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ASSESSMENT OF ECOLOGICAL AND CHEMICAL EFFICIENCY OF EXPLOITATION PROCESS OF RECIPROCATING ICE OF VEHICLE WITH CONSIDERATION OF EMISSION OF SULPHUR OXIDES, BENZO(a)PYRENE AND POLYCYCLIC AROMATIC HYDROCARBONS

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Abstract

In this study the previously proposed by the author techniques of determination of magnitudes of mass hourly emissions of sulphur oxides, benzo(a)pyrene and polycyclic aromatic hydrocarbons in diesel engine exhaust gases flow have been improved. Distributions of magnitudes of such emissions on operational regimes field of 2Ch10.5/12 autotractor diesel engine and on regimes of standardised steady testing cycle ESC were obtained. The mathematical apparatus and technique of application of index of ecology-chemical evaluation of ICE of Prof. P. M. Kanilo have been improved as the alternative for complex fuel-ecological criterion of Prof. I. V. Parsadanov. Distributions of magnitudes of such indicator of ecological safety level of power plants with reciprocating ICE exploitation process on operational regimes field of 2Ch10.5/12 autotractor diesel engine and on regimes of standardised steady testing cycle ESC were obtained together with its middle exploitational magnitude. It is established that, in case of considering of values of mass hourly emission of sulphur oxides, benzo(a)pyrene and other PAH in the criteria-based assessment of efficiency of exploitation process of vehicles with diesel ICE with using of mathematical apparatus of the integral indicator of ecological-chemical evaluation, the minimum efficiency is characterized by the maximum torque regime (F = 1.029), and by the maximum efficiency – regime with low effective power (F = 0.091), the regime of nominal effective power – by average efficiency (F = 0.500), and the minimal idle regime (F = 0.178) – by high efficiency. Middle exploitational magnitude of index F for the ESC standardised steady testing cycle and 2Ch10.5/12 diesel engine is 0.373.

Key words: system object, probabilistic entropy estimation, entropic state function, structural matrix, cognitive approach, complex estimation, equilibrium, research model.

Relevance of the study.

It is well known that the actual ecological status of all environmental components – the atmosphere, hydro and lithosphere – both on a planetary scale and on a scale of a single urbanized and anthropogenically loaded territory, is of considerable concern and has a clear tendency to worsen. This situation is caused by the gradual evolutionary development of civilization, which accelerated over the XX century and was accompanied by a steady increase in the level of scientific and technological progress and the rapid development of industrial production [1–3].

This tendency is mainly due to the expansion of the range of countries and regions of the world, where new types of production are being developed, innovative technologies (including the so-called «nano») are being introduced, new raw material deposits are being developed, environmental standards are being developed and put into operation. This naturally leads to a corresponding increase in the volume of production, and therefore the scale of pollution of environment with harmful substances and waste, as well as the progressive depletion of non-renewable natural resources. The intense component of such an impact is largely determined by the overall increase in the standard of living of the population and the inextricably linked increase in the demand for industrial products, including consumer goods, food, infotainment and so on [4, 5].

For implementation of complex assessment of magnitudes of indicators of ecological safety (ES) level of the exploitation process of power plants (PP) with reciprocating internal combustion engines (RICE) [6], namely vehicles, which are powerful sources of negative influence on environment [7], it is rational to use the mathematical apparatus of complex fuel and ecological criterion of Prof. I. V. Parsadanov K_{fe} (NTU «KhPI») [8] that was described in the monograph [9] and improved in the monograph [10] and developed on the basis of technique [11]. There is the main alternative to criterion K_{fe} – mathematical apparatus of integral index of ecology-chemical evaluation of RICE of Prof. P.M. Kanilo (KhNADU) [12]. This criterion was applied in several studies [13–24].

Emission of legislative normalized pollutants in RICE exhaust gas (EG) flow is ES factor that must be reduced and for that special devices are applied for purification of EG flow [6, 9, 10, 12, 25, 26] and other organization and technical measures. It is also well known that processes of thermal utilization of solid domestic wastes are also powerful sources of emissions of pollutants into atmospheric air [27, 28] as well as processes of combustion of pyrotechnics [29] and forest fires [30] that are detected by means of special measuring instruments [31, 32].

It is known that RICE operational process produces significant mass hourly emissions of sulphur dioxide SO_2 and polycyclic aromatic hydrocarbons (PAH) including benzo(a)pyrene (B(a)P) as toxic and carcinogenic pollutants [35 – 37]. Taking into account the fact that significant part of EG flow consists of products of completed combustion of motor fuel, namely CO_2 and H_2O, and also that the separate RICE is not powerful source of SO_2, PAH and B(a)P emission but their role and part in world energy balance (at to 70 % [9]) it is possible to conclude that evaluation of such emissions in complex calculated assessment of magnitudes of ES level indicators of PP with RICE exploitation process is scientific and technical problem, the relevance of which has no doubt.

It should be noted that obtained results can be the basis for the implementation of state regulation in the field of ES ensuring, as, for example, in the field of advertising [32] and other economic aspects of complex criteria-based assessment [33].

Purpose of the study. Obtaining of magnitudes of integral index of ecology-chemical evaluation characterizing the ES level of diesel engine exploitation process with taking into account the emissions of sulphur oxides, benzo(a)pyrene and polycyclic aromatic hydrocarbons as the toxic and carcinogenic pollutants.

Problem of the study. Obtaining of distribution of magnitudes of integral index of ecology-chemical evaluation for autotractor diesel engine 2Ch10.5/12 [39] on the standardised steady testing cycle ESC (UENCE Regulations No. 49 [38]) taking into account the emissions of sulphur oxides, benzo(a)pyrene and polycyclic aromatic hydrocarbons as the toxic and carcinogenic pollutants.

Object of the study. Ecological safety of diesel engine exploitation process, the exploitation model of which corresponds to testing cycle ESC.

Subject of the study. Influence of emissions of sulphur oxides, benzo(a)pyrene and polycyclic aromatic hydrocarbons as the toxic and carcinogenic pollutants on qualitative and quantitative aspects of object of the study.

Methods of the study. Analysis of specialized scientific and technical, reference and normative literature, analysis of results of motor bench tests, basics of scientific discipline «Theory of RICE», «Theory of ESMS», «Environment protection technologies», improved mathematical apparatus of complex fuel and ecological criterion, improved mathematical apparatus of integral index of ecology-chemical evaluation, method of least squares.

Tasks of the study.

1. Analysis of features of complex fuel and ecological criterion, integral index of ecology-chemical evaluation and standardised steady testing cycle ESC.

2. Obtaining of initial data set for implementing of calculated assessment for standardised steady testing cycle ESC and diesel engine 2Ch10.5/12 as a part of emergency and rescue vehicle.

3. Improving of application techniques for assessing of magnitudes of mass hourly emissions of sulphur oxides, benzo(a)pyrene and polycyclic aromatic hydrocarbons with RICE EG flow and potenderability of such ES factor as the toxic pollutant and as the carcinogenic substances.

4. Calculated assessment of magnitudes of integral index of ecology-chemical evaluation for standardised steady testing cycle ESC and analysis of its results.

Scientific novelty of obtained results. Received further development of the approach of Prof. P.M. Kanilo for criteria-based assessment of ecology-chemical efficiency of autotractor diesel engines exploitation process as a part of emergency and rescue vehicle taking into account of mass hourly emissions of sulphur oxides, benzo(a)pyrene and polycyclic aromatic hydrocarbons with RICE EG flow as the toxic pollutants and as the carcinogenic substances and also techniques for determination of such emissions and ponderability of such pollutants in direction of application of this mathematical apparatus for standardised steady testing cycles.

