UDC 621.43.068.4:504.064.4

S. Vambol, DSc, Professor, Head of Department
O. Kondratenko, PhD, Docent of Department
National University of Civil Defense of Ukraine
Chernyshevska Str., 94, Kharkiv, Ukraine, 61023

RESULTS OF COMPLEX CRITERIAL FUEL AND ECOLOGICAL ASSESSMENT OF DIESEL ENGINE 2Ch10.5/12 FOR EMERGENCY AND RESCUE POWER PLANTS

This article describes methodology, modified mathematical apparatus and results of application of prof. Parsadanov complex fuel and ecological criteria for assessment of ecological safety level of exploitation process of emergency and rescue equipment which powered with piston ICE on example of autotractor diesel engine 2Ch10.5/12. The study found that ratio between monetary equivalents of criteria components are vary from mode to mode of testing cycle and reaches maximum on minimal idling modes. Values of criteria reaches maximum on the mode of nominal power. Exploitation of diesel engine on loading characteristic with crankshaft speed of maximal torque mode is less preferred, than its exploitation on loading characteristic with crankshaft speed of nominal power mode. Exploitation of that diesel engine on modes with zero and low effective power is characterized by extremely low fuel and ecological effectiveness. Scientific novelty of the research results is that carried out using experimental data of motor bench tests on example of autotractor diesel engine 2Ch10.5/12, that operates on 13-mode standardized steady testing cycle both for the whole cycle, and for its individual modes. Practical value of the research results is that with modified mathematical apparatus can be carried out assessment of ecological safety level of exploitation process of emergency and rescue equipment, which powered with piston ICE of any type.

Keywords: technogenic and ecological safety, complex criterial assessment, emergency and rescue equipment, diesel engine.

Problem statement. Exploitation process of emergency and rescue power plants (PP) units, which are on combat duty of divisions of the State Emergency Service of Ukraine and equipped with diesel piston internal combustion engines (PICE), obviously, must be characterized by certain ecological safety (ES) level [1 – 3]. The main ES factors for such objects is pollutants mass hourly emissions with its engines exhaust gas (EG) flow, legislative established on Ukraine territory requirements to which contained in [4]. In order to ensuring the necessary ES level of that process was developed corresponding ecological safety management system (ESMS) and described in [1]. In study [2] was developed evaluation conception of the ESMS functioning efficiency, which involves calculated criterial assessment of ES level of PP with PICE exploitation process, and formulated main requirements for such criteria.

Analysis of the recent researches and publications. But in specialized science and technical literature unitary approach to ES level complex assessment of such objects exploitation process vas not find and that puts the actual task of developing of methodological basis and mathematical apparatus for such assessment [2, 3]. Most close to meet requirements to that criteria from number of known is prof. Parsadanov complex fuel and ecological criteria K_{FE}, which vas developed for assessment of current competitiveness level of diesel PICE and activities for its increasing [5]. Calculated assessment of fuel and ecological effectiveness of PP exploitation process, the results is present in these paper, carried out for example of autotractor diesel engine 2Ch10.5/12, description and technical characteristics of which are given in [6]. Initial data for calculated assessment were obtained in studies [7, 8].

Purpose of the study is calculated assessment of ES level of exploitation process of emergency and rescue PP, based on PICE, with using complex fuel and ecological criteria on example of autotractor diesel engine 2Ch10.5/12.

Object of the study is ES level of exploitation process of emergency and rescue PP with PICE.

Subject of the study is values of complex fuel and ecological criteria, which describes object of the study.

Tasks of the study is:

1. Analysis of methodic and mathematical apparatus of prof. I.V. Parsadanov complex fuel and ecological criteria.
2. Modification of mathematical apparatus of K_{FE} criteria in order to be able assess its value for the individual representative modes of the diesel operation in its exploitation model.
3. Obtaining the initial data for calculated assessment of K_{FE} criteria values.
4. Calculated assessment of ES level of exploitation process of emergency and rescue PP with PICE on example of autotractor diesel engine 2Ch10.5/12 for regimes of 13-mode standardized steady testing cycle.
5. Analysis of results of the study.

Methods of the study is analysis of specialized science and technical literature, processing of motor bench experimental testing data, calculating of middle exploitation values of technical, economical and ecological diesel engine operational indicators, mathematical apparatus of prof. Parsadanov complex fuel and ecological criteria.

