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TAKING INTO ACCOUNT THE EMISSIONS OF CO_2 AS A TOXIC POLLUTANT AND AS A GREENHOUSE GAS IN FUEL AND ECOLOGICAL COMPLEX CRITERIA-BASED ASSESSMENT OF DIESEL-GENERATOR OPERATION PROCESS

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Abstract

In this study analyzed the types and features of the known models of exploitation of reciprocating ICE as part of the electric generating power plant, among which the stationary standardized test cycle D2 according to ISO 8178-4: 2017 is selected. A set of initial data is obtained for the calculated criteria-based assessment of the ecological safety level of the exploitation process of power plants with a reciprocating ICE at an example of the autotractor diesel engine 2Ch10.5/12 based on the results of processing of bench motor tests data. The mathematical apparatus of the complex fuel and ecological criterion of prof. I.V. Parsadanov. The calculation methodica for assessment of the values of this criterion has been improved by taking into account the mass hourly emissions of carbon dioxide with the exhaust gases flow from the reciprocating ICE both as pollutant and as greenhouse gas. The calculated assessment of the values of specified criterion was carried out with taking into account carbon dioxide emissions. It has been detected that despite the high values of the hourly mass emission of carbon dioxide as a toxic pollutant, taking it into account when criteria-based assessment in average reduces the value of the complex fuel and ecological criterion by 0.164 %, which is due to the small magnitude of dimensionless relative aggressiveness index of this pollutant. Accounting for the emission of such pollutants as greenhouse gas showed that such a contribution is 0.003 %, and in total, taking into account both aspects of the emission reduces the value of the criterion by 0.167 %. The dependences of the values of the criterion and its changes on the value of the greenhouse coefficient are obtained.

Key words: ecological safety, environmental protection technologies, power plants, reciprocating internal combustion engines, pollutants emission, criteria-based assessment, greenhouse gases, carbone dioxide.

Relevance of the study.

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) [1], namely electric generating PP (diesel-generators), which are powerful sousces of negative influence on environment [2], it is rarional to use the mathematical apparatus of complex fuel and ecological criterion of Prof. I.V. Parsadanov K_{fe} (NTU «KhPI») [3] that was described in the monograph [4] and improved in the monograph [5].

For application of specified criterial mathematical apparatus for RICE of specific purpose it is necessary to presence of exploitation model that as close represents features of the process as it possible. All exploitation models which have taken forms of testing cycles are divided on steady and unsteady. There are approximately 20 steady exploitation models which all are sets of certaine number of steady RICE operational regimes that follows in certaine sequence and are characterized by magnitudes of coordinates of field of operational regimes, namely crankshaft speed n_{cs} and crankshaft torque M_T, and also magnitudes of the weight factor *WF*. From the number of steady exploitation models there are standardized the parameters of which are established in normative documents (standards). From the number of such models the most wide used in in most industrialized countries is testing cycles that described in standerd ISO 8178-4:2017 [6], although other operating models are also being developed in some cases [2]. In particular, the special interest is the test cycle D2 «Engines with constant crankshaft speed for electrical PP with variable load» (diesels, including diesel-generators with short-term load (intermittent, hopping), ship and locomotive auxiliaries (not for traction)) from the standard [6]. It is known that autotractor diesel engine 2Ch10.5/12 (D21A1) is dedicated including for application in composition of electric generating PP [7].

Emission of legislative normalized pollutants in RICE exhaust gas (EG) flow is ES factor that must be redused and for that are applicated special devices for purification of EG flow [1–5, 8, 9], selection of rational settings and adjustments of RICE operational process [10], catalyzing of intracylinder processes [11], optimization of construction of supercharging aggregates [12, 13] etc. It is also well known that processes of thermal utilization of solid domestic wastes also are powerfull sources of emissions of pollutants into atmospheric air [14, 15] as well as processes of combustion of pyrotechnics [16] and due to forrest fiers [17] that are detects with using of special mearuring instruments [18, 19].

It is known that RICE operational process produces significant mass hourly emissions of carbon dioxide CO_2 as the product of completed combustion of motor fuel and is the greenhouse gas. Taking into account that significant part of EG flow are products of of completed combustion of motor fuel, namely CO_2 and H_2O, and also that the separate RICE is not powerful source of CO_2 emission but their role and part in world energy balance (at to 70 % [4]) it is possible to conclude that taking into account such emissions in complex calculated assessment of magnitudes of ES level indicators of electric generating PP with RICE exploitation process is scientific and technical problem the relevance of which has no doubt.

Purpose of the study. Obtaining of magnitudes of complex fuel and ecological criterion that are characterized the ES level of diesel-generator exploitation process with taking into account the emissions of carbon dioxide as the toxic pollutant and as the greenhouse gas.

Problem of the study. Obtaining of distribution of magnitudes of complex fuel and ecological criterion and its components for autotractor diesel engine 2Ch10.5/12 on the standatdized steady testing cycle D2 «Engines with constant crankshaft speed for electrical PP with variable load» (diesels, including diesel-generators with short-term load (intermittent, hopping), ship and locomotive auxiliaries (not for traction)) (ISO 8178-4:2017) with taking into account the emissions of carbon dioxide as the toxic pollutant and as the greenhouse gas.

Object of the study. ES of diesel-generator exploitation process the exploitation model of which corresponds to testing cycle D2.

Subject of the study. Influence of emissions of carbon dioxide as the toxic pollutant and as the greenhouse gas on qualitative and quantitative aspects of object of the study.

Methods of the study. Analysis of specialized scientific and technical literature, analysis of results of motor bench tests, basics of scientific discipline «Theory of RICE», improved mathematical apparatus of complex fuel and ecological criterion, method of least squares.

Tasks of the study.

1. Analysis of features of complex fuel and ecological criterion and standatdized steady testing cycle D2.

2. Obtaining of initial data set for implementing of calculated assessment for standatdized steady testing cycle D2 and diesel engine 2Ch10.5/12 as a part of electric generating PP.

3. Impriving of application methodica for assessing of magnitudes of mass hourly emission of carbone dioxide with RICE EG flow and potenderability of such ES factor as the toxic pollutant and as the greenhouse gas.

4. Calculated assessment of magnitudes of complex fuel and ecological criterion and its components for standatdized steady testing cycle D2 and analysis of its results.

Scientific novelty of obtained results. For the first fime obtained the distribution of magnitudes of complex fuel and ecological criterion and its components for autotractor diesel engine 2Ch10.5/12 which operates on the standatdized steady testing cycle D2 as a part of electric generating PP with taking into account the emissions of carbon dioxide as the toxic pollutant and as the greenhouse gas.

Practical value of obtained results. Obtained results suitable for providing the qualitative and quantitative assessment of ES level of diesel-generators exploitation process with taking into account the emissions of carbon dioxide as the toxic pollutant and as the greenhouse gas.

1. Analysis of mathematical apparatus of complex fuel and ecological criterion

Magnitudes of the criterion K_{fe} for i-th RICE steady representative operational regime with magnitude of weight factor WF are determined by formula (1) and its components – by formulas (2) – (10) [4, 5].