Practical value of obtained results. Obtained results are suitable for providing the qualitative and quantitative assessment of ES level of different types of diesel engine exploitation process taking into account the emissions of sulphur oxides, benzo(a)pyrene and polycyclic aromatic hydrocarbons with RICE EG flow as the toxic pollutant and as the carcinogenic substances.

1. Analysis of mathematical apparatus of integral index of ecology-chemical evaluation of RICE of Prof. P.M. Kanilo

In studies of Prof. P.M. Kanilo (KhNADU) [12–15] he has proposed the integral index of ecology-chemical evaluation of RICE and degree of efficiency of its improving that in accordance with developed by author of this study classification of criteria-based mathematical apparatuses that are suitable for implementation of complex calculated assessment of operation efficiency of ES management system (ESMS) of the process of accident-free exploitation process that was developed by author in study [8] related to types of causal or internal.

Magnitudes of the index F for one complete cycle on testing of RICE of the test bench with running drums are determined by formula (1) [12, 16]:

$$F_j = 10^{-3} \times \left\{ \begin{aligned} &\left(\begin{aligned} &\frac{M_{CO}}{[CO]} + \frac{M_{CH}}{[CH]} + \\ &+ a \cdot \frac{M_{NO_2}}{[NO_2]} + b \cdot \frac{M_{Soot}}{[Soot]} \end{aligned} \right) + \\ &+ \left(c \cdot \frac{M_{SO_2}}{[SO_2]} + d \cdot \frac{\Sigma CA_{(EG)}}{[B(a)P]} \right) \end{aligned} \right\}_{tc} \qquad (1)$$

where M_k – mass of emission of k-th pollutant during one complete cycle on testing of RICE (see index «*ts*»), kg/cycle; $[k] = [MPC_k]_{dn}$ – maximum permissible concentration of k-th pollutant, kg/m^3; a = 3,0; b = 3,0; c = 2,0; d = 4,0 – coefficients that take into account the further intensification of the total effect of toxic and carcinogenic substances in the composition of EG of RICE on humans.

In this study modified variant of formula (1) was used, i.e. index F. Instead of the values of mass of emission of k-th pollutant during one complete cycle on testing of RICE M_k (in kg/cycle) author proposes to use in it the values of mass hourly emission of of k-th pollutant G(k) on individual regime of exploitation model (in kg/h). Such approach allows excepting solution of problem of absence of initial data of appropriate type (i.e. values of M_k) and also obtaining the individual regime values of index F that is values for each separate representative steady operational regime of RICE exploitation model. Because of this, the index F gets the dimension [kg/h] / [kg/m^3] = [m^3/h].

The main problem of application of index F and formula (1) is the uncertainty of magnitudes of empirical coefficients a, b, c and d for RICE of different types and models besides those, for which studies described in monograph [12] were carried out. It this study the values of the empirical coefficients recommended in Prof. Kanilo`s studies were used.

Index F is the alternative to complex fuel-ecology criterion of Prof. I.V. Parsadanov K_{fe}.

In this case the need for determination of middle exploitation value of index F appears. In this study author proposes to obtain it as the weighted arithmetic mean i.e. by the formula (2).

$$F = \sum_{i=1}^{N}\left(F_i \cdot WF_i\right) / \sum_{i=1}^{N}\left(WF_i\right); \sum_{i=1}^{N}\left(WF_i\right) = 1{,}0 . \qquad (2)$$

2. Obtaining an initial data set for a standardised steady test cycle ESC

Several approaches for performing the criteria-based assessment of the ES level of PP with RICE exploitation process are known and described in the studies [8, 10] and the technique [11].

Standardised steady testing cycle ESC (European Steady Cycle) described in standard [38] is used to build a test program for passenger vehicles and contains 13 steady regimes of RICE operation.

Parameters of ESC cycle regimes for 2Ch10.5/12 diesel engine according to [38] are determined by the formula (3) (see Fig. 1):

$$n_k = n_{lo} + G \cdot \left(n_{hi} - n_{lo}\right), \text{ rpm}; \qquad (3)$$

where n_{lo} i n_{hi} – low and high crankshaft speed i.e. minimal crankshaft speed at what RICE effective power reaches 50 % and 75 % of its declared nominal magnitude, rpm; at k = A → G = 0,25; at k = B → G = 0,50; at k = C → G = 0,75.

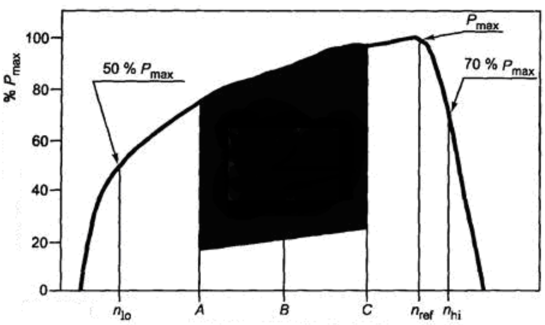
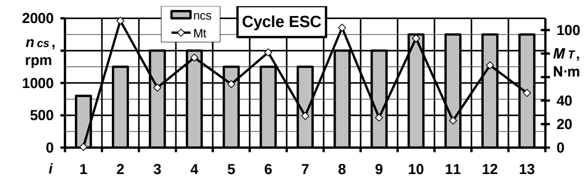


Figure 1 – Distribution of parameters of standardised steady testing cycle ESC on operational regimes field of diesel engine [38]

For 2Ch10.5/12 diesel engine the maximum effective power is 21 kW reached at M = 110 N·m та n_{cs} = 1800 rpm [39]. Using the results of analysis of the diagram of operation of this disel engine we obtain following initial data: n_{lo} = 1000 rpm, n_{hi} = 2000 rpm, than: n_A = 1250 rpm, n_B = 1500 rpm, n_C = 1750 rpm. In this case: $M_{A\max}$ = 108 N·m, $M_{B\max}$ = 102 N·m, $M_{C\max}$ = 93 N·m, than: $N_{eA\max}$ = 14,136 kW, $N_{eB\max}$ = 16,021 kW, $N_{eC\max}$ = 17,042 kW.

Also from analysis of results of motor bench tests of D21A1 (2Ch10.5/12/12 in accordance with ISO 3046-1:2002) diesel engine performed in the Laboratory of Piston Power Plants of Department of Hydrogen Energy of A. Pidgorny Institute for Mechanical Engineering Problems of NAS of Ukraine (Kharkiv) initial data were taken for regimes of ESC testing cycle, which are illustrated at Fig. 2 (technical and economical indicators) and Fig. 3 (ecological indicators).