Statement of the problem and its solution. Mathematical apparatus of prof. Parsadanov complex fuel and ecological criteria K_{FE} described in [5] and assumes calculation middle exploitation value, that is, the only for separately taken exploitation model. For separately taken individual representative i-th operational regime of exploitation model it apparatus can be modified and described by following formulas

$$K_{FEi} = \eta_{ei} \cdot (1-\beta_i) = 3600/(H_u \cdot g_{ei}) \cdot (1 - Z_{ei}/(Z_{fei})) = = 3600/(H_u \cdot G_{fi}/N_{ei}) \cdot (1 - Z_{ei}/(Z_{fi} + Z_{ei})), \quad (1)$$

$$Z_{fi} = g_{ei} \cdot P_f, \quad (2)$$

$$Z_{ei} = G_{fi} \cdot \delta \cdot \sigma \cdot f \cdot \sum_{m=1}^{h} (A_k \cdot G_{mki}/G_{fi}) / N_{ei}, \quad (3)$$

$$N_{ei} = M_{\kappa pi} \cdot n_{\kappa \varepsilon i}/9550, \quad (4)$$

where index i represent i-th operational regime of exploitation model; H_u – motor fuel lower heat of combustion (H_u = 42,7 MJ/kg [5]); N_{ei} – diesel engine effective power, kW; G_{fi} – mass hourly fuel consumption by diesel engine, kg/h; G_{mki} – mass hourly pollutant emission with diesel engine EG flow, kg/h; A_m – dimensionless index of relative aggressiveness of m-th pollutant as a EG component (A_{NOx} = 41,1; A_{PM} = 200; A_{CnHm} = 3,16; A_{CO} = 1,0 [5]); h – number of legislative normalized pollutants in EG (h = 4 [1, 4, 5]); δ – dimensionless index of relative dangerous of pollution for various territories (for vehicle diesel engine δ = 1,0, for tractor diesel engine δ = 0,25 [5]); f – dimensionless coefficient, which taking into account the character of EG dispersion in atmosphere (for Ukraine territory f = 1,0 [5]); σ – dimension coefficient for converting scoring assessment of damage in the monetary (σ = P_f [5]); WF_i – weight factor operational mode in exploitation model (relative lobar engine run time on i-th polygon of exploitation model); η_e – effective efficiency coefficient of diesel engine; β – coefficient of relative exploitation ecological monetary costs; Z_e, Z_f and Z_{fe} – ecological damage compensation monetary costs, motor fuel monetary costs and total fuel and ecological monetary costs, \$/(kW·h); g_e – specific effective mass hourly fuel consumption by diesel engine, kg/(kW·h); P_f – price of motor fuel mass unit (results of choice of monetary equivalents units of K_{FE} criteria components given in [2], P_f = 0,871 \$/kg at P_f = 20,0 UAH/l, ρ_f = 0,85 kg/m^3 and currency exchanging course at December 2016 27,0 UAH/\$); $M_{\kappa pi}$ – torque of diesel engine, N·m; $n_{\kappa \varepsilon i}$ – crankshaft speed of diesel engine, min^{-1}.

Formulas (1)–(3) for whole diesel engine exploitation model formed in following formula [5].

$$K_{FE} = \frac{3600}{H_u \cdot \dfrac{\sum_{i=1}^{z}(G_{fi} \cdot \overline{P}_i)}{\sum_{i=1}^{z}(N_{ei} \cdot \overline{P}_i)}} \times \frac{\sum_{i=1}^{z}(G_{fi} \cdot \overline{P}_i)}{\sum_{i=1}^{z}(G_{fi} \cdot \overline{P}_i) + \delta \cdot f \cdot \sum_{i=1}^{z}\left[G_{fi} \cdot \overline{P}_i \cdot \sum_{m=1}^{h} \dfrac{A_m \cdot G_{mi}}{G_{fi}}\right]}, \quad (5)$$

$$\eta_{e.me} = 3600/(H_u \cdot g_{e.me}), \quad (6)$$

$$g_{e.me} = \sum_{i=1}^{z}(G_{fi} \cdot WF_i) / \sum_{i=1}^{z}(N_{ei} \cdot WF_i), \quad (7)$$

$$Z_f = g_{e.me} \cdot P_f, \quad (8)$$

$$Z_e = \sum_{i=1}^{z}(G_{fi} \cdot WF_i \cdot U_{Ei}) / \sum_{i=1}^{z}(N_{ei} \cdot WF_i), \quad (9)$$

$$U_{Ei} = \delta \cdot \sigma \cdot f \cdot g_{pri}, \quad (10)$$

$$g_{pri} = \sum_{m=1}^{h}(A_k \cdot G_{pki}/G_{fi}), \quad (11)$$

where $\eta_{e.me}$ – middle exploitation values of effective efficiency coefficient of diesel engine; $g_{e.me}$ – middle exploitation values of specific effective mass hourly fuel consumption by diesel engine, kg/(kW·h); U_{Ei} – ecological damage compensation monetary valuation, \$/kg; $g_{pr.i}$ – specific effective mass hourly pollutant emission by diesel engine, kg/(kW·h); Z_e і Z_f – middle exploitation values of ecological damage compensation monetary costs, motor fuel monetary costs, \$/(kW·h).