$$K_{fe}=\eta_e\cdot(1-\beta)=\frac{3600}{H_u\cdot g_e}\cdot\left(1-\frac{Z_e(P_f)}{Z_f(P_f)+Z_e(P_f)}\right)\cdot 10^3=$$
$$=\frac{3600\cdot N_e(M_{кр},n_{кв})}{H_u\cdot G_{fuel}}\cdot\frac{10^3}{1+\sigma\cdot f\cdot\sum_{m=1}^{h}(A_k\cdot G_k)/G_{fuel}},\ ‰;\quad(1)$$

$$\eta_e=3600/(H_u\cdot g_e);\quad(2)$$

$$\beta=Z_e/Z_{fe};\quad(3)$$

$$Z_{fe}=Z_f+Z_e,\ \$/(\text{kW·h});\quad(4)$$

$$N_e=M_{кр}\cdot n_{кв}/9550,\ \text{kW};\quad(5)$$

$$Z_f=g_e\cdot P_f,\ \$/(\text{kW·h});\quad(6)$$

$$Z_e=g_e\cdot U_e,\ \$/(\text{kW·h});\quad(7)$$

$$U_e=\delta\cdot\sigma\cdot f\cdot g_{pr},\ \$/\text{kg};\quad(8)$$

$$g_{pr}=\sum_{k=1}^{m}(A_k\cdot G_k/G_f);\quad(9)$$

$$\sum_{m=1}^{h}(A_k\cdot G_k)=A(PM)\cdot G(PM)+A(NO_x)\cdot G(NO_x)+$$
$$+A(C_nH_m)\cdot G(C_nH_m)+A(CO)\cdot G(CO),\ \text{kg/h};\quad(10)$$

where the index i indicates the values for a separate representative mode of RICE operation or landfill in the its exploitation model; H_u = 42.7 MJ/kg [4] – lower fuel combustion heat; N_e – effective power, kW; G_{fuel} – mass hourly fuel consumption, kg/h; G_k – mass hourly emission of k-th pollutant in EG flow, kg/h; A_k – dimensionless index of relative aggressiveness of k-th pollutant in EG flow (A_{NOx} = 41.,1; $A_{ТЧ}$ = 200; A_{CnHm} = 3.16; A_{CO} = 1.0 [4]); h = 4 [4] – number of pollutants in EG flow; σ – dimensionless index of relative dangerous of pollution of different territories (for automotive diesel engine σ = 1,0, for tractor diesel engine 0.25 [4]); f – dimensionless coefficient that takes into account the character of dispersion of EG in atmosphere (for Ukraine f = 1.0 [4]); $\delta = P_f$ – dimension index that converts of the score assessment into monetary \$/kg; WF – weight factor; η_e – effective efficiency coefficient; β – coefficient of relative exploitational ecological monetary costs; Z_e and Z_f – monetary costs on compensation of ecological damage and on motor fuel, \$/(kW·h); g_e – specific effective mass hourly fuel consumption, kg/(kW·h); M_T and n_{cs} – crankshaft torque and speed, N·m and rpm; P_f = 1.36 \$/kg – price of weight unit of motor fuel (P_f = 25.0 UAH/l, excange ratio 26.0 UAH/\$, fuel density ρ_{fuel} = 0.850 kg/m^3); U_e – monetary compensation of ecological damage, \$/kg; g_{pr} – specific reduced emission of pollutants with EG flow.

In monograph [5] the ways were detected for improving of mathematical apparatus of complex fuel and ecological criterion, namely:

a) selection and grounding of rational measuring units of monetary components of the criterion, namely Z_f and Z_e;

b) selection and grounding of rational methods for obtaining the individual regime and middle exploitational values of the criterion;

c) selection and grounding of rational initial data set for implementation of calculated criteria-based assessment;

d) expanding the nomenclature of ES factors that takes into account.

General considerations and calculated studies on the first of these ways presented in [5], where was recommended the usage of US dollar as the world reserve freely convertible currency the one that the existence history of which fully covers the history of the existence of RICE as such. Also selected the method of «Non zero idle» and detected that it necessary to use only whole number of initial data.

2. Obtaining an initial data set for a standardized steady test cycle D2

Standardized steady test cycle D2 described in standert [6] using for developing the testing program for RICE with constant crankshaft speed for electrical PP with variable load» (diesels, including diesel-generators with short-term load (intermittent, hopping), ship and locomotive auxiliaries (not for traction) and containe 5 steady operational regimes. Parameters of regimes of cycle D2 according to [6] for diesel engine 2Ch10.5/12 presented in Table 1. Technical, economic and ecological indicators of operation of the diesel for cycle D2 contained in Tables 1 and 2. Distribution of magnitudes of values from Tables 1 and 2 on regimes of cycle D2 showed on Fig. 1 – 3. Technical characteristic of diesel engine 2Ch10.5/12 contained in source [7], its operational indicators was obtained by experimental way in studies [8, 9].

Middle exploitational magnitude of criterion K_{fe} describes by formula (11) as it was propose in study [5].

$$K_{feme} = \sqrt[7]{\sum_{i=1}^{N}\left(K_{fei}^{7} \cdot WF_i\right) / \sum_{i=1}^{N}\left(WF_i\right)} \cdot 1000, \text{‰}. \quad (11)$$

In Table 1 following magnitudes of invariant values were used [4, 5]: A(PM) = 200; $A(NO_x)$ = 41.1; $A(C_nH_m)$ = 3.2; A(CO) = 1.0; $\sigma = f = 1.0$; $A(CO_2)$ = 0.002; P_f = 1.153 $/kg; $A(CO_2)_{GH}$ = 0.00004; H_u = 42.7 MJ/kg.

3. Technique for calculation assessment of magnitudes of complex fuel and ecological criterion with taking into account of carbon dioxide emissions as the toxic pollutant

In accordance with the classification of ES factors the source of which are RICE as a part of PP in its exploitation process proposed in monograph [5] the mass hourly emissions of carbon dioxide CO_2 with EG flow is classified as indirectly legislative normalized, namely as emission of greenhouse gas and also there is magnitudes of its maximum permissible concentration MPC (CO_2) in % or ppm in [20], normative requirements to CO_2 emission of vehicle (not RICE) in g/km [21] and also quotas for total CO_2 emission from territory of particular country in accordance to the Kioto protocol in millions tons/year [22].

At the normal conditions the concentration of CO_2 in dry atmospheric air equals 0.025 … 0.045 % (250 … 450 ppm), physiologically normal content of CO_2 in air of buildings equals 0.060 … 0.080 % (600 … 800 ppm), feels negative influence on human health from the magnitude of 0.1 % (1000 ppm), MPC(CO_2) in air of buildings is limited by magnitude 0.14 % (1400 ppm), letal dose LD_{50} equals 90 thousand mg/m^3 [20].

Nowadays the normative of CO_2 emission in accordance with requirements of European Comission and European Automobile Manufacturers Association (ACEA) that are put forward to the average emission level of the entire production line of vehicle models (but not individual vehicle unit) and apply within the EU (but not Ukraine) equals 130 g/km and in 2020 must be reduced to 95 g/km [21].

Table 1 – Parameters of standardized steady test cycle D2 [6]

№ reg.	Crancshaft speed n_{cs}		Crancshaft torque M_T		Weight factor *WF*
	marking	prm	–	N·m	–
1	nominal	1800	100	95	0.05
2		1800	75	71	0.25
3		1800	50	47	0.30
4		1800	25	24	0.30
5		1800	10	9.5	0.10

For Ukraine the quota of CO_2 emission according to Kioto protocol equals 922 million tons/year from number of which due to reducing of volume of indusrtial production remaine unclaimed about 420 million tons per year (that is 45 %) which are sold to other industrialized nations of the world [22, 23].

Thus, except that CO_2 is greenhouse gas and its emission with EG flow causes increasing the greenhouse effect (global warming) it also has the toxic impact in certaine concentration in atmospheric air what are characterized magnitudes of appropriate MPC.

Nowadays to take into account both of worded above features of CO_2 emission as ES factor of PP with RICE accident-free exploitation process using of mathematical apparatus of criterion K_{fe} is possible only in case of determination of magnitude of ponderability of such ES factor in both contexts in comparison with the ponderability of etalonic pollutant – carbon monoxide CO, namely appropriate magnitudes of coefficient of relative aggressiveness of pollutant $A(CO_2)$ and $A(CO_2)_{gh}$.

