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SOME ASPECTS OF COMPLEX CRITERIA-BASED ASSESSMENT OF THE LEVEL OF ECOLOGICAL SAFETY OF THE EXPLOITATION PROCESS OF RECIPROCATING INTERNAL COMBUSTION ENGINES

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Annotation: in the study methods of calculation assessment of reference values of complex fuel-ecological criterion of Prof. Igor Parsadanov as reference points of psychophysical scale of partial desiability function at its use as the ecological safety factor of exploitation process of power plants with reciprocating ICE are developed as well as was improved methods of calculated assessment of the magnitudes of this criterion and the Index of ecological and chemical assessment of Prof. Pavlo Kanilo, taking into account: emissions of sulfur oxides and benzo(a)pyrene and other polycyclic aromatic hydrocarbons in the composition of exhaust gases diesel engine.

Key words: ecological safety, criteria-based assessment, internal combustion engine, benzo(a)pyrene, reference values, transport technologies, pondrability

Part 1. Determination of reference values of complex fuel-ecological criterion and ponderability of its fuel component

Introduction. The relevance of this study is due to the following. In the monograph [1] the analysis of 9 known mathematical apparatuses suitable for realization of complex calculated assessment of ecological safety (ES) level of accident-free exploitation process of power plants (PP) with reciprocating internal combustion engines (RICE) is carried out. According to the results of analysis and systematization in the form of appropriate classification, it is established that the most suitable for achieving this goal can be considered mathematical apparatuses of complex fuel and ecological criterion of prof. Igor Parsadanov K_{fe} and the generalized desirability function of Harrington D. In the same source a comparative analysis of the advantages and disadvantages of selected alternative criterion mathematical apparatuses is made and it is concluded that it is expedient for further research to use both apparatuses with mutual strengthening of advantages and weakening of disadvantages. The first step in this way is to use the mathematical apparatus of the generalized desirability function with the structure of the considered influencing factors, identical to the complex fuel-ecological criterion. Since the main advantage of the K_{fe} criterion is taking into account the mass hourly fuel consumption G_{fuel} of RICE, to use this advantage it is necessary to determine the ponderability of this environmental damage factor compared to others – emissions of legislative normalized pollutants with exhaust gas (EG) flow G_k, carried out in the monograph [2]. The source [1] also provides an improved classification of ES factors, the source of which is the RICE in PP, which consists of 15 items, as well as the character of the impact of G_{fuel} on all other ES factors in this classification. However, the analysis of scientific and technical literature did not reveal the results of such a study, so obtaining a set of magnitudes of the criterion K_{fe}, which can be correlated with the reference points of the scale of partial desirability function d, is an urgent scientific and technical problem.

Purpose of the study: determination of reference values of complex fuel-ecological criterion of prof. Igor Parsadanov as reference points of the psychophysical scale of the partial function of desirability. *Object of the study:* quantitative characteristics of the fuel-ecological criterion of prof. Igor Parsadanov as the ES factor. *Subject of the study:* magnitudes of reference values of fuel-ecological criterion of prof. Igor Parsadanov for different levels of legislative established environmental standards and depending on the level of fuel efficiency of RICE.

Material and research results. Given that the fuel component of the K_{fe} criterion completely determines its ecological component, as detected in the monograph [1], it is rational to explore the features of another approach, namely the use of the K_{fe} criterion as a separate influencing factor in the structure of the generalized desirability function D. At the same time it becomes possible to consider indicators of vibration (degree of non-uniformity of crankshaft rotation δ_{cs}, Klimov-Stechkin criterias ξ_{cs} and η_{cs}), noise (equivalent L_{Aequ} and maximum $L_{A\max}$ noise level), thermal pollution (mass hourly fuel consumption G_{fuel} separately from fuel component of the K_{fe} criterion), emission of sulfur oxides G_{SOx}, etc. To implement such approach, as follows from the algorithm for applying formula (1), which describes the Harrington generalized desirability function given in [1], it is necessary to have data on the values of such ES factor (i.e. the response of the local quality criterion r), which can be correlated with the reference points of the psychophysical scale of evaluation of desirability of the response value r «good» and «badly», as well as their corresponding magnitudes of the scale of values of the basic evaluation of the magnitudes of the partial desirability function d = 0.63… 0.8 and d = 0.2… 0.32.