Features of engine test bench and methodic of experimental researches with it, which are used for determination of 2Ch10.5/12 diesel engine and its DPF operational characteristics in articles [1, 7, 8], involves the following activities. Firstly, the G_{PMi} value in kg/h for i-th exploitation mode obtained with using following known conversion formula, which described and grounding in the study [5], depended on value of light flow weakening coefficient in EG probe N_D (indicator of EG opacity), %, unburned hydrocarbons of motor fuel and oil C_nH_m volume concentration in EG flow C_{CH}, ppm, mass hourly consumption of fuel and air G_{air} і G_f, kg/h

$$G_{PMi} = \Bigg(2{,}3 \cdot 10^{-3} \cdot N_{Di} + 5 \cdot 10^{-5} \cdot N_{Di}^2 + 0{,}145 \cdot \frac{C_{CHi} \cdot 4{,}78 \cdot 10^{-7} \cdot (G_{airi} + G_{fi})}{0{,}7734 \cdot G_{airi} + 0{,}7239 \cdot G_{fi}} + 0{,}33 \cdot \left(\frac{C_{CHi} \cdot 4{,}78 \cdot 10^{-7} \cdot (G_{airi} + G_{fi})}{0{,}7734 \cdot G_{airi} + 0{,}7239 \cdot G_{fi}}\right)^2\Bigg) \times \frac{(0{,}7734 \cdot G_{airi} + 0{,}7239 \cdot G_{fi})}{1000}. \quad (12)$$

Secondly, values of mass hourly emissions of NO_x, C_nH_m and CO G_{mNOx}, G_{mCH} and G_{mCO} in kg/h converts from experimentally obtained values of volume concentrations in EG probe C_{VNOx} C_{VCOi} and C_{VCnHmi} in ppm with using methodic in [5] by following formulas, which taking into account correction coefficients of laboratory air humidity F_{NOxi} and F_{COi}.

$$G_{NOxi} = 1{,}587 \cdot 10^{-3} \cdot C_{VNOxi} \cdot F_{NOxi} \cdot (G_{пали} + G_{пові}), \quad (13)$$

$$G_{COi} = 9{,}66 \cdot 10^{-4} \cdot C_{VCC.i} \cdot F_{COi} \cdot (G_{пали} + G_{пові}), \quad (14)$$

$$G_{CnHmi} = 4{,}78 \cdot 10^{-4} \cdot C_{VCnHmi} \cdot (G_{пали} + G_{пові}), \quad (15)$$

$$F_{NOxi} = (1 + (0{,}044 \cdot G_{пали}/G_{пові} - 0{,}0038) \cdot (7 \cdot d - 75) + (0{,}0053 - 0{,}116 \cdot G_{пали}/G_{пові}) \cdot 1{,}8 \cdot (T_0 - 302))^{-1}, \quad (16)$$

$$d = 6{,}21 \cdot \varphi_0 \cdot P_s / (B_0 - 0{,}01 \cdot \varphi_0 \cdot P_s), \quad (17)$$

$$F_{COi} = 1 - 1{,}85 \cdot G_{пали}/G_{пові}, \quad (18)$$

$$P_s = 6{,}1121 \cdot \exp((18{,}678 - t_0/234{,}5) \cdot t_0/(257{,}14 + t_0)), \quad (19)$$

where d = 5,367 g/kg – mass concentration of water steam in air; φ_0 = 50 % – relative air humidity;

B_0 = 995 hPa – barometric pressure; P_s = 17,052 hPa – water vapor saturated pressure; t_0 = 15 °C – temperature of environmental air.

Diesel engine 2Ch10.5/12 is autotractor naturally aspirated two-cylinder in-line four-stroke two-valve air-cooled piston internal combustion engine with internal mixture formation and compression ignition; with traditional trunk-piston axial crankshaft mechanism, cylinder diameter 105 mm, piston stroke 120 mm, piston-rod length 270 mm, working volume 2.0 l, compression ratio 16.5; with nominal power 21_{-3} kW (at n_{cs} = 1800 min^{-1}), maximal torque 111_{-16} N·m (at n_{cs} =1200 min^{-1}), middle exploitation specific mass hourly fuel consumption 235 g/(kW·h); with direct injection in undivided semispherical combustion chamber in piston by one-plunger high-pressure fuel pump of distributional type with all-regimes mechanical regulator and hydromechanical nozzles; with weight 280 kg, external dimensions 693×687×855 mm; with starting from the starter; made by Vladimir Tractor Plant. It using on tractors, automotive chassis, selecting combines, asphalt and concrete placers, mobile electric welding, water pump and air compressor stations [6].

Parameters of 13-mode standardized steady testing cycle as an autotractor diesel engine exploitation model describing in UNECE Regulations № 49 [4] and shown on table 1. Legislative established on Ukraine territory requirements to PP with PICE ES level indicators in historical dynamic shown on table 2. [1].