In present study is proposed following methodica for such assessment that takes into account the toxic influence of CO_2 emission on a human in accordance of which formula (10) converts into the formula (12) where value of coefficient $A(CO_2)$ determinated be formulas (13) – (14) [24, 31].

$$\begin{aligned}\sum_{m=1}^{h}(A_k \cdot G_k) &= A(PM)\cdot G(PM) + \\ &+ A(NO_x)\cdot G(NO_x) + A(C_nH_m)\cdot G(C_nH_m) + \\ &+ A(CO)\cdot G(CO) + A(CO_2)\cdot G(CO_2)\end{aligned} \quad (12)$$

$$A_k = a_k \cdot \alpha_k \cdot \beta_k \cdot \delta_k, \quad (13)$$

$$a_k = \sqrt{\frac{MPC_{cd}(CO)\cdot MCP_{pз}(CO)}{MPC_{cd}(k)\cdot MPC_{pз}(k)}}, \quad (14)$$

where a_k – index of relative danger of presense of k-th gaseous or aerosol pollutant in atmospheric air that a human breaves; α_k – corrective that takes into account the probability of accumulation of k-th gaseous or aerosol pollutant in environment components, trophic chaines 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 exapt a human; $MPC_{ad}(CO)$ and $MPC_{ot}(CO)$, $MPC_{ad}(k)$ and $MPC_{ot}(k)$ – maximum permissible concentration of etalon ($MPC_{ad}(CO) = 3.0$ mg/m^3, $MPC_{ot}(CO) = 20.0$ mg/m^3, $A_{CO} = 1.0$ [5, 24]) and k-th pollutant in air average day-and-night and maximal one-time, mg/m^3.

In formula (14) $MCP(CO_2) = 9000$ mg/m^3 (dencity at normal conditions $\rho(CO_2) = 1.98$ kg/m^3 and molar mass $\mu(CO_2) = 44$ g/mole [5, 24]) and equalls 0.002 because magnitude of indicator a_k (see formula (13)) equalls 1/450 or 0.002 and magnitudes of correctives α_k, β_k and δ_k accepted as 1,0, that means $A(CO_2) = 0.002$.

Thus, the structure of ponderability of factors of ecological component of criterion K_{fe} with taking into account the CO_2 emissions can be illustrated by Fig. 5.

Table 2 – Technical, economic and ecological indicators of operation of diesel 2Ch10.5/12 for standardized steady testing cycle D2

№	N_e	η_e	G_{fuel}	G_{air}	G_{EG}	$G(PM)$	$G(NO_x)$	$G(C_nH_m)$	$G(CO)$	g_e
reg.	kW	–	kg/h			g/h				kg/(kW·h)
1	17.906	0.318	4.750	113.210	117.960	14.3	335.0	4.1	95.0	0.265
2	13.382	0.327	3.450	113.111	116.561	12.5	240.0	2.8	25.0	0.258
3	8.859	0.272	2.750	112.543	115.293	8.0	200.0	2.1	8.0	0.310
4	4.524	0.201	1.900	110.623	112.523	2.2	115.0	3.3	20.0	0.420
5	1.791	0.097	1.550	110.100	111.650	1.5	55.0	5.0	31.0	0.866
Aver.	**9.292**	**0.243**	**2.880**	**111.917**	**114.797**	**7.7**	**189.0**	**3.5**	**35.8**	**0.424**
№	$\Sigma(A_k \cdot G_k)$	g_{kpr}	U_e	Z_f	Z_e	Z_{fe}	β	K_{fe}	$K_{fe} \cdot WF$	$G(CO_2)$
reg.	kg/h	–	$/kg	$/(kW·h)			–	‰	‰	g/h
1	16.737	3.523	4.063	0.366	1.078	1.444	0.746	70.259	4.032	14995.6
2	12.398	3.594	4.143	0.377	1.068	1.445	0.739	71.192	21.330	10956.0
3	9.835	3.576	4.123	0.313	1.280	1.593	0.803	59.347	16.014	8758.0
4	5.197	2.735	3.154	0.231	1.325	1.556	0.851	53.737	8.956	6031.8
5	2.608	1.682	1.940	0.112	1.679	1.791	0.937	36.311	0.611	4891.1
Aver.	**9.355**	**3.022**	**3.485**	**0.280**	**1.286**	**1.566**	**0.815**	**62.943**	**10.189**	**9126.5**

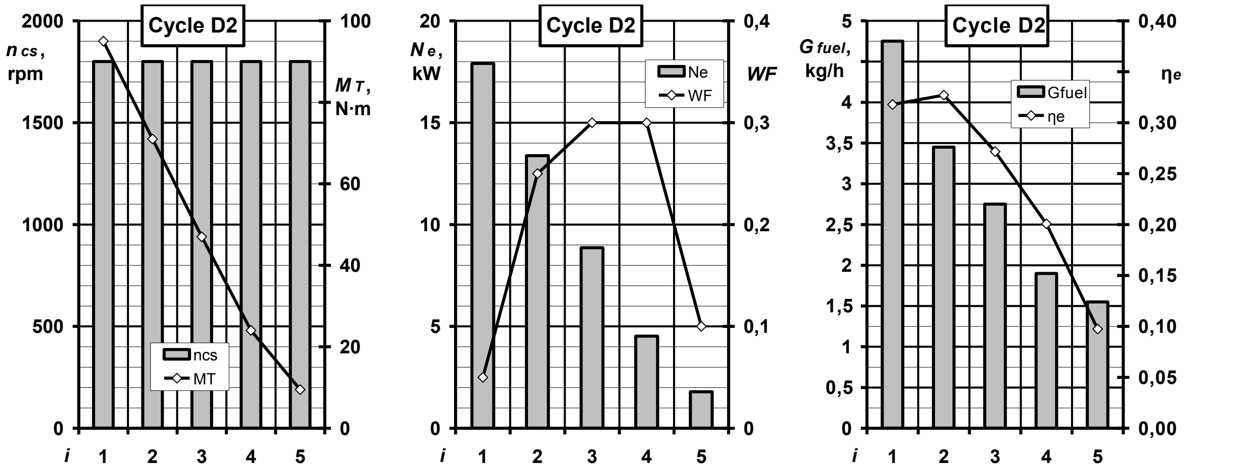


Figure 1 – Magnitudes of parameters of standardized steady testing cycle D2 for diesel engine 2Ch10.5/12

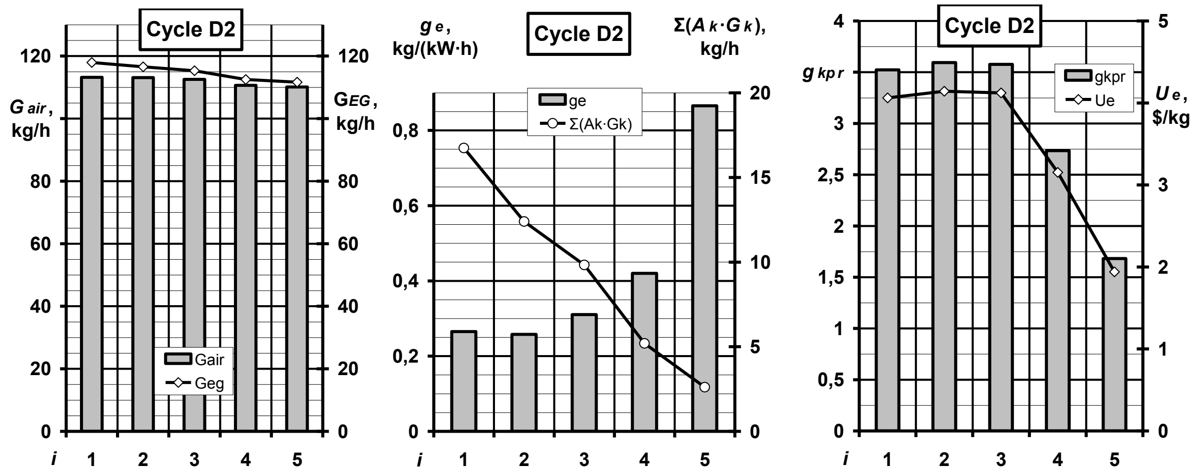


Figure 2 – Technical and economic parameters indicators of diesel engine 2Ch10.5/12 operation on D2 cycle