$$D_i = \sqrt[\sum_{k=1}^{n} \upsilon_k]{\prod_{k=1}^{n} d_{ki}^{\upsilon_k}} = \sqrt[(\upsilon_{k_1} + \upsilon_{k_2} + \ldots + \upsilon_{k_n})]{d_i(k_1)^{\upsilon_{k_1}} \cdot d_i(k_2)^{\upsilon_{k_2}} \cdot \ldots \cdot d_i(k_n)^{\upsilon_{k_n}}}, \quad (1)$$

$$d_{ki} = \exp[-\exp(a_{ki} + b_{ki} \cdot r_{ki})]; k = \{K_{fe}, G_{SO_x}, \delta_{cs}, \xi_{cs}, \eta_{cs}, L_{Aequ}, L_{A\max}, \ldots\}, \quad (2)$$

where d_k – partial desirability function that meets the k^{th} quality criterion, d_k = 0 1,0, and $k_1 = K_{fe}$; n – the number of considered quality criteria; υ_k – ponderability coefficient of considered k^{th} quality criterion, $0 < \upsilon_k \leq 1$, and υ_{k1} = 38,4 + 245,3 = 283,7, r_{ki} – the actual value of the k^{th} quality criterion on the i^{th} representative RICE operation regime in the model of its exploitation; a_{ki} and b_{ki} – coefficients determined on the basis of establishing of correspondence between a pair of characteristic values r_{ki} and d_{ki} according to following data: r_{ki} = «Very good» → d_{ki} = 1.0 … 0.8; r_{ki} = «Good» → d_{ki} = 0.8 … 0.63; r_{ki} = «Satisfactory» → d_{ki} = 0.63 … 0.37; r_{ki} = «Badly» → d_{ki} = 0.37 … 0.2; r_{ki} = «Very badly» → d_{ki} = 0.2 … 0.0 [1, 2, 4].

It is proposed to choose as the reference value of emissions of legislative normalized pollutants contained in the relevant standards (see [1 – 3]) for the current values («good» and d = 0.8) and previous scores «badly» and d = 0.2) EURO levels. However, different RICE which are currently in exploitation belong to different generations of such equipment and are in different current technical condition (corresponding to the degree of physical wear and compliance with the order of routine maintenance and repair) and therefore are characterized by different levels of fuel efficiency, i.e. magnitude of specific effective mass hourly fuel consumption g_e. Therefore, it is necessary to obtain the dependences of the magnitudes of the criterion K_{fe}, in the structure of which the indicators of the ecological component acquire the legislative normalized values, from the magnitude of the fuel component of the criterion for different levels of EURO standards. The data allowing to choose the parameters of the components of formula (2) for the partial desirability functions d_k are obtained by solving of systems of two equations (see [4]) for cases that correspond to each other the characteristic values of r_{ki} and d_{ki}, known from practice or regulations.

The essence of the proposed method is that as the magnitudes of r_{kiup} will be used the individual regime magnitude of the criterion K_{fe} (see formula (3)), the factors of the ecological component of which (G_{PM}, G_{NOx}, G_{CnHm}, G_{CO}) meet current legal standards (i.e. EURO level VI, the most stringent in terms of historical retrospect), and as the magnitudes of r_{kidn} – the magnitudes of the criterion K_{fe}, the factors of the ecological component of which meet less stringent in terms of historical retrospect standards (i.e. levels EURO I…VI). Such requirements in historical retrospect are summarized in [4].

The standards of toxicity of EG of RICE [1 – 5] indicate the maximum allowable values of specific effective mass hourly emissions of pollutants with the EG flow (g_{PM}, g_{NOx}, g_{CnHm}, g_{CO} in kg/(kW·h)), and not the values of their mass hourly emission (G_{PM}, G_{NOx}, G_{CnHm}, G_{CO} in kg/h), which appear in the formula (3) for determining the magnitude of the criterion K_{fe}.