Table 1 – Parameters of 13-mode standardized steady testing cycle and its values for diesel engine 2Ch10.5/12 [1, 4, 5]

№ of mode	n_{cs}, min^{-1}		M_T, N·m		WF
	designation at regime of	value	designation % $M_{T\max}$	value	
13-mode cycle					
1	minimal idle	800	0	0	0,25/3
2	maximal torque	1200	2	2,2	0,08
3	maximal torque	1200	25	27,5	0,08
4	maximal torque	1200	50	55	0,08
5	maximal torque	1200	75	82,5	0,08
6	maximal torque	1200	100	110	0,25
7	minimal idle	800	0	0	0,25/3
8	nominal power	1800	100	95	0,10
9	nominal power	1800	75	71,3	0,02
10	nominal power	1800	50	47,5	0,02
11	nominal power	1800	25	23,8	0,02
12	nominal power	1800	2	1,9	0,02
13	minimal idle	800	0	0	0,25/3

Table 2 – Legislative established requirements of ecological indicators of diesel engines [1, 4, 5]

EURO level	Year of goes into effect	Specific mass hourly emission of pollutant, g/(kW·h)			
		PM	NO_x	C_nH_m	CO
I	1992	0,612	8,0	1,1	4,5
II	1996	0,25…0,15	7,0	1,1	4,0
III	2000	0,10	5,0	0,66	2,1
IV	2005	0,02	3,5	0,46	1,5
V	2008	0,02	2,0	0,25	1,5
VI	2012	0,01	0,5	0,2	1,0

In monograph [5] K_{FE} criteria values and its components β, Z_e, Z_f and Z_{fe} was assessed for different models of exploitation as a whole, but not for its individual modes. These due to presents in that exploitation models regimes with zero (idling) and low effective power. For idling regimes N_{ei} → 0 kW and therefore $\eta_e \to 0$, $g_e \to \infty$ kg/(kW·h) and Z_e, Z_f, $Z_{fe} \to \infty$ \$/(kW·h), β → 1 and $K_{FE} \to 0$ (see formulas (1) – (3)). For regimes with low effective power K_{FE} criteria values are not informative.

For obtaining opportunities of assessment K_{FE} criteria values for individual regimes of exploitation models in present paper propose the following method. It is necessary to use interpretation of the term "idle run" is not in adopted in engine theory, but in the engine operating practices as a part of the PP. In this case, the on idling run engine produces non zero effective power that is spent on the needs of secondary energy consumers of PP and on providing comfortable working conditions for the PP operator. The first-mentioned case includes charging an electric battery, powering electronic control systems, powering hydraulic and pneumatic servo systems end others. The second-mentioned case includes lighting of workplace and passenger compartment, powering light indicators and control panel, powering air conditioning, multimedia and navigation systems system, end etc.

Then we take the following assumption: the effective power N_{ei} on the idle run regime of engine operating models defined by the formula (4), in which the torque $M_{\kappa p i}$ is equal to 1 % of the maximum diesel torque (110 N·m), and crankshaft speed $n_{\kappa в i}$ equal to the crankshaft speed of minimal idling regime (900 min^{-1}), that is for diesel 2Ch10.5/12, it is equal to 46.1 W.

Results of calculated assessment, which based on experimental data obtained in [7, 8] (presented on fig. 1–3), for autotractor diesel engine 2Ch10.5/12 and, that operates on 13-mode standardized steady testing cycle, shown on Fig. 3 and 5.

From the Fig. 2 and 3 we can see, that that ratio between monetary equivalents of compensation of ecological damage costs Z_e, motor fuel costs Z_f and total fuel and ecological costs Z_{fe} are vary from mode to mode of testing cycle and reaches maximum on modes of minimal idling (modes № 1, 7, 13).

Values of K_{FE} criteria without taking into account weight factor value WF reaches maximum on the mode of nominal power (mode № 8) and with taking into account WF value – on the mode of maximal torque (mode № 6).

Exploitation of diesel engine 2Ch10.5/12 on loading characteristic with crankshaft speed of maximal torque mode (modes № 2–6) by K_{FE} criteria value is less preferred, than its exploitation on loading characteristic with crankshaft speed of nominal power mode (modes № 8–12).

Exploitation of that diesel engine on modes with zero effective power (modes № 1, 7, 13) and also on modes with low effective power (modes № 2, 12) is characterized by extremely low fuel and ecological effectiveness.

Middle exploitation value of K_{FE} criteria (e.i. with taking into account distribution of value WF by modes of testing cycle) is $43.989 \cdot 10^{-3}$, and middle value (e.i. in case of equality of value WF for all modes of model of diesel engine exploitation) is $41.204 \cdot 10^{-3}$.

Conclusions. Thus, in present study describes methodology, modified mathematical apparatus and results of application of prof. Parsadanov complex fuel and ecological criteria and its components.

The study found that ratio between monetary equivalents of criteria components are vary from mode to mode of testing cycle and reaches maximum on minimal idling modes. Values of criteria reaches maximum on the mode of nominal power. Exploitation of diesel engine on loading characteristic with crankshaft speed of maximal torque mode is less preferred, than its exploitation on loading characteristic with crankshaft speed of nominal power mode. Exploitation of that diesel engine on modes with zero and low effective power is characterized by extremely low fuel and ecological effectiveness.