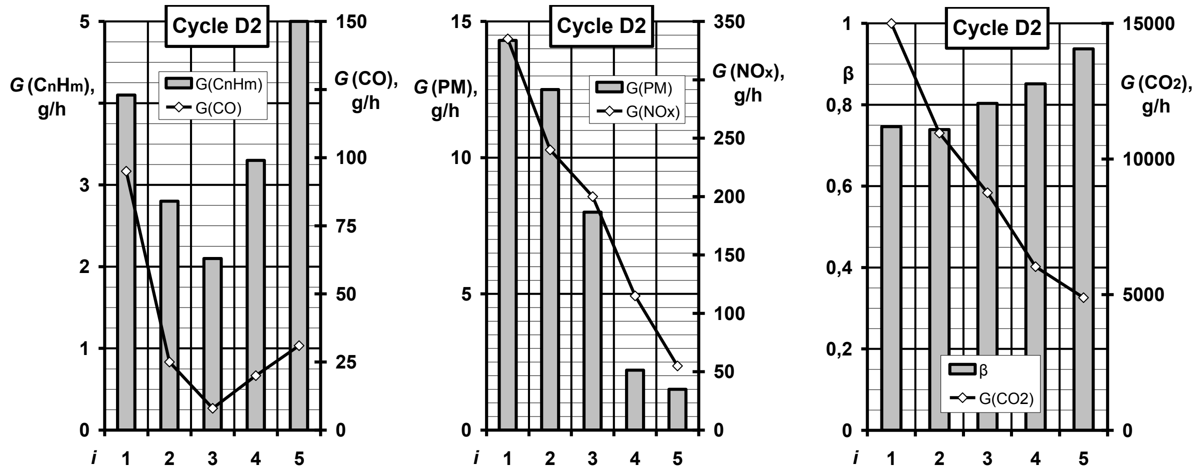


Figure 3 – Ecological parameters indicators of diesel engine 2Ch10.5/12 operation on D2 cycle

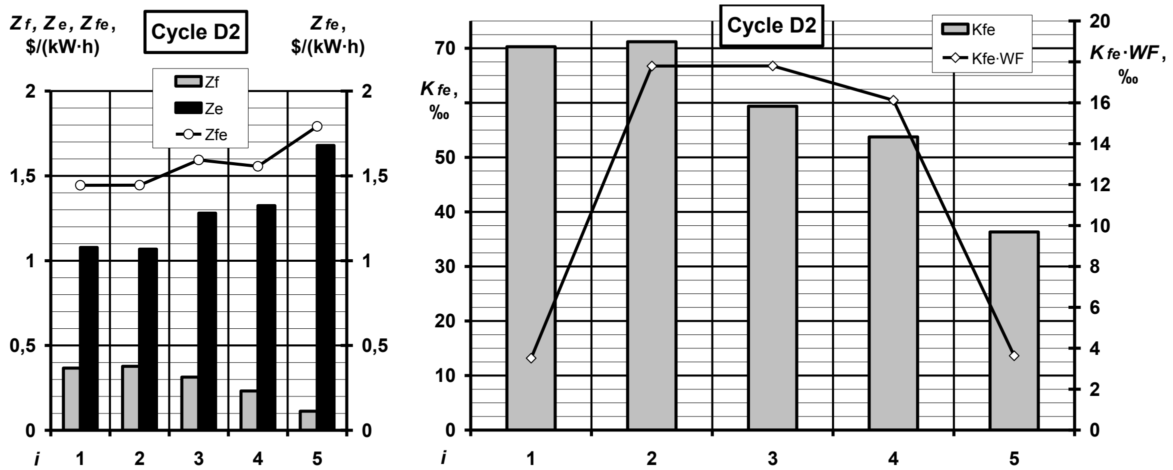


Figure 4 – Magnitudes of criterion K_{fe} and its components of diesel engine 2Ch10.5/12 operation on D2 cycle

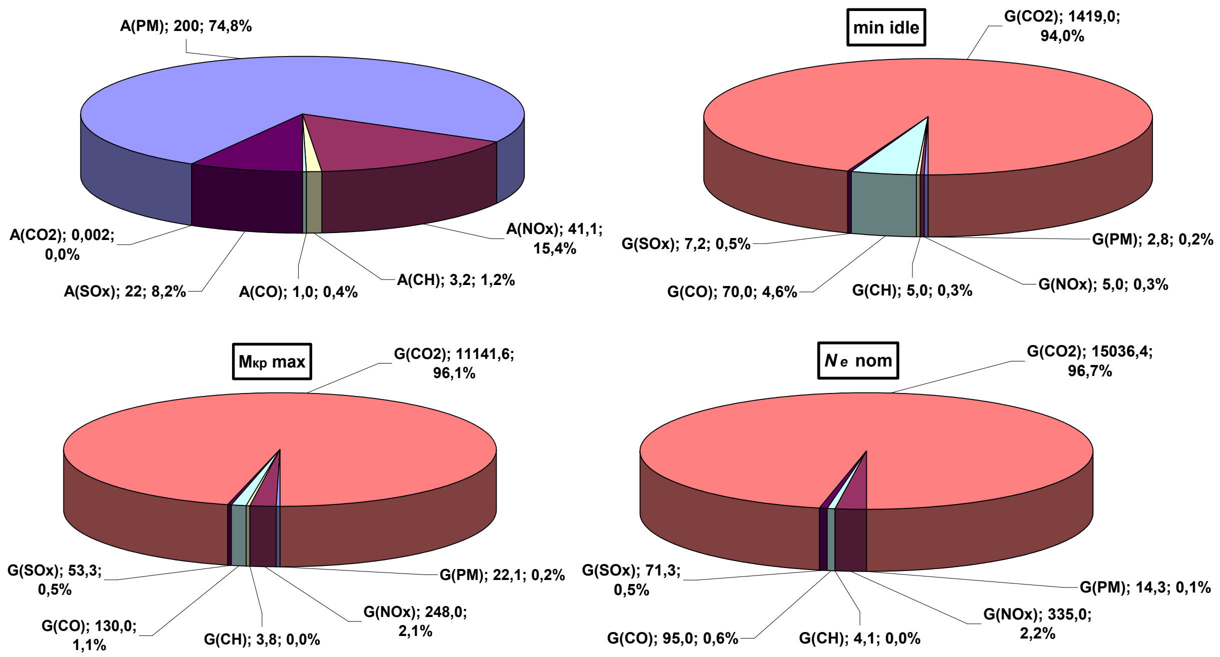


Figure 5 – Structure of ponderability of factors of ecological component of criterion K_{fe} taking into account CO_2 emissions and structure of volume of mass hourly emissions of pollutants in the composition of EG flow that is used in complex criteria-based assessment for special operational regimes of diesel engine 2Ch10.5/12

For determination of magnitudes of mass hourly emission of carbon dioxide $G(CO_2)$ in the study is proposed the following approach.

Since CO_2 is the product of complited combustion of motor fuel which in case of petroleum origin consists of different hydrocarbons (in average for diesel fuel it is cetane $C_{16}H_{34}$) and has the following elemental chemical composition: $C_f(C)$ = 0.87, $C_f(H)$ = 0.12, $C_f(O)$ = 0.01 [25], than the value $G(CO_2)$ is completely determined by the values of mass hourly fuel consumption G_{fuel} and degree of completeness of combustion of fuel by carbon that can be determinate by formula (15).

$$G(CO_2) = G_{fuel} \cdot k(CO_2) - \frac{G(CO) \cdot C(CO)}{C(CO_2)} - \frac{G(C_nH_m) \cdot C(C_nH_m)}{C(CO_2)} - , \quad (15)$$
$$- \frac{G(PM) \cdot C(PM) \cdot C(CO)}{C(CO_2)}$$

where G_{fuel} – mass hourly fuel consumption, kg/hr; $G(CO)$ – mass hourly carbon monoxide emission, kg/hr; $G(C_nH_m)$ – mass hourly unburned hydrocarbons emission, kg/hr; $G(PM)$ – mass hourly particulate matter emission, kg/hr; $k(CO_2)$ – coefficient that takes into account the elemental chemical composition of motor fuel; $C(CO_2)$ – mass fraction of carbon in CO_2; $C(CO)$ – mass fraction of carbon in CO; $C(C_nH_m)$ – mass fraction of carbon in unburned hydrocarbons C_nH_m, $C(PM)$ – mass fraction of carbon in particulate matter PM.