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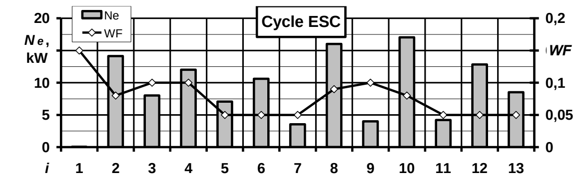

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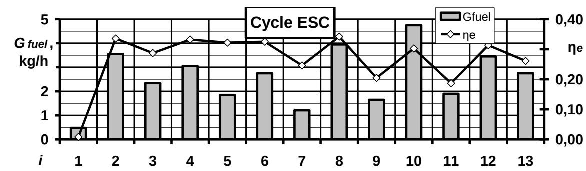
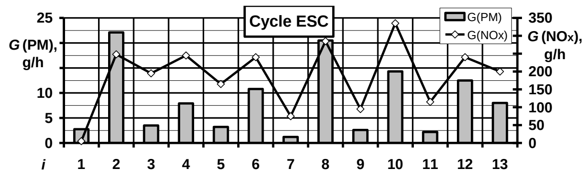


c

Figure 2 – Distribution of magnitudes of values of technical and economical indicators of operation of 2Ch10.5/12 diesel engine on regimes of ESC testing cycle



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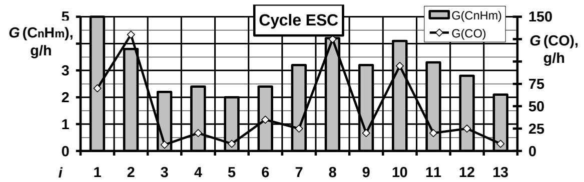

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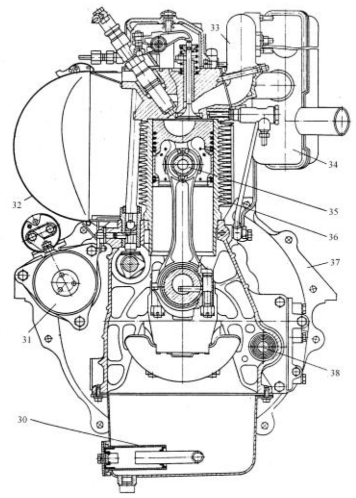
Figure 3 – Distribution of magnitudes of values of economical indicators of operation of 2Ch10.5/12 diesel engine on regimes of ESC testing cycle

Distribution of magnitudes of values of coordinates of operational regimes field – *M* and n_{cs} – on Fig. 2,a, effective power N_e and weight factor *WF* – on Fig. 2,b, mass hourly consumption of motor fuel G_{fuel} and effective efficiency coefficient η_e – on Fig. 2,c, mass hourly emission of particulate matter *G*(PM) and nitrogen oxides $G(NO_x)$ – on Fig. 3,a, mass hourly emission of unburned hydrocarbons $G(C_nH_m)$ and carbon monoxide *G*(CO) – on Fig. 3,b.

Studies [16–24] performed together by Prof. P.M. Kanilo and Assoc. Prof. M.V. Sarapina are dedicated to such topic to one degree or another.

Technical characteristic of 2Ch10.5/12 diesel engine is contained in source [39].

Diesel engine D21A1 (2Ch10.5/12 in accordance with GOST 10150–2014 «Reciprocating internal combustion engines. General technical requirements») is autotractor non supercharged air-cooled two-cylinder in-line four-stroke two-valve reciprocating ICE with internal mixture formation and ignition of compression, with traditional trunk axial crankshaft mechanism, with cylinder diameter 105 mm, piston stroke 120 mm and connecting road length 270 mm, working volume 2.0 l, compression degree 16.5, nominal effective power (at 1800 rpm) 21_{-3} kW, maximum torque 111 N·m (at 1200 rpm), with specific effective mass hourly fuel consumption 235 g/(kW·h), with undivided hemispherical combustion chamber in the piston and direct injection, with one-plunger high pressure fuel pump of distribution type, hydromechanical nozzles and all-regimes mechanical regulator, with mass 280 kg and overall dimensions 693×687×855 mm, with starting by electric starter. It was produced by Vladimir Tractor Plant and used for driving tractors, self-propelled chassis and breeding combines, asphalt and concrete pavers, mobile electric welding, water pumping and air compressor stations [39]. Longitudinal section and cross-section of such diesel engine are illustrated on Fig. 4 [39].



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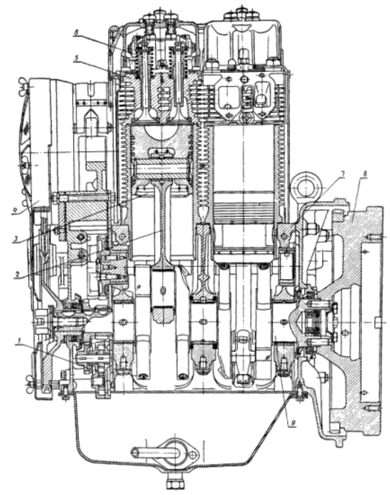


b

Figure 4 – Longitudinal section and cross-section of 2Ch10.85/12 diesel engine [39]

4.2. Technique of calculated evaluation of magnitudes of integral index of ecology-chemical evaluation of RICE with taking into account of emission of sulphur oxides, benzo(a)pyrene and PAH

From specialized literature [6, 9, 10, 12, 25, 26, 35–38] it is well known that in the structure of PM as the legislative normalized pollutant in composition of EG of RICE are contained different types of PAH in number of which is B(a)P what, firstly, is not legislative normalized pollutant in EG composition but at the same time, secondly, is the indicator of presence of PAH in EG and, thirdly, is the strongest and most typical carcinogen in environment, toxicant and mutagen, so because of that assigned to the first class of danger.

B(a)P is chemical compound that has chemical formula $C_{20}H_{12}$ (registration No. CAS 50-32-8, PubChem 2336, EINECS 200-028-5, ChEBI 29865, ChemSpider 2246) and magnitude of molar mass 252.3 g/mole, at the normal conditions (25 °C, 100 kPa) is the solid crystalline substance with pale yellow colour with magnitude of density 1.24 g/dm^3, magnitude of melting temperature 179 °C, boiling temperature 495 °C, has poor solubility in water $6.2\cdot10^{-5}$ g/100 ml [35–38].

Structure of B(a)P molecule is illustrated at Fig. 5.

In accordance with hygienic standard 2.1.6.3492-17 «Maximum permissible concentrations (MPC) of pollutants in the air of urban and rural settlements» that approved on 12/22/2017 MPC_{ad}(B(a)P) = 10^{-6} mg/m^3. In accordance with hygienic standard 2.1.7.2041-06 in the soil MPC(B(a)P) = $2\cdot10^{-2}$ mg/kg. In accordance with regulations TPTC 021/2011 containment of B(a)P in different foods should not exceed 0.2 – 5.0 μkg/kg.

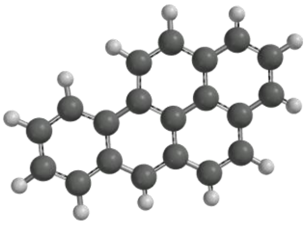


Figure 5 – Structure of B(a)P molecule [35]

For carrying out of complex criteria-based assessment of ES level of exploitation process of PP with RICE, namely vehicles, it is rational to use one of the two following mathematical apparatuses which are most suitable for implementation of such scientific task.

1. Complex fuel and ecological criterion of Prof. I.V. Parsadanov K_{fe} described in monograph [9] and improved in monograph [10].