With modified mathematical apparatus can be carried out assessment of ecological safety level of exploitation process of emergency and rescue equipment, which powered with piston ICE of any type, and in what is *practical value* of results of the study. The study carried out using experimental data of motor bench tests on example of autotractor diesel engine 2Ch10.5/12, that operates on 13-mode standardized steady testing cycle both for the whole cycle, and for its individual modes, and in what is *scientific novelty* of results of the study.

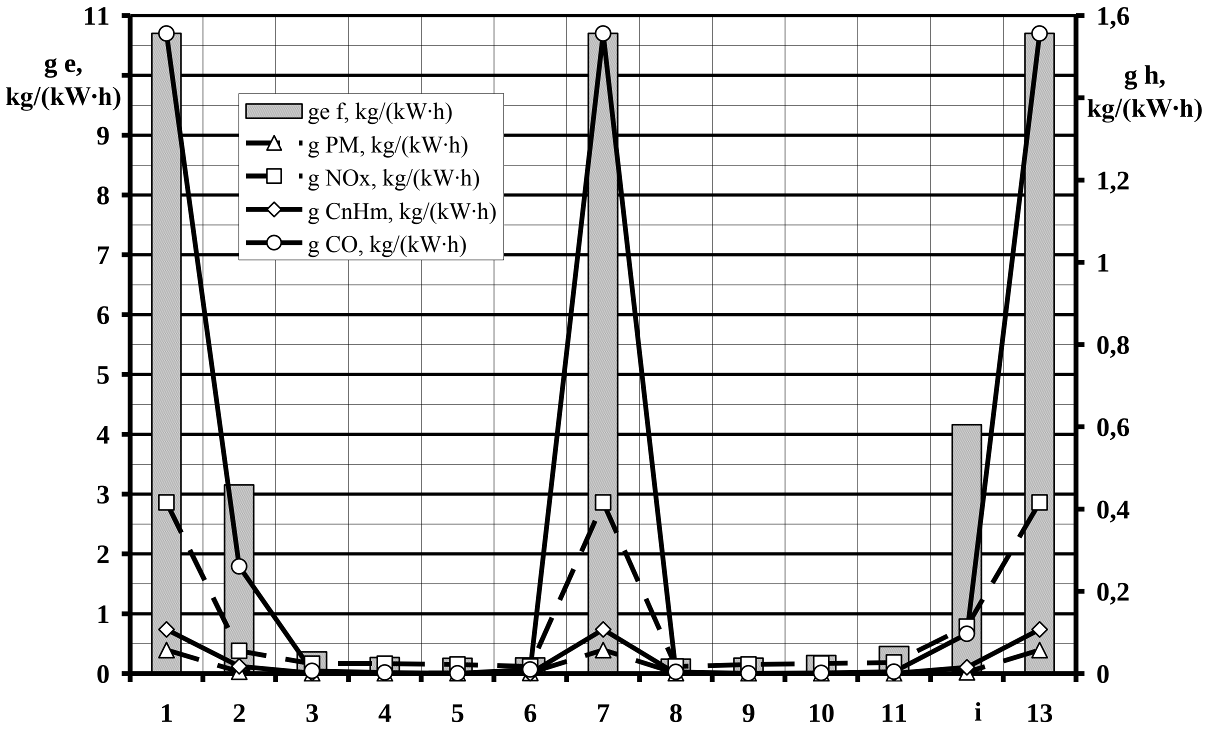

Figure 1 – Initial data for calculated estimation of values of complex fuel and ecological criteria K_{FE} for diesel engine 2Ch10.5/12 and 13-modes testing cycle, experimentally obtained in [7, 8]