Magnitudes of coefficient $k(CO_2)$ can be determined at condition of complete combustion of motor fuel, that is complete oxidation of carbon in RICE combustion chamber up to CO_2, and determined by stoichiometric ratios by full analogy to the coefficient $k(SO_2)$ (see monograph [5]). In particular, the reaction of complete oxidation of carbon of motor fuel is the formula (16). That is, if magnitude of molar mass of carbon $\mu(C)$ = 12 g/mole, oxygen $\mu(O)$ = 16 g/mole, carbon dioxide $\mu(CO_2)$ = 44 g/mole, than the magnitude of coefficient $k(CO_2)$ can be described by formula (17).

For determination of magnitudes of coefficient $k(C_nH_m)$ it necessary to obtain the data about average elemental chemical composition of unburned hydrocarbons in EG flow of diesel engine. In this study it will be assumed that the typical representative chemical compound of unburned hydrocarbons which do not condense in EG flow is pentane C_5H_{12}, the magnitude of molar mass of which $\mu(C_5H_{12})$ = 72 g/mole (magnitude of molar mass of hydrogen $\mu(H)$ = 1.0 g/mole). That's why magnitude of value $C(C_nH_m)$ is described by formula (18). The values of quantities are similarly determined – by formulas (19) and (20). Magnitude of value $C(PM)$ is described as the sum of carbon content in PM $C_{soot}(C)$ and in liquid which do condense in EG flow of motor fuel and motor oil origin $C_{of}(C)$ that is by formula (21).

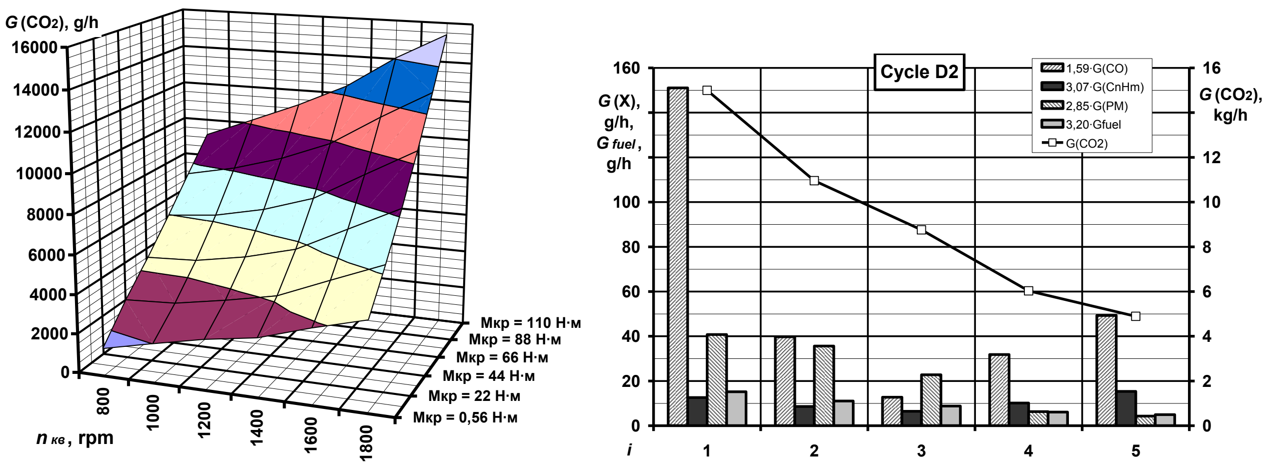
$$C + O_2 \rightarrow CO_2. \quad (16)$$
$$k(CO_2) = C_f(C) \cdot \mu(CO_2) \, / \, \mu(C) =$$
$$= 0.87 \cdot 44 \, / \, 12 = 3.2. \quad (17)$$
$$C(C_nH_m) = (n \cdot \mu(C)) \, / \, \mu(C_nH_m) =$$
$$= (5 \cdot 12) \, / \, 72 = 0.83. \quad (18)$$
$$C(CO) = \mu(C) \, / \, \mu(CO) = 12 \, / \, 28 = 0.43. \quad (19)$$
$$C(CO_2) = \mu(C) \, / \, \mu(CO_2) = 12 \, / \, 44 = 0.27. \quad (20)$$

When analyzing the data from sources [1, 4, 26, 27] in was determined that carbon content in the soot of PM $C_{soot}(C)$ depends from RICE operational regime and equals in average about 43 % mass, content of liquid fraction which do condense in EG flow of motor fuel and motor oil origin in PM equals in average about 10 and 29 % mass. That means what if magnitudes of mass carbon concentration in motor fuel and motor oil equals 87 % mass than magnitude of value $C_{of}(C)$ = 34 % mass and value $C(PM)$ = 77.0 %. Thus, formula (15) converts to formula (22).

$$C(PM) = C_{soot}(C) + C_{of}(C) =$$
$$= 0.43 + (0.10 + 0.29) \cdot 0.87 = 0.77. \quad (21)$$
$$G(CO_2) = G_{fuel} \cdot 3.20 + G(CO) \cdot 1.59 -$$
$$- G(C_nH_m) \cdot 3.07 - G(PM) \cdot 2.85. \quad (22)$$

Distribution of magnitudes of value G_{CO2} on operational regimes field of diesel engine 2Ch10.5/12 and distribution of magnitudes of value G_{CO2} and other components of formula (15) on regimes of testing cycle D2 are illustrated on Fig. 6. Such distributions for all components of formula (15) are illustrated on Fig. 7.

Averaged on operational regimes field of diesel engine 2Ch10.5/12 magnitudes of value G_{CO2} equals 7095 g/h and changes from 1419.3 to 15463.4 g/h.



a b

Figure 6 – Distribution of magnitudes of value G_{CO2} on operational regimes field of diesel engine 2Ch10.5/12 (a) and distribution of magnitudes of value G_{CO2} and other components of formula (15) on regimes of testing cycle D2 (b)