2. Integral index of ecology-chemical evaluation of RICE of Prof. P.M. Kanilo F described in monograph [12].

For such studies it is necessary to obtain the magnitude of ponderability of values of mass hourly emissions G(B(a)P) and G(PAH) in comparison with ponderability of value of mass hourly emission of reference pollutant G(CO), which is determined by the magnitude of dimensionless indicator of the relative aggressiveness of the k-th pollutant A_k, which is determined by formulas (4) and (5) according to technique [11]:

$$A_k = a_k \cdot \alpha_k \cdot \beta_k \cdot \delta_k , \quad (4)$$

$$a_k = \sqrt{\frac{MPC_{ad}(CO) \cdot MPC_{ot}(CO)}{MPC_{ad}(k) \cdot MPC_{ot}(k)}} , \quad (5)$$

where a_k – index of relative danger of presence of k-th gaseous or aerosol pollutant in atmospheric air that a human breathes; α_k – corrective that takes into account the probability of accumulation of k-th gaseous or aerosol pollutant in environment components, trophic chains and admission to the human body by non-inhalation way; β_k – corrective that takes into account the probability of formation of other (secondary) pollutants, more harmful than the original, by the source of the k-th gaseous or aerosol pollutant emitted into the atmosphere; δ_k – corrective that takes into account the impact of k-th gaseous or aerosol pollutant on other recipients except human; MPC_{ad}(CO) and MPC_{ot}(CO), $MPC_{ad}(k)$ and $MPC_{ot}(k)$ – maximum permissible concentration of reference (A_{CO} = 1.0, MPC_{ad}(CO) = 3.0 mg/m^3, MPC_{ot}(CO) = 20.0 mg/m^3) and k-th pollutant in air average day-and-night and maximum one-time, mg/m^3.

In [12] information is contained about components of formulas (4) and (5) for value A(B(a)P) that is given in Table 1 and illustrated at Fig. 6. Thus, value A(B(a)P) is equal to 12.6·10^5, which is 6 orders of magnitude greater than for reference pollutant A(CO), 5 orders of magnitude greater than $A(NO_x)$ and $A(C_nH_m)$, and 4 orders of magnitude greater than A(PM).

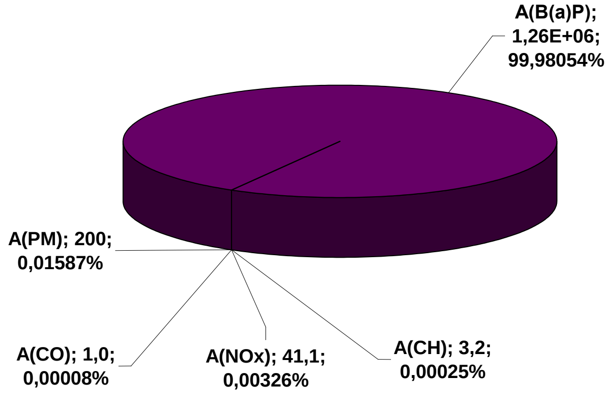
At Fig. 6 and in Table 1 you may see that in case of considering of magnitudes of value of G(B(a)P) in criteria-based assessment the magnitude of value $A(PM)$ is about 1.587·10^{-2} % from total ponderability of ecological component of criterion K_{fe}, magnitude of value $A(NO_x)$ – 3.262·10^{-3} %, magnitude of value $A(CO)$ – 7.932·10^{-5} % and the rest of such ponderability 99.981 % accounted for magnitude of value A(B(a)P).

In case of considering of magnitudes of value of G(PAH) the ponderability of such pollutant is 0.990 % from total ponderability and for value A(PM) – 1.571·10^{-2} %, value $A(NO_x)$ – 3.232·10^{-3} %, value $A(C_nH_m)$ – 2.503·10^{-4} %, value A(CO) – 7.826·10^{-5} %, value A(B(a)P) – 98.991 %.

Structure of ponderability of complete set of ES factors considered in ecological component of criterion K_{fe}, discussed in this study, is illustrated at Fig. 7.

Table 1 – Parameters of B(a)P as the pollutant in composition of EG of diesel RICE [12]

Pollutant	Indicator				
	a_k	α_k	β_k	δ_k	A_k
CO	1.0	1.0	1.0	1.0	1.0
C_nH_m	0.63	1.0	5.0	1.0	3.16
NO_2	27.4	1.0	1.0	1.5	41.1
SO_2	11.0	1.0	1.0	2.0	22.0
C (Soot)	17.5	2.0	1.0	1.2	41.5
PM	–	–	–	–	200
B(a)P	6.3·10^5	2.0	1.0	1.0	12.6·10^5
PAH	6.3·10^5	2.0	1.0	1.0	12.6·10^3



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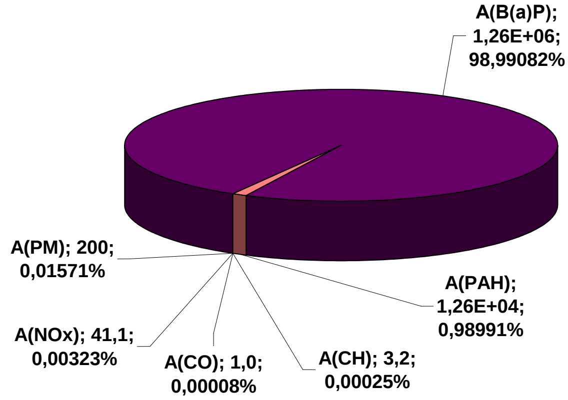

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Figure 6 – Structure of ponderability of complete set of ES factors considered in ecological component of criterion K_{fe} with taking into account of emissions of B(a)P (a) and PAH (b)

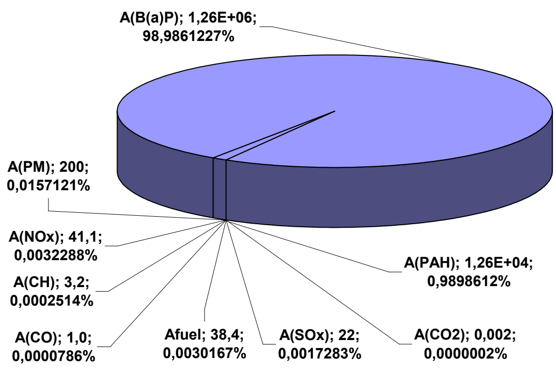


Figure 7 – Structure of ponderability of complete set of ES factors considered in ecological component of criterion K_{fe} with taking into account except of emissions of B(a)P and PAH also emissions of CO_2, SO_x and consumption of motor fuel G_{fuel}

At Fig. 7 it can be seen that in the structure of total ponderability of ecological component of criterion K_{fe} the contribution of separate considered ES factors is following: 98.986 % for A(B(a)P), 0.989 % for A(PAH), $1.571\cdot10^{-2}$ % for A(PM), $3.229\cdot10^{-3}$ % for $A(NO_x)$, $2.514\cdot10^{-4}$ % for $A(C_nH_m)$, $7.862\cdot10^{-5}$ % for A(CO), $3.017\cdot10^{-3}$ % for A_{fuel}, $1.728\cdot10^{-3}$ % for $A(SO_x)$ and $2.122\cdot10^{-7}$ % for $A(CO_2)$.

Information about the value of A(B(a)P) can be obtained from sources [12, 16–24] according to the following considerations.

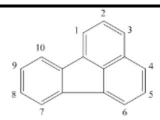
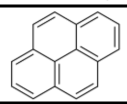
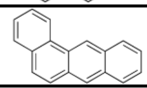
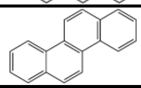
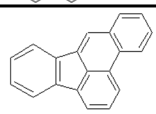
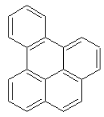
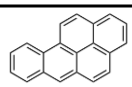
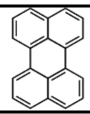
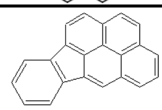
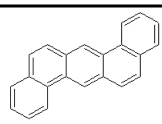
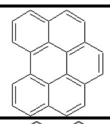
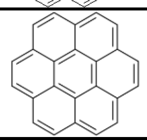
In study [16] it is firmly determined that B(a)P is the indicator of presence of another PAH in composition of RICE EG flow an obtained correlation dependences between magnitudes of value G(PAH) for all of this ingredients and value G(B(a)P). These correlations is degree dependences in form of formula (6) that was linearized in form of formula (7):

$$m_j = a_1 \cdot m_{B(a)P}^{a_2}\ , \ \mu\text{kg/test}; \qquad (6)$$

$$m_j = a_3 \cdot m_{B(a)P}\ , \ \mu\text{kg/test}. \qquad (7)$$

Information about the list of ingredients of PAH of priority group in composition of EG, magnitudes of their carcinogenic activity index *CAI*, and magnitudes of coefficients in formula (6) is summarised in Table 2.