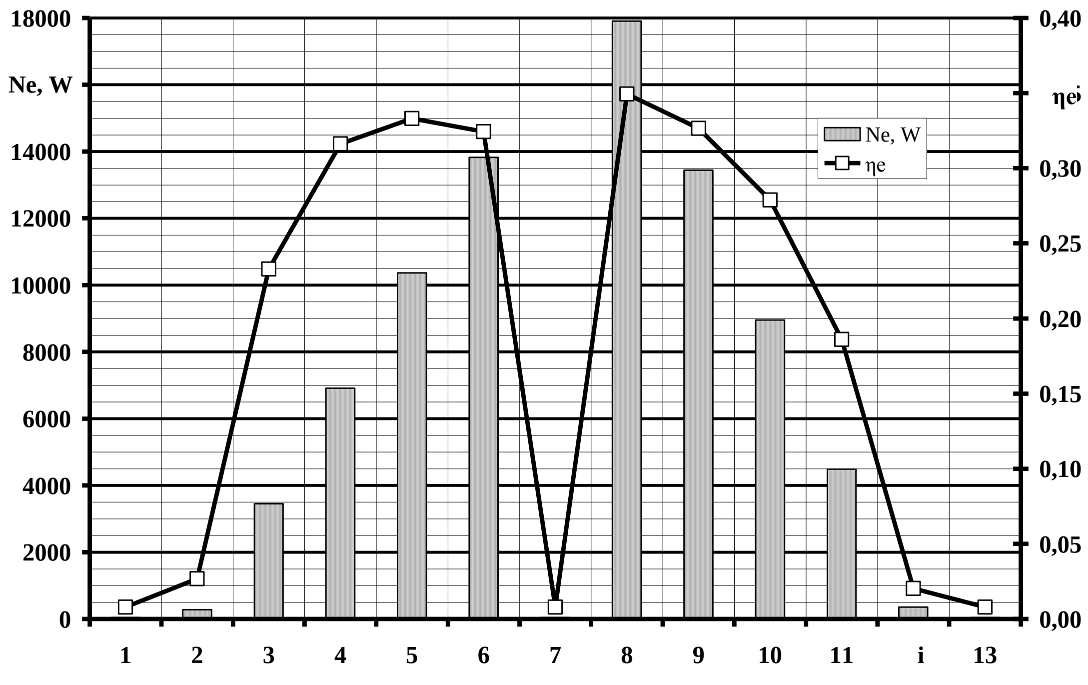

Figure 2 – Initial data for calculated estimation of values of complex fuel and ecological criteria K_{FE} for diesel engine 2Ch10.5/12 and 13-modes testing cycle, experimentally obtained in [7, 8]

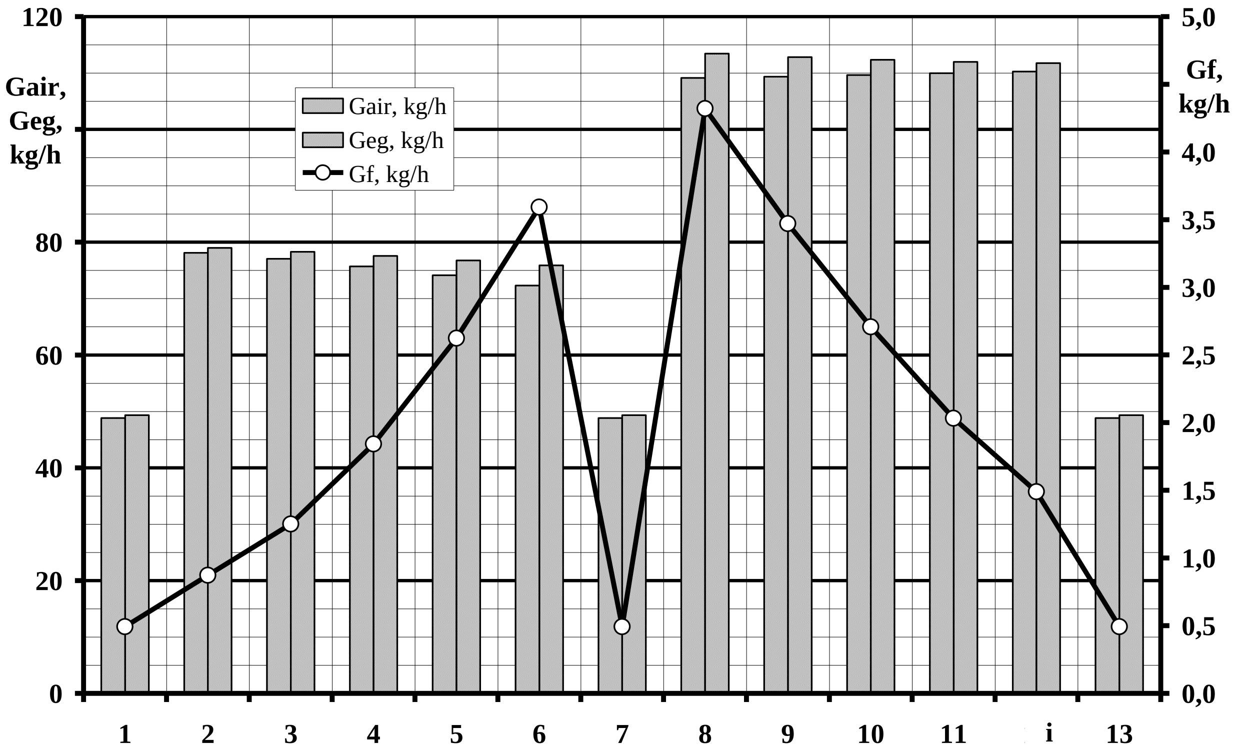

Figure 3 – Initial data for calculated estimation of values of complex fuel and ecological criteria K_{FE} for diesel engine 2Ch10.5/12 and 13-modes testing cycle, experimentally obtained in [7, 8]