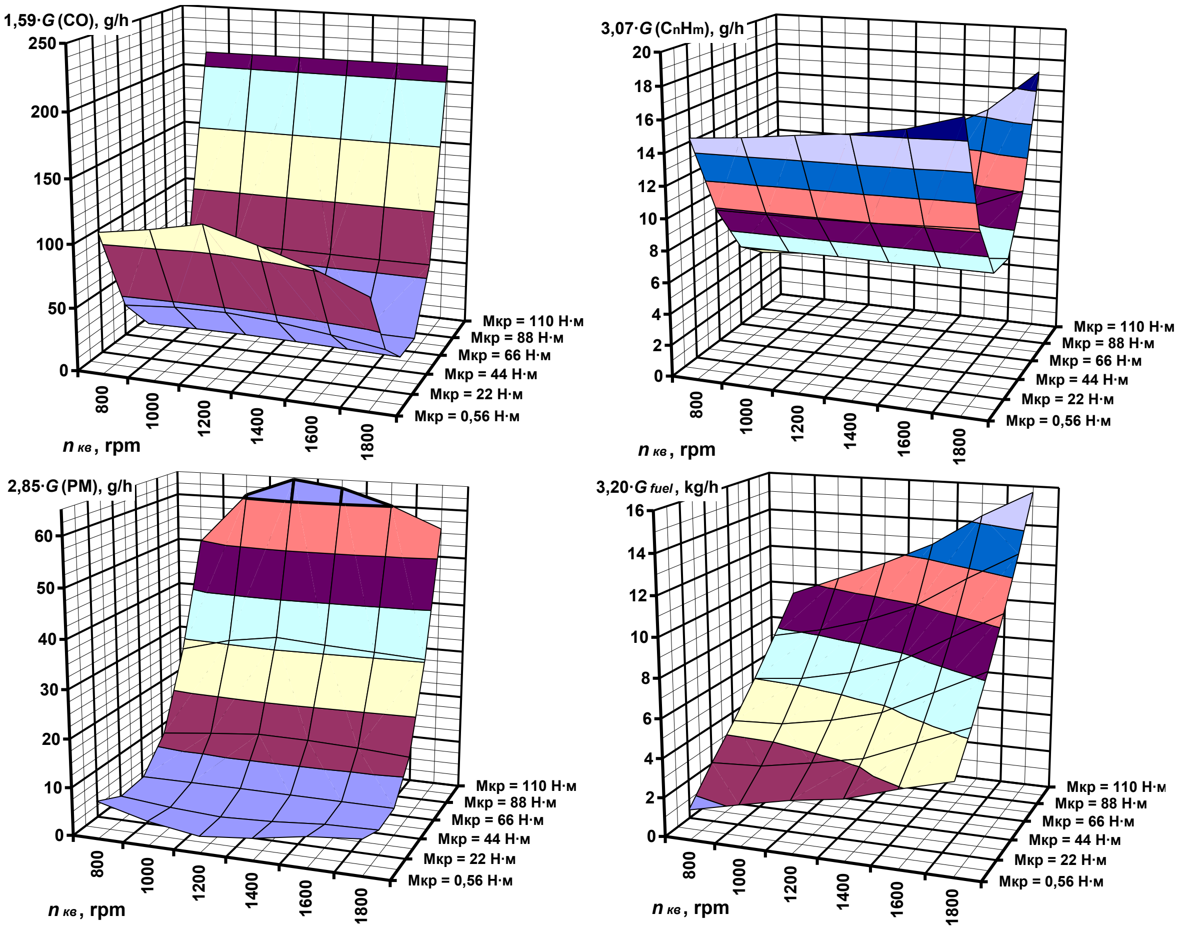


Figure 7 – Distribution of magnitudes of values 1.59 · G_{CO} and 3.07 · G_{CnHm} , 2.85 · G_{PM} and 3.20 · G_{fuel} on operational regimes field of diesel engine 2Ch10.5/12

4. Technique for calculation assessment of magnitudes of complex fuel and ecological criterion taking into account carbon dioxide emissions as the greenhouse gas

In previous part of the study parameters of carbon dioxide CO_2 in EG flow as the toxic pollutant were determined. That is the substance that has toxic impact on living organisms. Also it was detected that CO_2 emissions causes the so called greenhouse effect and rises the climate global warming, that means what CO_2 is greenhouse gas and so the complex ES factor which needs to be taken into account when implementing the criteria-based assessment of ES level of PP with RICE exploitation process.

To the number of greenhouse gases gaseous artificial and natural components of atmospheric air are included, which are characterized with high transparency over electromagnetic radiation in the visible wavelength range and also with high absorption ability in the far infrared diapasone [28]. The wavelengths of 4.26 μm (vibrations with asymmetric stretching of the molecule) and 14.99 μm (bending oscillations) are special.

To the number of main greenhouse gases the following ones are included (in order of descending of contribution to the thermal balance of the atmosphere): water steam H_2O (contribution is 36 – 72 %), carbon dioxide CO_2 (contribution is 9 – 26 %), methane CH_4 (contribution is 4 – 9 %) and ozone O_3 (contribution is 3 – 7 %) [28].

The main sources of CO_2 emissions into atmospheric air are volcanic activity, life activity of biomass (breathing and decay), emergency situations (forest and steppe fire), human manufacturing and agricultural activity. In this case the main anthropogenic sources of CO_2 emissions are combustion of fossil fuels, combustion of biomass, technological processes of chemical and construction industry. The main consumers of CO_2 are plants in the process of photosynthesis but the balance of such consummation in conjunction with the CO_2 emission in biocenosis process during biomass decay process is almost zero. Less noticeable but important consumer of CO_2 (with flora up to 57 % CO_2 of anthropogenic genesis) is represented with waters of the oceans that absorb and accumulate it in the form of solution and carbonate and hydrocarbonate ions. Anthropogenic activity has led to increased concentration of CO_2 in atmospheric air during the last 300 years from 277 to 415 ppm (0.021 – 0.0415 % vol.), that is on 146 % (in average by 1.7 – 2.2 % per year) [28].

World balance of CO_2 emission in accordance to the information in source [29] as of 2017 is as following:

– aggregate emissions from all major sources equal to 603.2 billion tons (100 %);

– natural component (92.5 %): emitted in decay of biomass process 220 billion tons (92.5 %); emitted from waters of the oceans 330 billion tons (54.7 %); emitted at volcanic activity 0.2 million tons (0.3 %); emitted at fires 8 billion tons (1.3 %);

– anthropogenic component (7.5 %):

– emitted in processes of combustion of fossil fuels and biomass 32 billion tons (5.3 %): combustion of petroleum products 12 billion tons (2.0 %); combustion of coal 10 billion tons (1.6 %); combustion of natural gas 5.5 billion tons (0.9 %); combustion of other types of fuel 4.5 billion tons (0.7 %);

– emitted in other anthropogenic activity 13 billion tons (2.2 %).

Herewith the structure of output of various petroleum products in the processing of 1 barrel (159 l) of crude oil (after processing 168 l) are following [30]: benzine 102 l; diesel 30 l, kerosene and gasoil 25 l; refinery gas 11 l; petroleum coke 10 l; masut 6.8 l; liquefied gas 5.4 l; solid residue is the rest.

Structure of CO_2 emission world balance is illustrated at Fig. 8. Structure of output of various petroleum products in the processing of 1 barrel of crude oil is shown at Fig. 9.

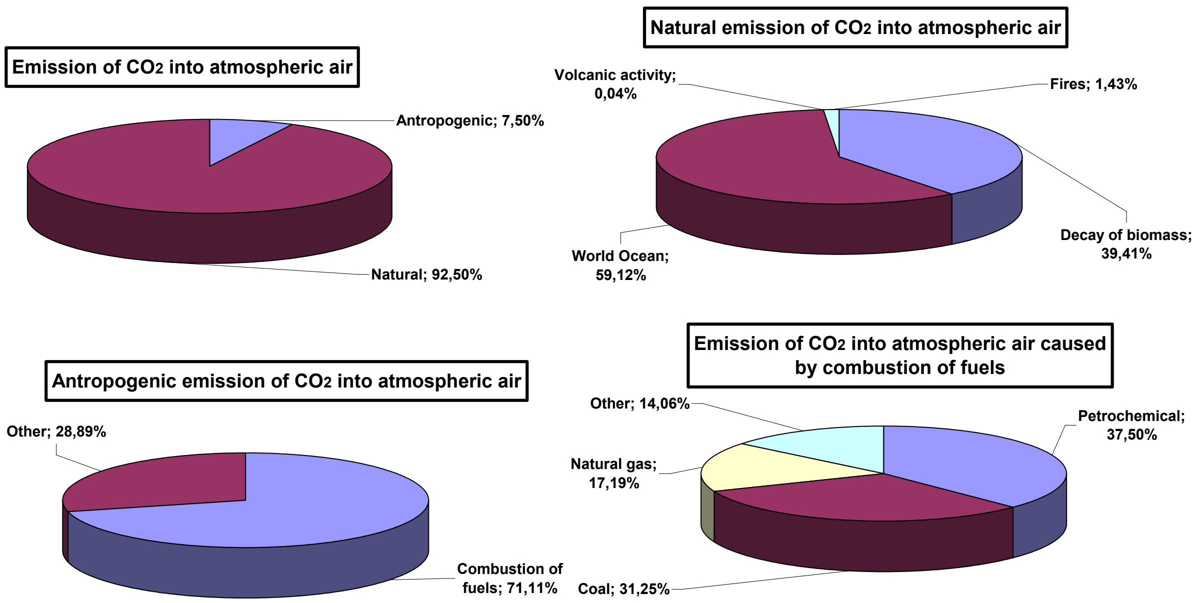


Figure 8 – Structure of CO_2 emission world balance (from [29])

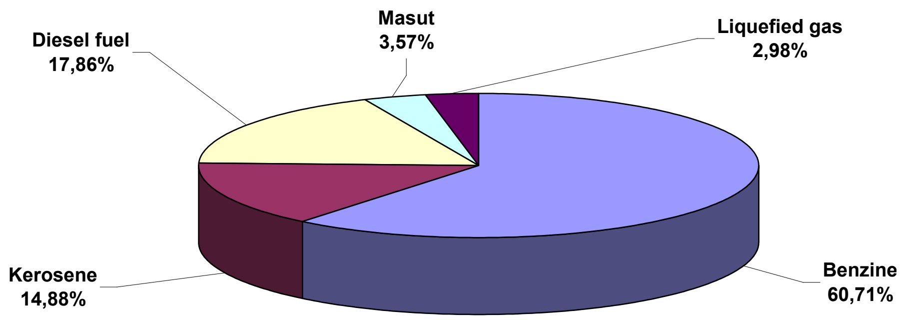


Figure 9 – Structure of output of various petroleum products in the processing of 1 barrel of crude oil (from [30])

For accounting of CO_2 emission in RICE EG flow as the greenhouse gas in criteria-based assessment with using of mathematical apparatus of fuel and ecological criterion K_{fe} it is proposed to use formula (23):

$$\sum_{m=1}^{h}(A_k \cdot G_k) = A(PM)\cdot G(PM) + A(NO_x)\cdot G(NO_x) + A(C_nH_m)\cdot G(C_nH_m) + A(CO)\cdot G(CO) + A(CO_2)\cdot G(CO_2) + A(CO_2)_{GH}\cdot G(CO_2)_{GH}, \quad (23)$$

where $A(CO_2)_{GH}$ – dimensionless index of relative aggressiveness of CO_2 as the greenhouse gas; $G(CO_2)_{GH}$ – mass hourly emission of CO_2 as the greenhouse gas, kg/h.

