characteristic (design, normal). The general relative resistance characteristic and characteristic of propulsion engine's effective power has been determined statistically (on confidence level $\alpha = 0.95$) on the basis of gathered data, selected from among 3500 registered voyages of vessels by AIS system.

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