Magnitude of the mass hourly emission of the k^{th} pollutant G_k, which corresponds to the normatively established magnitude of the specific effective mass hourly emission of the same pollutant g_k, depends on the value of RICE effective power N_e in kW, and therefore, from the coordinates of the field of operating regimes of the engine (crankshaft speed n_{cs} in rpm and torque M in N·m).

Dependence of the reference values of the K_{fe} criterion on the magnitude of the specific effective mass hourly fuel consumption of RICE g_e for different levels of EURO and the basic magnitudes of coefficient σ = 1,0, factor f = 1,0 and value H_u = = 42,7 MJ/kg, shown in Table 1.

Table 1. Dependence of the reference values of criterion $K_{fe} = f(g_e)$ for different levels of EURO and σ = 1,0, f = 1,0 and H_u = 42,7 MJ/kg

K_{fe}, ‰		g_e, g/(kW·h)										
		0	50	100	150	200	250	300	350	400	450	500
Level EURO	I	183.6	165.5	150.7	138.4	127.9	118.9	111.0	104.2	98.1	92.7	87.9
	II	251.5	218.8	193.7	173.7	157.5	144.0	132.7	123.0	114.7	107.4	100.9
	III	367.0	301.4	255.7	222.0	196.2	175.7	159.1	145.4	133.9	124.0	115.5
	IV	558.9	419.8	336.1	280.2	240.3	210.3	187.0	168.3	153.0	140.3	129.5
	V	952.5	608.7	447.2	353.5	292.2	249.0	217.0	192.2	172.6	156.5	143.2
	VI	3484.9	1136.3	678.8	484.0	376.0	307.5	260.0	225.3	198.7	177.8	160.8

Part 2. Taking into account of emission of polycyclic aromatic hydrocarbons in criteria-based assessment of ecological safety level of vehicle with RICE exploitation process

Introduction. The relevance of this study is due to the following. According to the results of the analysis of the mathematical apparatus of the complex fuel-ecological criterion of prof. Igor Parsadanov K_{fe} in the monograph [1], which also proposed a faceted classifier of such mathematical apparatuses, found that it should be classified as «Internal» or «Causal». The main alternative to it is the mathematical apparatus of the integral index of ecological-chemical evaluation prof. Pavlo Kanilo. The original versions of these apparatuses is described respectively in monographs [3, 8]. The main disadvantage of the K_{fe} criterion is the absence in the composition of the considered ecological safety (ES) factors, specified in their hierarchical classifier, proposed in the monograph [1]. The same source formulates the concept of improving the mathematical apparatus and methods of applying the K_{fe} criterion, one of the main points of which is the partial overcoming of this disadvantage, namely, the introduction of the criterion of new ES factors, which are essentially emissions of gaseous pollutants. In particular, in the classification of ES factors improved by the author, the source of which is reciprocating internal combustion engine (RICE) in the power plant (PP), with the corresponding hierarchical classifier in addition to legally regulated directly gaseous and aerosol pollutants in the exhaust gases (EG) flow, there are also legally regulated indirectly – sulfur oxides SO_x, polycyclic aromatic hydrocarbons (PAH) (including benzo(a)pyren (B(a)P)) etc., as well as legally unregulated – emissions of vapors of motor fuel and oil, aerosol of crankcase gases and etc. However, the analysis of scientific and technical literature by the authors of the study to expand the range of ES factors taken into account by the mathematical apparatus of the K_{fe} criterion is not revealed, so the implementation of such research and analysis of its results is an urgent scientific and technical task.

Purpose of the study: expansion of the nomenclature of ES factors, which are taken into account by the mathematical apparatus of the complex fuel-ecological criterion K_{fe}, in particular B(a)P and PAH. *Object of the study:* the place of emissions of B(a)P and PAH in the structure of the influencing ES factors of the complex fuel-ecological criterion K_{fe} and the integrated index of ecological-chemical assessment *F*. *Subject of the study:* quantitative and qualitative aspects of the object of the study.