Magnitudes of index $A(CO_2)_{GH}$ are proposed to be used in formula (24):

$$A(CO_2)_{GH} = A(CO_2)\cdot k_{GH} = A(CO_2)\cdot G(CO_2)_{\Sigma RICE} / G(CO_2)_W, \quad (24)$$

where $A(CO_2)$ = 0.002 – dimensionless index of relative aggressiveness of CO_2 as the toxic pollutant (coefficient of ponderability of this ES factor in structure of ecological component of criterion K_{fe}); k_{GH} – greenhouse coefficient; $G(CO_2)_{\Sigma RICE}$ – total CO_2 emission that produced by all of RICE in world balance, kg/h; $G(CO_2)_W$ – total CO_2 emission that produced by PP and life organisms in world balance, kg/h.

From the data on Fig. 8 it can be seen that combustion of all types of petroleum products in total causes annual mass CO_2 emission into atmospheric air of about 12 billion tons that equals about 2.0 % from the total annual mass CO_2 emission from all sources of both natural and anthropogenic origin.

That's why magnitude of proposed greenhouse coefficient k_{GH} equals 0.02 what gives magnitude of dimensionless index of relative aggressiveness of CO_2 as the greenhouse gas $A(CO_2)_{GH}$ equal to $4.0{\cdot}10^{-5}$. In connection with the above structure of ponderability of factors of ecological component of criterion K_{fe} taking into account CO_2 emissions as the toxic pollutant and as the greenhouse gas can be illustrated by Fig. 10.

Then the obvious thing is that magnitude of mass hourly CO_2 emission as the greenhouse gas is described with formula (25):

$$G(CO_2)_{GH} = G(CO_2),\ \text{kg/h}. \quad (25)$$

In this calculated study the following variants are considered.

Variant A – «Reference» – without taking CO_2 emission into account.

Variant B – «Pollutant» – taking CO_2 emission into account as the toxic pollutant.

Variant C – «Greenhouse gas» – taking CO_2 emission into account as the greenhouse gas.

Variant D – «Total» – taking CO_2 emission into account as the toxic pollutant and as the greenhouse gas.

The results of calculated study are summarized in Table 3 for individual regime magnitudes and in Table 4 for middle exploitation magnitudes of investigated values and also are illustrated on Fig. 11.

The dependences of magnitudes of values of K_{fe} and δK_{fe} from magnitudes of greenhouse coefficient k_{GH} were obtained which are summarized in Table 5 and presented on Fig. 12 and also described by formulas (25) and (26) using the least squares method.

$$K_{fe} = -8.484 \cdot 10^{-2} \cdot k_{GH} + 6.253 \cdot 10^{-2}\ ;\ R^2 = 1.0\ ‰, \quad (25)$$

$$\delta K_{fe} = -0.155 \cdot k_{GH} - 0.139\ ;\ R^2 = 0.995\ \%. \quad (26)$$

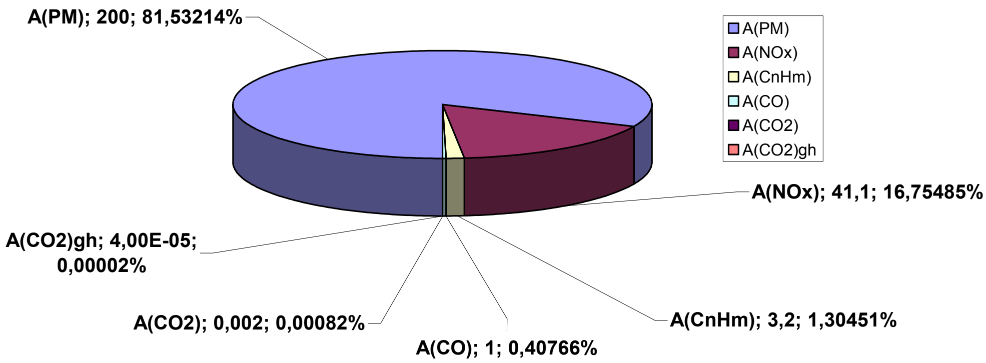


Figure 10 – Structure of ponderability of factors of ecological component of criterion K_{fe} taking into account CO_2 emissions as the toxic pollutant and as the greenhouse gas

Table 3 – Individual regime magnitudes of criterion K_{fe} and value δK_{fe} for all variants of calculated study

№ regime	Variant						
	A	B		C		D	
	K_{fe}	K_{fe}	δK_{fe}	K_{fe}	δK_{fe}	K_{fe}	δK_{fe}
	‰	‰	%	‰	%	‰	%
1	70.259	70.161	-0.139	70.257	-0.00279	70.159	-0.142
2	71.192	71.093	-0.138	71.190	-0.00277	71.091	-0.141
3	59.347	59.264	-0.139	59.345	-0.00278	59.263	-0.142
4	53.737	53.646	-0.170	53.736	-0.00340	53.644	-0.173
5	36.311	36.226	-0.235	36.309	-0.00471	36.224	-0.239
Aver.	**62.943**	**62.854**	**-0.164**	**62.941**	**-0.00329**	**62.852**	**-0.167**

Table 4 – Average exploitational magnitudes of criteria K_{fe} and value δK_{fe} for all variants of calculated study

Parameter	Measur. units	Variant			
		A	B	C	D
K_{fe}	‰	62.943	62.854	62.941	62.852
δK_{fe}	%	0.0	–0.164	–0.0033	–0.167

Table 5 – Dependences of magnitudes of values of K_{fe} and δK_{fe} from magnitudes of greenhouse coefficient k_{GH}

Parameter	Measur. units	Magnitude				
k_{GH}	–	0.0	0.02	0.10	0.50	1.0
K_{fe}	‰	62.535	62.533	62.526	62.492	62.450
δK_{fe}	%	-0.135	-0.138	-0.161	-0.219	-0.292

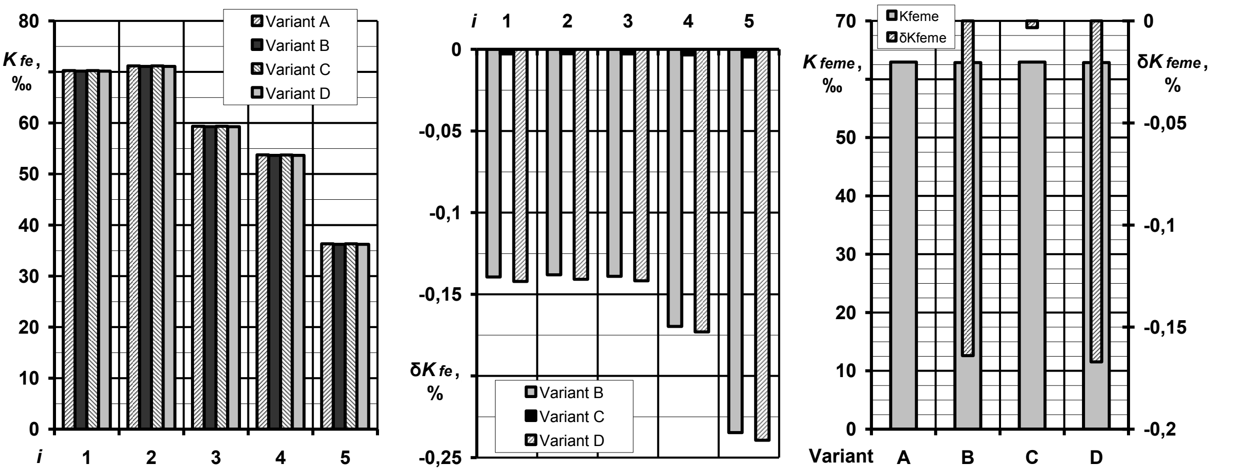


Figure 11 – Distribution of magnitudes of values K_{fe} and δK_{fe} and average exploitational magnitudes of its values on regimes of testing cycle D2 for all variants of calculated study