Table 2 – Parameters of PAH of priority group in EG composition for gasoline RICE for testing on cycle EDC [16, 35 – 37]

PAH of priority group	Chemical formula	Class of hazard	Structural formula	Indicator			
				ICA	*a*1	*a*2	*a*3
Fluoranthene	$C_{16}H_{10}$	–		< 0.01	6.2	1.06	–
Pyrene	$C_{16}H_{10}$	I		< 0.01	8.6	1.07	–
Benzo(a)antrathene	$C_{18}H_{12}$	–		0.01	0.55	1.22	–
Chrysen	$C_{18}H_{12}$	–		0.01	2.46	1.24	–
Benzo(b)fluoranthene	$C_{20}H_{12}$	–		0.1	0.94	1.20	–
Benzo(e)pyrene	$C_{20}H_{12}$	–		< 0.01	0.59	1.17	–
Benzo(a)pyrene	$C_{20}H_{12}$	**I**		**1.0**	**1.0**	**1.0**	**–**
Perilen	$C_{20}H_{12}$	–		< 0.01	0.59	0.87	–
Indeno[1,2,3-c,d]pyrene	$C_{22}H_{12}$	–		< 0.01	0.37	1.22	–
Dibenzo(a,h)anthracene	$C_{22}H_{14}$	–		< 0.01	0.36	1.23	–
Benzo(g,h,i)perilene	$C_{22}H_{12}$	–		0.01	0.94	1.20	–
Coronene	$C_{24}H_{12}$	–		< 0.01	0.69	1.06	–
$M_{\Sigma PAH}$	–	–	–	–	22.85	1.11	34.6
$M_{\Sigma PAH(K)}$	–	–	–	–	5.8	1.20	11.93
ΣCA(EG)	–	–	–	–	1.12	1.04	1.28

In Table 2 for the number of carcinogenic related PAH with magnitude of *CAI* ≥ 0,01 (marked as PAH(K)), by value $M_{\Sigma PAH}$ is marked the total emission of carcinogenic PAH and by value ΣCA(EG) – carcinogenic activity of EG determined by formula (8):

$$\Sigma CA_{(EG)} = \sum_{j=1}^{m}\left(CAI_j \cdot m_j\right). \quad (8)$$

Besides in the study [16] they have also obtained the formula (9) that connects magnitudes of mass emission of B(a)P in EG flow for gasoline engine $m_{Б(А)П}$ and mass part of PAH in motor fuel C_{PAH}:

$$m_{B(a)P} = 0{,}87 \cdot C_{PAH} + 3{,}3,\ \mu\text{kg/test}. \quad (9)$$

In study [12] was detected that: relation between magnitudes of mass emission of B(a)P and other PAH in EG composition is correlated as well for gasoline RICE as for diesel RICE; relation between magnitudes of mass emission of B(a)P for gasoline RICE and for diesel RICE k_{RICE} is about 5.0 i.e. in equal volume of EG of diesel RICE emitted almost in 5 times more B(a)P than in EG of gasoline RICE.

That's why in this study it is accepted that magnitude of dimensionless index of relative aggressiveness of PAH except B(a)P A_{PAH} can be determined as product of magnitude of relative aggressiveness index of B(a)P $A_{B(a)P}$ and magnitude of ratio of averaged *CAI* for PAH (equals 0.01) and B(a)P (equals 1.0) (see formula (10)):

$$A_{PAH} = k_{CAI} \cdot A_{B(a)P} = CAI_{PAH} / CAI_{B(a)P} \cdot A_{B(a)P} = 0.01 / 1.0 \cdot 12.6 \cdot 10^5 = 12.6 \cdot 10^3. \quad (10)$$

The next unsolved task of this study was to obtain individual regime magnitudes of mass hourly emission of B(a)P *G*(B(a)P) and PAH *G*(PAH) for 2Ch10.5/12 diesel engine. For solution of this task we need to obtain the middle exploitation magnitude of such emissions and character of distribution of such emissions on operational regimes field of specified RICE.

For determination of middle exploitation magnitude of emissions *G*(B(a)P) and *G*(PAH) in this study author used magnitudes of their ratio described by linearized formula (9) with magnitudes of coefficients from Table 2 and also magnitude of ratio between magnitudes of emissions of B(a)P for diesel and gasoline RICE k_{RICE} = 5.0 [12].

The basis of proposed approach for obtaining of individual regime magnitudes of value *G*(B(a)P) is ratio between middle exploitation magnitudes of $G(B(a)P)_{me}$ and another legislative normalized pollutant-prototype namely that distribution on RICE operational regimes field of what will repeat this distribution of magnitude of *G*(B(a)P).

For determination of form of distribution of magnitudes of value *G*(B(a)P) on RICE operational regimes field it is proposed to suggest that this distribution in the form completely replicates this distribution for another legislative normalized pollutant-prototype in EG composition.

As such pollutant-prototype it is proposed to choose either unburned hydrocarbons C_nH_m or particulate matter PM. The uncertainty in the selection of the pollutant-prototype is explained with the fact, that the PAH, which include B(a)P, are heavy hydrocarbons, which, at the EG temperature is characterized with a live cross-section of their flow in the plane of the output flange of the RICE exhaust manifold, may be in a gaseous state and at the EG temperature characterized with a live cross-section of their flow in the plane of the cut-off of the RICE exhaust pipe are mostly in the liquid state and make up both separate fractions of PM and adsorbed on PM with soot cores.

Therefore, determination of the individual regime magnitudes of value *G*(B(a)P) is possible by menas of the formulas (11) or (12), and the value of *G*(PAH) may be determined by the formula (13):

$$G(B(a)P) = G(B(a)P)_{me} / G(C_nH_m)_{me} \cdot k_{RICE} \times G(C_nH_m)(n_{cs}; M); \quad (11)$$

$$G(B(a)P) = G(B(a)P)_{me} / G(PM)_{me} \cdot k_{RICE} \times G(PM)(n_{cs}; M); \quad (12)$$

$$G(PAH) = (a_3 - 1{,}0) \cdot G(B(a)P). \quad (13)$$

According to materials of studies [12, 16–24] it was determined that for diesel engines magnitude of ratio between values $G(B(a)P)_{me}$ and $G(PM)_{me}$ in average is about ($6.5 \cdot 10^{-3}$ g/h / 50.0 g/h) = $1.3 \cdot 10^{-4}$ and ratio between values $G(PM)_{me}$ and $G(C_nH_m)_{me}$ is 2.775 (see monograph [31]), so magnitude of coefficient k_{RICE} in this study was established as 5.0 and coefficient a_3 – 11.93. Than formulas (11)–(13) are converted to formulas (14)–(16):