Material and research results. Magnitudes of the criterion K_{fe} for *i*-th RICE steady representtative operational regime with value of weight factor *WF* are determined by formula (3) and its components – by formulas (4) [1–4]. Average exploitation magnitude of criterion K_{fe} is described by formula (5) as it proposed in study [2].

$$K_{fe} = \eta_e \cdot (1-\beta) \cdot 10^3 = f\left(\sum_{m=1}^{h} (A_k \cdot G_k)/G_{fuel} \right), \text{‰}; \qquad (3)$$

$$\sum_{m=1}^{h} (A_k \cdot G_k) = A(PM) \cdot G(PM) + A(NO_x) \cdot G(NO_x) +$$

$$A(C_nH_m) \cdot G(C_nH_m) + A(CO) \cdot G(CO), \text{ kg/h}; \qquad (4)$$

$$K_{feme} = \sqrt[7]{\sum_{i=1}^{N} \left(K_{fei}^7 \cdot WF_i \right) / \sum_{i=1}^{N} (WF_i)} \cdot 1000, \text{‰}. \qquad (5)$$

where the index i indicates the values for a separate representative mode of RICE operation or range in the its exploitation model; 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; $h = 4$ – number of pollutants in EG flow; η_e – effective efficiency coefficient; β – coefficient of relative exploitation ecological monetary costs.

In present study the following methods is proposed for such assessment that takes into account the toxic influence of B(a)P and PAH emission on a human in accordance of which formula (2) converts into the formula (6) where value of coefficients A(B(a)P) and A(PAH) determine the approach from [3, 7 – 10].

$$\sum_{m=1}^{h} (A_k \cdot G_k)_{improved} = \sum_{m=1}^{h} (A_k \cdot G_k)_{basic} + A(B(a)P) \cdot G(B(a)P) + A(PAH) \cdot G(PAH). \qquad (6)$$

In studies of prof. Pavlo Kanilo which analyzed in study [9, 10] was proposed the integral index of ecology-chemical evauation of RICE and degree of efficiency of its improving that in accordance with develops by author of this study classifycation of criteria-based mathematical apparatuses that are suitable for implementation of complex calculated assessment of operation efficiency of ES management system of the process of accident-free exploitation process that was developed in study [1] also related to types of «Internal» or «Causal».

Magnitudes of the index F for one complete cycle on testing of RISE of the test bench with running drums are determined by formula (7) [1, 8].

$$F_j = 10^{-3} \times \left\{ \left(\frac{M_{CO}}{[CO]} + \frac{M_{CH}}{[CH]} + a \cdot \frac{M_{NO_2}}{[NO_2]} + b \cdot \frac{M_{Soot}}{[Soot]} \right) + \left(c \cdot \frac{M_{SO_2}}{[SO_2]} + d \cdot \frac{\Sigma CA_{(EG)}}{[B(a)P]} \right) \right\}_{tc} \qquad (7)$$