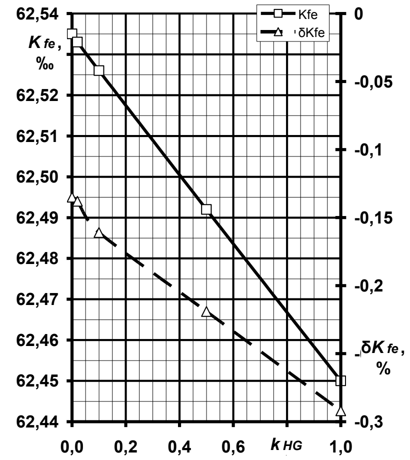


Figure 12 – Graphics of dependences of magnitudes of values of K_{fe} and δK_{fe} from magnitudes of greenhouse coefficient k_{GH}

In the study it was detected that despite the high values of mass hourly emission of carbon dioxide as a toxic pollutant, taking into account such emission in the criteria-based assessment on average reduces the value of the complex fuel and ecological criterion by 0.164 %, which is caused by the small value of the dimensionless indicator of the relative aggressiveness of such polutant.

It also was detected that taking into account the emission of such a pollutant as a greenhouse gas showed such a contribution is 0.003 %, and the sum of taking into account both aspects of the emission reduces the value of the criterion by 0.167 %.

It should be noted that the results obtained 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].

Conclussions

Thus, according to the analysis of the results of the study, we can draw the following conclusions.

1. In this study the types and features of the known models of exploitation of RICE as part of the electric generating power plant were analyzed, among which the steady standardized test cycle D2 according to ISO 8178-4: 2017 is selected.

2. A set of initial data is obtained for the calculated criteria-based assessment of the ecological safety level of the exploitation process of PP with a RICE at an example of the autotractor diesel engine 2Ch10.5/12 based on the results of processing of bench motor tests data.

3. The mathematical apparatus of the complex fuel and ecological criterion of prof. I.V. Parsadanov.

4. The calculation methodica for assessment of the values of this criterion has been improved by taking into account the mass hourly emissions of carbon dioxide with the EG flow from the RICE both as pollutant and as greenhouse gas.

5. The calculated assessment of the values of specified criterion was carried out with taking into account carbon dioxide emissions.

It has been detected that despite the high values of the hourly mass emission of carbon dioxide as a toxic pollutant, taking it into account when criteria-based assessment in average reduces the value of the complex fuel and ecological criterion by 0.164 %, which is due to the small magnitude of dimensionless relative aggressiveness index of this pollutant. Accounting for the emission of such pollutants as greenhouse gas showed that such a contribution is 0.003 %, and in total, taking into account both aspects of the emission reduces the value of the criterion by 0.167 %.

The dependences of the values of the criterion and its changes on the value of the greenhouse coefficient are obtained. The identified dependencies are described by formulas using the least squares method.

Acknowledgements.

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Conflicts of Interest.

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

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Кондратенко О. М.

ВРАХУВАННЯ ВИКИДІВ CO_2 ЯК ТОКСИЧНОГО ПОЛЮТАНТА ТА ПАРНИКОВОГО ГАЗУ ПРИ КОМПЛЕКСНОМУ КРИТЕРІАЛЬНОМУ ОЦІНЮВАННІ РОБОТИ ДИЗЕЛЬ-ГЕНЕРАТОРА

У даному дослідженні проаналізовано види й особливості відомих моделей експлуатації поршневого ДВЗ у складі електрогенеруючої енергоустановки, серед яких виділено стаціонарний стандартизований випробувальний цикл D2 за ISO 8178-4:2017. Отримано набір вихідних даних для розрахункового критеріального оцінювання рівня екологічної безпеки процесу експлуатації енергоустановок з поршневим ДВЗ на прикладі автотракторного дизеля 2Ч10,5/12 за результатами обробки даних стендових моторних випробувань. Проаналізовано математичний апарат комплексного паливно-екологічного критерію проф. І.В. Парсаданова. Вдосконалено методики розрахункового оцінювання значень цього критерію з урахуванням масових годинних викидів діоксиду вуглецю з потоком відпрацьованих газів поршневого ДВЗ як полютанта та як парникового газу. Здійснено розрахункове оцінювання значень вказаного критерію з урахуванням викидів діоксиду вуглецю з потоком відпрацьованих газів поршневого ДВЗ як полютанта та як парникового газу. Встановлено, що незважаючи на високі значення масового годинного викиду діоксиду вуглецю як токсичного полютанту врахування такого викиду при критеріальному оцінюванні у середньому зменшує значення комплексного паливно-екологічного критерію на 0,164 %, що зумовлено малим значенням безрозмірного показника відносної агресивності такого полютанту. Врахування викиду такого полютанту як парникового газу показало, такий внесок становить 0,003 %, а у сумі врахування обох аспектів викиду знижує значення критерію на 0,167 %. Отримано залежності значень критерію та його зміни від значення парникового коефіцієнту.

Ключові слова: екологічна безпека, технології захисту навколишнього середовища, енергетичні установки, поршневі двигуни внутрішнього згоряння, викиди полютантів, критеріальне оцінювання, парникові гази, діоксид вуглецю.

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УЧЁТ ВЫБРОСОВ CO_2 КАК ТОКСИЧНОГО ПОЛЛЮТАНТА И ПАРНИКОВОГО ГАЗА ПРИ КОМПЛЕКСНОМ КРИТЕРИАЛЬНОМ ОЦЕНИВАНИИ РАБОТЫ ДИЗЕЛЬ-ГЕНЕРАТОРА

В данном исследовании проанализированы виды и особенности известных моделей эксплуатации поршневих ДВС в составе электрогенерирующей энергоустановки, среди которых выделен стационарный стандартизированный испытательный цикл D2 по ISO 8178-4: 2017. Получен набор исходных данных для расчетного критериального оценивания уровня экологической безопасности процесса эксплуатаци и энергоустановок с поршневым ДВС на примере автотракторного дизеля 2Ч10,5/12 по результатам обработки данных стендовых моторных испытаний. Проанализирован математический аппарат комплексного топливно-экологического критерия проф. И.В. Парсаданова. Усовершенствована методика расчетного оценивания значений этого критерия с учетом массовых часовых выбросов диоксида углерода с потоком отработавших газов поршневого ДВС как полютантами и как парникового газа. Осуществлено расчетное оценивание значений указаного критерия с учетом выбросов диоксида углерода. Установлено, что несмотря на высокие значения массового часового выброса диоксида углерода как токсичного поллютанта его учет при критериальном оценивании в среднем уменьшает значение комплексного топливно -экологического критерия на 0,164 %, что обусловлено малым значением безразмерного показателя относительной агрессивности этого полютантами. Учет выброса такого полютантам как парникового газа показал, что такой вклад составляет 0,003%, а в сумме учет обоих аспектов выброса снижает значение критерия на 0,167 %. Получены зависимости значений критерия и его изменения от значения парникового коэффициента.

Ключевые слова: экологическая безопасность, технологии защиты окружающей среды, энергетические установки, поршневые двигатели внутреннего сгорания, выброс поллютантов, критериальное оценивание, парниковые газы, диоксид углерода.