$$G(B(a)P) = 18.0 \cdot 10^{-4} \cdot G(C_nH_m)(n_{cs}; M); \quad (14)$$

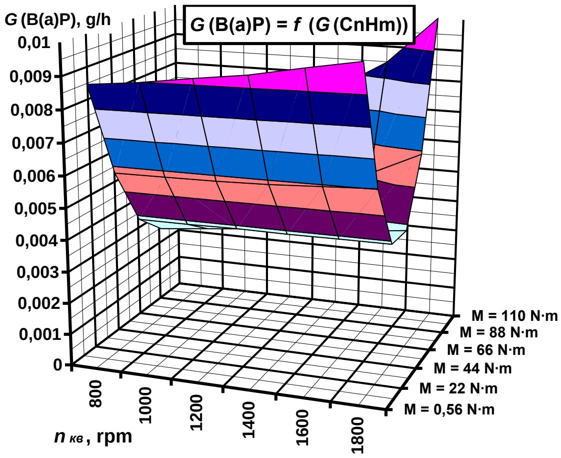
$$G(B(a)P) = 6.5 \cdot 10^{-4} \cdot G(PM)(n_{cs}; M); \quad (15)$$

$$G(PAH) = 10.93 \cdot G(B(a)P). \quad (16)$$

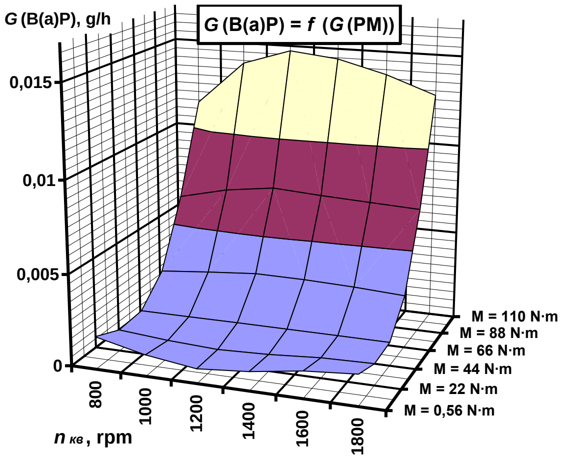
Thus, distributions of magnitudes of values *G*(B(a)P) and *G*(PAH) on operational regimes field of 2Ch10.5/12 autotractor diesel engine obtains with using of proposed approach (see formulas (14) – (16)) are illustrated at Fig. 8 and 9.

At Fig. 8,a it can be seen that magnitude of value *G*(B(a)P) repeating the pattern of distribution on operational regimes field of 2Ch10.5/12 diesel engine of magnitude of value $G(C_nH_m)$ reaches maximum equal to 0.01 g/h on regime of nominal effective power and minimum equal to 0.0038 g/h on regime in the middle of external speed characteristics and is. At Fig. 8,b it can be seen that magnitude of value *G*(B(a)P) repeating the pattern of distribution on operational regimes field of 2Ch10.5/12 diesel engine of magnitude of value *G*(PM) reaches maximum equal to 0.015 g/h on regime of maximum torque and minimum equal to 0.0015 g/h on regime in the middle of idle characteristics.

At Fig. 9,a it can be seen that magnitude of value *G*(PAH) repeating the pattern of distribution on operational regimes field of 2Ch10.5/12 diesel engine of magnitude of value $G(C_nH_m)$ reaches maximum equal to 0.1 g/h on regime of nominal effective power and minimum equal to 0.042 g/h on regime in the middle of external speed characteristics.

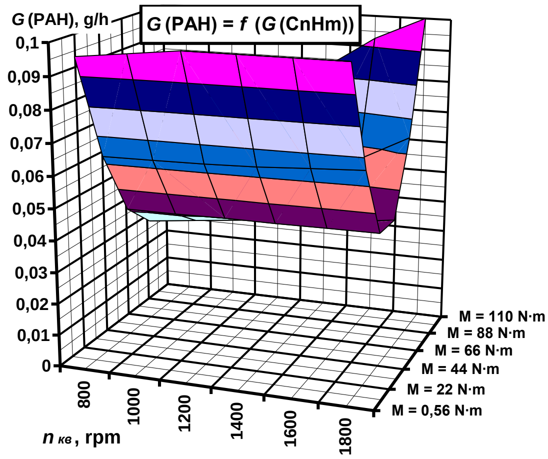


a

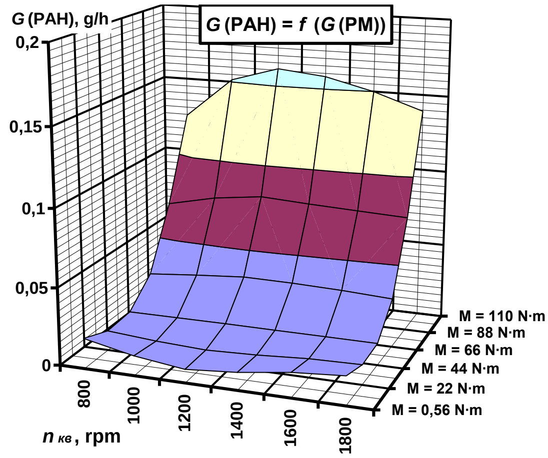


b

Figure 8 – Distribution of magnitudes of values G(B(a)P) = f (G(C_nH_m)) (a) and G(B(a)P) = f (G(PM)) (b) on operational regimes field of 2Ch10.5/12 autotractor diesel engine



a



b

Figure 9 – Distribution of magnitudes of values G(PAH) = f (G(C_nH_m)) (a) and G(PAH) = f (G(PM)) (b) on operational regimes field of 2Ch10.5/12 autotractor diesel engine

At Fig. 9,b it can be seen that magnitude of value G(PAH) repeating the pattern of distribution on operational regimes field of 2Ch10.5/12 diesel engine of magnitude of value G(PM) reaches maximum equal to 0.175 g/h on regime of maximum torque and minimum equal to 0.020 g/h on regime in the middle of idle characteristics.

Distribution of individual regime magnitudes of values G(B(a)P) and G(PAH) for both of studied types of forms of distribution on 2Ch10.5/12 diesel engine operational regimes field for regimes of standardised steady testing cycle ESC is illustrated at Fig. 10.

For following calculation study following types of distribution were chosen: G(B(a)P) = f (G(PM)) and G(PAH) = f (G(PM)).

At Fig. 10 it can be seen that maximum magnitude of emissions G(B(a)P) and G(PAH) repeating the pattern of distribution on operational regimes field of 2Ch10.5/12 diesel engine of magnitude of value G(PM) for regimes of testing cycle ESC is observed on regime of maximum torque (No. 2, n_{cs} = 1250 rpm, M = 110 N·m) and equal to 0.0145 g/h and 0.16 g/h respectively. On regime of nominal effective power (No. 10, n_{cs} = 1750 rpm, M = 95 N·m) such magnitudes are 0.0095 g/h and 0.15 g/h. Minimal magnitude of emissions observed on regime of low effective power (No. 7, n_{cs} = 1250 rpm, M = 27 N·m) are 0.0007 g/h and 0.008 g/h. On regime of minimal idle (No. 1, n_{cs} = 750 rpm, M = 0 N·m) such magnitudes are 0.0018 g/h and 0.025 g/h.

In structure of formula (1) there is the mass emission of sulphur oxides SO_x in RICE EG flow. Magnitude of ponderability of such pollutant A(SO_x) in this study were obtained from monograph [12] (see Table 1).

At Fig. 11 structure of ponderability of ES factors in ecological component of criterion K_{fe} is illustrated both with and without taking into account emission of SO_x.

Magnitude of mass hourly emission G(SO_x) in this study obtained by using technique that was proposed by author in monograph [10].

At Fig. 12 distribution of magnitudes of value G(SO_2) on operational regimes field of diesel engine 2Ch10.5/12 at the basic magnitude of coefficient k_{SO2} = 0.015 is illustrated.