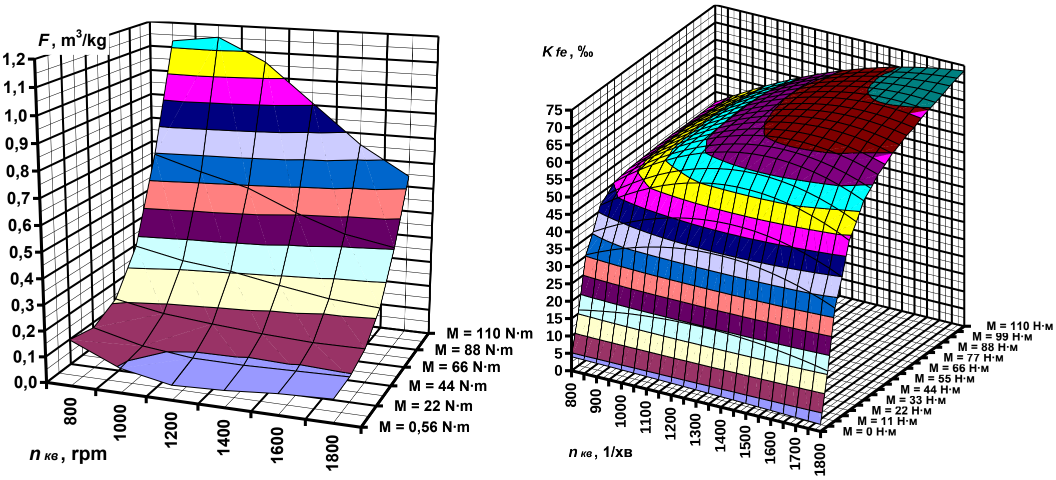
where M_k – mass of emission of k-th pollutant during one complete cycle on testing of RICE (see index «*ts*»), kg/cycle; [k] = $[MPC_k]_{dn}$ – maximum permissible concentration of k-th pollutant, kg/m^3; a = 3,0; b = 3,0; c = 2,0; d = 4,0 – coefficients that take into account the further intensification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

In this study was used modified variant of formula (7), i.e. index F, in which instead the values of mass of emission of k-th pollutant during one complete cycle on testing of RICE M_k (in kg/cycle) author is proposes to use the values of mass hourly emission of of k-th pollutant G(k) on individual regime of exploitation model (in kg/h). Such approach which will allow except solution of problem of absence of initial data of appropriate type (i.e. values of M_k) also obtained 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 (7) is the uncertainty of magnitudes of empirical coefficients a, b, c and d for RICE of different types and models besides for wich studies described in monograph [2] was carried out. It this study the values of the empirical coefficients recommended in prof. Kanilo`s studies were used. In this case appears the need for determination of middle exploitation value of index F what in this study author is proposes to obtained as the weighted arithmetic mean i.e. by the formula (8).

$$F = \sum_{i=1}^{N}\left(F_i \cdot WF_i\right) / \sum_{i=1}^{N}\left(WF_i\right); \sum_{i=1}^{N}\left(WF_i\right) = 1{,}0\,. \qquad (8)$$

Thus, distributions of magnitudes of values criterion K_{fe} and index F on operational regimes field of 2Ch10.5/12 autotractor diesel engine obtaines with using of proposed in study [9, 10] approaches are illustrated of Fig. 1.



a **b**

Figure 1. Distribution of magnitudes of index *F* (a) and criterion K_{fe} (b) on operational regimes field of diesel engine 2Ch10.5/12

It is necessary to be noted that from structure of formula (1) can be seen that the larger the index *F* the lower the ES level of exploitation process of RICE on separate operational regime unlike the complex fuel-ecological criterion K_{fe} and generalized desirability function of Harrington D.

Conclusions.

1. Methods of calculation assessment of reference values of complex fuel-ecological criterion as reference points of psychophysical scale of partial function of desirability at its use as the ES factor of exploitation process of PP with RICE are developed. The calculated study of reference values of RICE ecological indicators as components of the complex fuel-ecological criterion is carried out. The calculated evaluation of the reference values of the complex fuel-ecological criterion and its fuel and ecological components is performed. The calculated evaluation of the values of the coefficients of partial desirability functions for the complex fuel-ecological criterion in accordance with the selected reference values of the response functions and the desirability scale is carried out.

2. Methods of calculated assessment of the magnitudes of the complex fuel and ecological criterion of prof. Igor Parsadanov and the Index of ecological and chemical assessment of prof. Pavlo Kanilo, taking into account: emissions of sulfur oxides and consumption of engine oil for fumes and emissions of B(a)P and other PAH in

the composition of EG diesel RICE. Set of initial data for calculated assessment for a standardized steady testing cycle ESC was obtained. Calculated assessment of the magnitudes of the criterion and the index is carried out taking into account the RICE emissions of the specified pollutants.

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