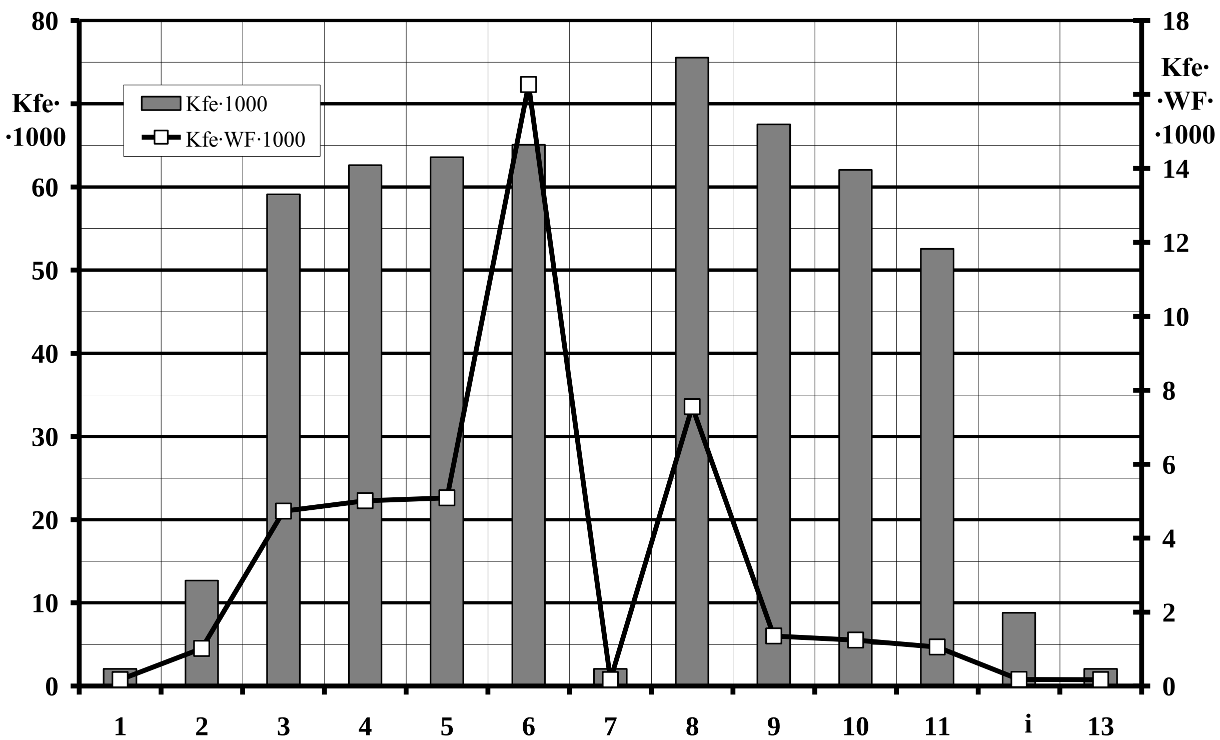

Figure 4 – Results of calculated quantitative estimation of complex fuel and ecological criteria K_{FE} for diesel engine 2Ch10.5/12 and 13-modes testing cycle

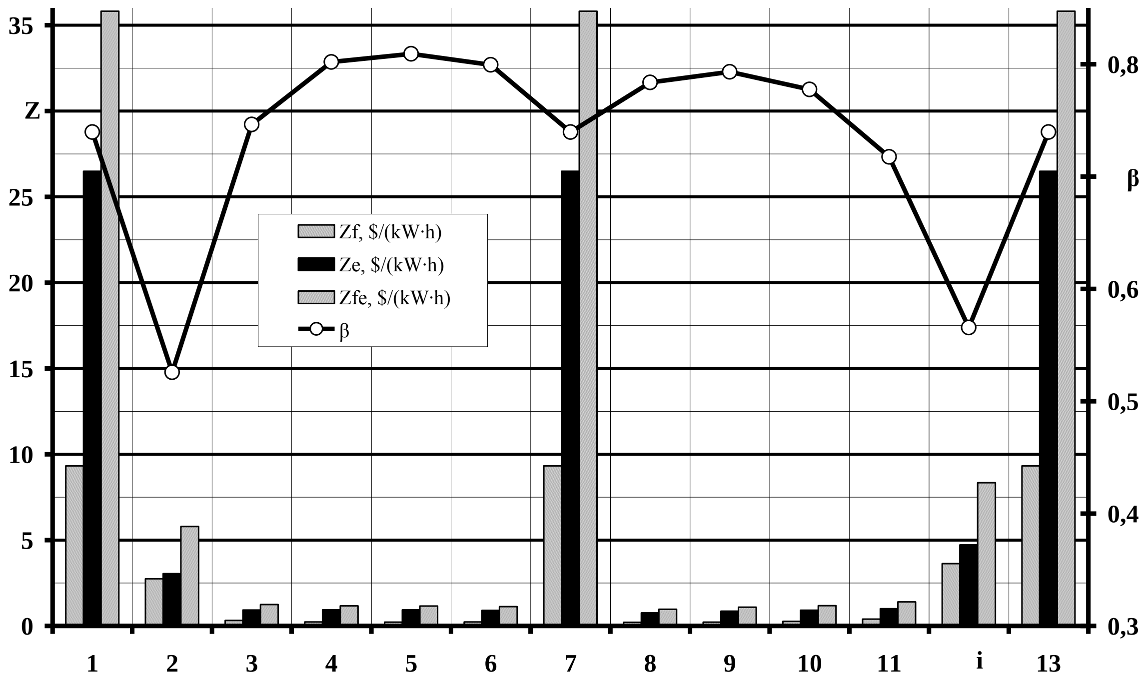

Figure 5 – Results of calculated quantitative estimation of components of complex fuel and ecological criteria K_{FE} for diesel engine 2Ch10.5/12 and 13-modes testing cycle