Such magnitude of coefficient k_{SO2} obtained for magnitudes of mass concentration of sulphur in motor fuel C_{sf} = 0.5 %, in motor oil C_{so} = 0.5 % and at magnitude of relative costs of motor oil on fumes C_{fo} = 0.5 %.

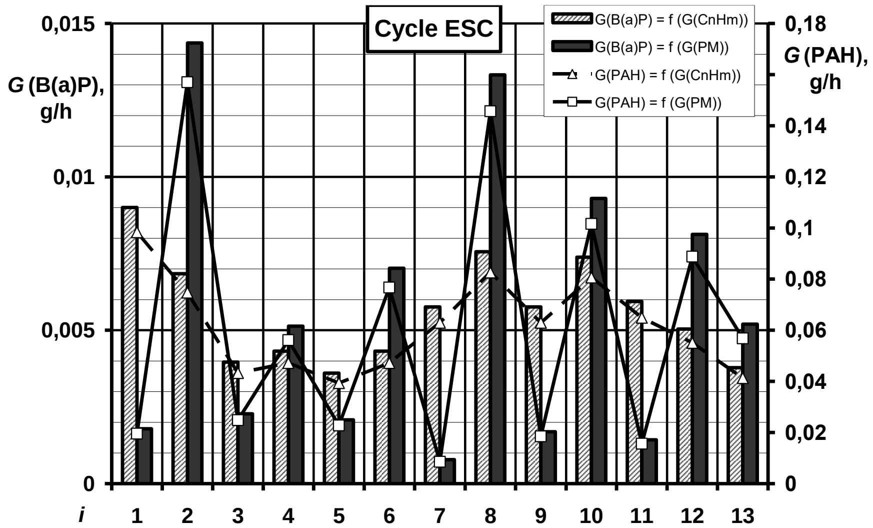
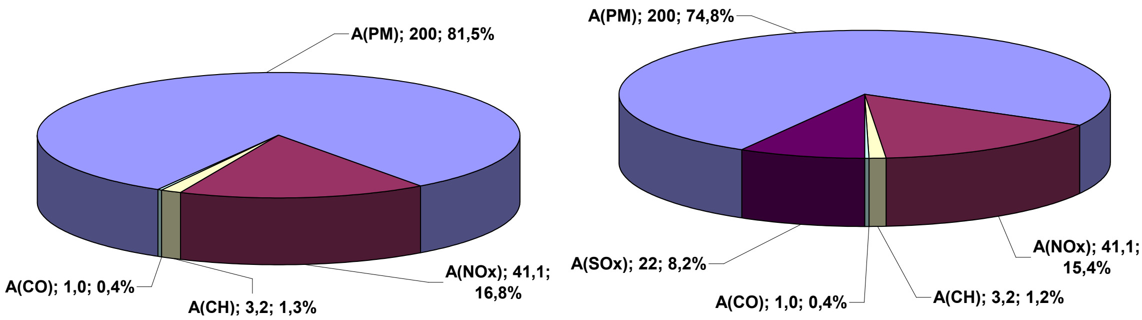


Figure 10 – Distribution of individual regime magnitudes of values G(B(a)P) = f (G(C_nH_m)) and G(B(a)P) = f (G(PM)), G(PAH) = f (G(C_nH_m)) and G(PAH) = f (G(PM)) for regimes of standardised steady testing cycle ESC 2Ch10.5/12 autotractor diesel engine



a b

Figure 11 – Structure of ponderability of ES factors in ecological component of criterion K_{fe} taking into account of emission of SO_x (a) and without taking into account of such pollutant (b) [10]

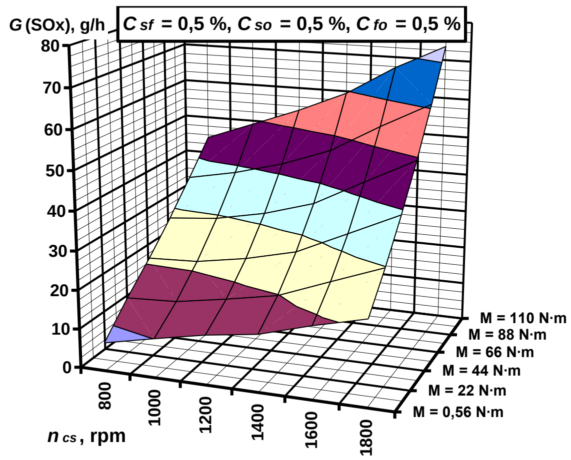


Figure 12 – Distribution of magnitudes of value $G(SO_2)$ on operational regimes field of diesel engine 2Ch10.5/12 at the basic magnitude of coefficient k_{SO2} = 0.015 [10]

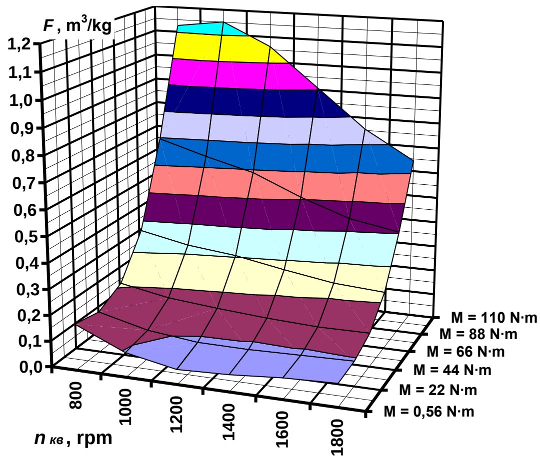


Figure 13 – Distribution of magnitudes of index F on operational regimes field of diesel engine 2Ch10.5/12

At Fig. 12 it can be seen that such distribution has nonlinear character and maximum magnitudes of emission $G(SO_2)$ = 75 g/h are reached on regime of nominal effective power (when magnitudes of mass hourly consumption of motor fuel G_{fuel} and costs of motor oil on fumes also has maximum) and minimal magnitudes 6 g/h – on regime of minimal idle.

At Fig. 13 distribution of magnitudes of index F on operational regimes field of diesel engine 2Ch10.5/12 obtained by formula (1) is illustrated.

At Fig. 13 it can be seen that such distribution is uneven, minimal magnitude 0.058 (i.e. the one characterized with the highest ecology-chemical efficiency of 2Ch10.5/12 diesel engine exploitation process) the index F is reached on regime in the middle of idle characteristic and maximum magnitude 1.151 (i.e. the one characterized with the lowest ecology-chemical efficiency of 2Ch10.5/12 diesel engine exploitation process) – on regime on external speed characteristic between regimes of maximum torque and nominal effective power.

At Fig. 14 distribution of magnitudes of value $G(SO_x)$ and $\delta\Sigma(A_k \cdot G_k)$ on regimes of testing cycle ESC for the basic variant of the study is illustrated.

At Fig. 14 it can be seen that maximum magnitudes of emission $G(SO_x)$ = 73 g/h is observed on regime of nominal effective power (No. 10) and minimal 8 g/h – on regime of minimal idle (No. 1), so on regime of maximum torque (No. 2) such magnitude is 53 g/h.

At Fig. 15 distribution of magnitudes of index F on regimes of ESC testing cycle obtained by formula (1) is illustrated.

At Fig. 15 it can be seen that maximum magnitude of index F = 1.029 is reache on maximum torque regime (No. 2) and minimal F = 0.091 – on regime of low effective power (No. 7), on regime of nominal effective power (No. 10) F = 0.500 and on minimal idle regime (No. 1) – F = 0.178.