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The article was received by the editorial board 03.03.2017

С. О. Вамболь,О. М. Кондратенко

РЕЗУЛЬТАТИ КОМПЛЕКСНОГО КРИТЕРІАЛЬНОГО ПАЛИВНО-ЕКОЛОГІЧНОГО ОЦІНЮВАННЯ ДИЗЕЛЬНОГО ДВИГУНА 2Ч10,5/12 ДЛЯ АВАРІЙНО-РЯТУВАЛЬНИХ ЕНЕРГЕТИЧНИХ УСТАНОВОК

У цій статті описано методику, модифікований математичний апарат та результати застосування комплексного паливно-екологічного критерію проф. І.В. Парсаданова для оцінювання рівня екологічної безеки процесу експлуатації аварійно-рятувальної техніки, що живиться поршневим ДВЗ на прикладі автотракторного дизеля 2Ч10,5/12. Дослідження показало, що співвідношення між значеннями вартісних еквівалентів компонентів критерію є змінними по режимах випробувального циклу і сягають максимумів на режимах мінімального холостого ходу. Значення самого критерію сягають максимуму на режимі номінальної потужності. Експлуатація дизеля на навантажувальній характеристиці з частотою обертання колінчастого валу режиму максимального крутного моменту є менш бажаною, аніж його експлуатація на режимах навантажувальній характеристиці з частотою обертання колінчастого валу режиму номінальної потужності. Експлуатація цього дизеля на режимах з нульовою та мінімальною ефективною потужністю характеризується вкрай низькою паливно-екологічною ефективністю. Наукова новизна отриманих результатів полягає в тому, що вперше застосовано комплексний паливно-екологічний критерій для автотракторного дизеля 2Ч10,5/12 з використанням експериментальних даних стендових моторних досліджень за окремими режимами 13-режимного стандартизованого стаціонарного випробувального циклу і для всього циклу. Практичне значення отриманих результатів полягає в тому, що з використанням модифікованого математичного апарату стає можливим оцінювання рівня екологічної безпеки процесу експлуатації аварійно-рятувальної техніки, що живиться поршневим ДВЗ будь-якого типу.

Ключові слова: техногенно-екологічна безпека, комплексне критеріальне оцінювання, аварійно-рятувальна техніка, дизельний двигун.

С. А. Вамболь, А. Н. Кондратенко

РЕЗУЛЬТАТЫ КОМПЛЕКСНОГО КРИТЕРИАЛЬНОГО ТОПЛИВНО-ЭКОЛОГИЧЕСКОГО ОЦЕНИВАНИЯ ДИЗЕЛЬНОГО ДВИГАТЕЛЯ 2Ч10,5/12 ДЛЯ АВАРИЙНО-СПАСАТЕЛЬНЫХ ЭНЕРГЕТИЧЕСКИХ УСТАНОВОК

В данной статье описана методика, видоизмененный математический аппарат и результаты применения комплексного топливно-экологического критерия проф. И.В. Парсаданова для оценки уровня экологической безопасности процесса эксплуатации аварийно-спасательной техники, оснащенной поршневым ДВС на примере автотракторного дизеля 2Ч10,5/12. Исследование показало, что соотношение между значениями стоимостных эквивалентов компонентов критерия являются переменными по режимам испытательного цикла и достигают максимумов на режимах минимального холостого хода. Значение самого критерия достигают максимума на режиме номинальной мощности. Эксплуатация дизеля на нагрузочной характеристике с частотой вращения коленчатого вала режима максимального крутящего момента менее предпочтительна, чем его эксплуатация на режимах нагрузочной характеристике с частотой вращения коленчатого вала режима номинальной мощности. Эксплуатация этого дизеля на режимах с нулевой и минимальной эффективной мощностью характеризуется крайне низкой топливно-экологической эффективностью. Научная новизна полученных результатов состоит в том, что впервые применен комплексный топливно-экологический критерий для автотракторного дизеля 2Ч10,5/12 с использованием экспериментальных данных стендовых моторных исследований по отдельным режимами 13-режимного стандартизированного стационарного испытательного цикла, а также для всего цикла. Практическое значение полученных результатов состоит в том, что с использованием видоизмененного математического аппарата становится возможным оценивание уровня экологической безопасности процесса эксплуатации аварийно-спасательной техники, оснащенной поршневым ДВС любого типа.

Ключевые слова: техногенно-экологическая безопасность, комплексное критериальное оценивание, аварийно-спасательная техника, дизельный двигатель.