Middle exploitational magnitude of index F for ESC testing cycle obtained by formula (2) is 0.373.

It is necessary to note that from structure of formula (1) it can be seen that the larger the index F the lower the ES level of exploitation process of RICE on separate operational regime will be, unlike the complex fuel-ecological criterion of Prof. I.V. Parsadanov K_{fe} and generalized desirability function of K.E. Harrington D [10].

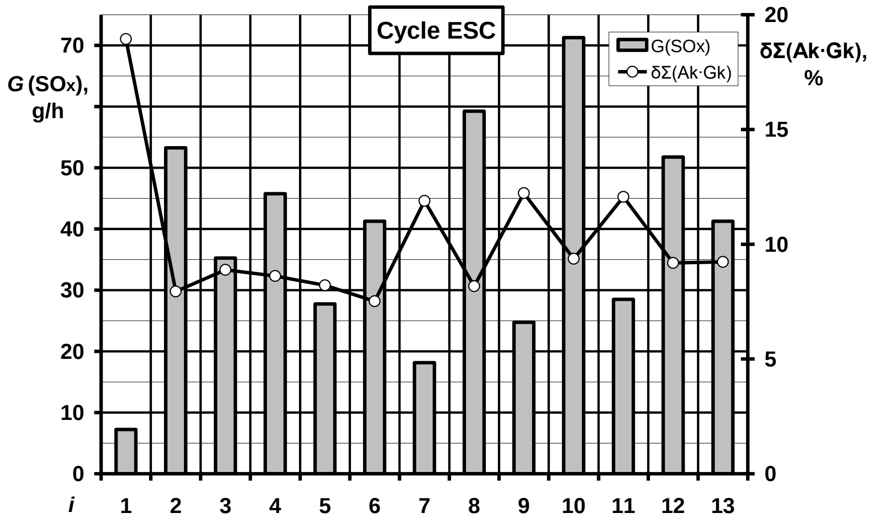


Figure 14 – Distribution of magnitudes of value $G(SO_x)$ and $\delta\Sigma(A_k \cdot G_k)$ on regimes of testing cycle ESC for the basic variant of the study [10]

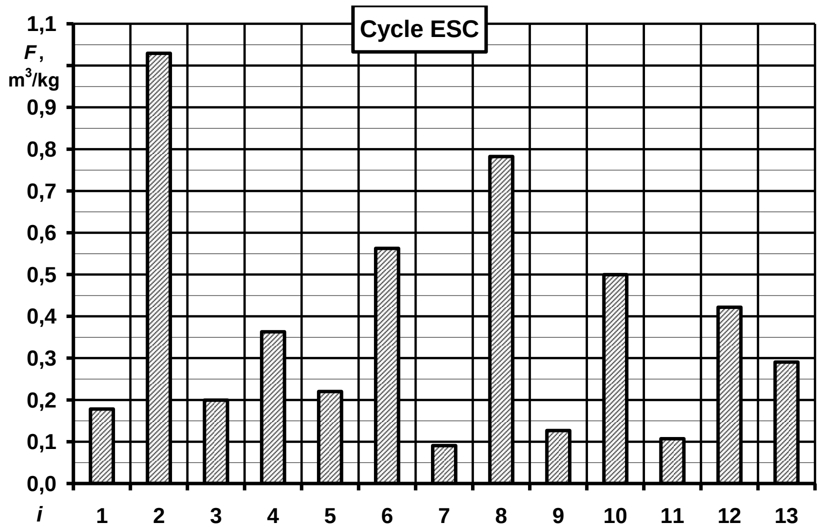


Figure 15 – Distribution of magnitudes of index F on regimes of testing cycle ESC

Conclusions

Thus, in this study a calculated assessment was made for the efficiency of exploitation process of vehicles with diesel RICE by determining the distribution of values of the integral index of ecological-chemical evaluation of Prof. P.M. Kanilo, taking into account the emissions of sulphur oxides, benzo(a)pyrene and other PAH, both on the engine operating regimes field and in the regimes of the standardised steady test cycle ESC. At the same time, it was proposed to improve the technique of determination of emissions of benzo(a)pyrene and other PAH based on analysis of the results of bench motor tests of 2Ch10.5/12 autotractor diesel engine and the scientific works of Prof. P.M. Kanilo.

It is established that, in case of considering of values of mass hourly emission of sulphur oxides, benzo(a)pyrene and other PAH in the criteria-based assessment of ES level of exploitation process of vehicles with diesel RICE with using of mathematical apparatus of the integral indicator of ecological-chemical evaluation, the minimum efficiency is characterized by the maximum torque regime (No. 2, $F = 1.029 = \max$), and by the maximum efficiency – regime with low effective power (No. 7, $F = 0.091 = \min$), the regime of nominal effective power – by average efficiency (No. 10, $F = 0.500$), and the minimal idle regime (No. 1, $F = 0.178$) – by high efficiency. Middle exploitational magnitude of index F for the ESC standardised steady testing cycle is 0.373.

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Conflicts of Interest.

None of the authors has any potential conflicts of interest associated with this present study.

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ОЦІНЮВАННЯ ЕКОЛОГО-ХІМІЧНОЇ ЕФЕКТИВНОСТІ ПРОЦЕСУ ЕКСПЛУАТАЦІЇ ПОРШНЕВОГО ДВЗ ТРАНСПОРТНОГО ЗАСОБУ З УРАХУВАННЯМ ВИКИДІВ ОКСИДІВ СІРКИ, БЕНЗ(а)ПІРЕНА ТА ПОЛІЦИКЛІЧНИХ АРОМАТИЧНИХ ВУГЛЕВОДНІВ

У даному дослідженні вдосконалено запропоновані автором раніше методики визначення значення масових годинних викидів оксидів сірки, бенз(а)пірену та поліциклічних ароматичних вуглеводнів з потоком відпрацьованих газів дизельного двигуна. Отримано розподіли таких викидів по полю робочих режимів автотракторного дизеля 2Ч10,5/12 та по режимах стандартизованого стаціонарного випробувального циклу ESC. Вдосконалено математичний апарат та методику застосування індексу еколого хімічної оцінки ДВЗ проф. П.М. Каніло як альтернативи комплексному паливно-екологічно критерію проф. І.В. Парсаданова. Отримано розподіли значень цього показника рівня екологічної безпеки процесу експлуатації енергоустановок з поршневим ДВЗ по полю робочих режимів автотракторного дизеля 2Ч10,5/12 та по режимах стандартизованого стаціонарного випробувального циклу ESC, а також його середньоексплуатаційне значення. Встановлено, що за умови врахування значень масового годинного викиду оксидів сірки, бенз(а)пірену та інших ПАВ при критеріальному оцінюванні ефективності експлуатації автотранспортного засобу з поршневим ДВЗ за допомогою математичного апарату інтегрального показника екологохімічної оцінки, мінімальною ефективністю характеризується режим максимального крутного моменту (Φ = 1,029), а максимальною ефективністю – режим з малою ефективною потужністю (Φ = 0,091), режим номінальної ефективної потужності – середньою (Φ = 0,500) ефективністю, а режим мінімального холостого ходу (Φ = 0,178) – високою ефективністю. Середньоексплуанаційним значенням критерію Φ для циклу ESC та дизеля 2Ч10,5/12 є 0,373.

Ключові слова: екологічна безпека, технології захисту навколишнього середовища, енергетичні установки, поршневі двигуни внутрішнього згоряння, викиди полютантів, критеріальне оцінювання, оксиди сірки, бенз(а)пірен, поліциклічні ароматичні вуглеводні.

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