Shipfer: Carter gases (Картерні гази)

«TAKING INTO ACCOUNT OF EMISSION OF CARTER GASES IN CRITERIA-BASED ASSESSMENT OF ECOLOGICAL SAFETY LEVEL OF RECIPROCATING ICE EXPLOITATION PROCESS»

(державною мовою: ««ВРАХУВАННЯ ВИКИДУ КАРТЕРНИХ ГАЗІВ В КРИТЕРІАЛЬНОМУ ОЦІНЮВАННІ РІВНЯ ЕКОЛОГІЧНОЇ БЕЗПЕКИ ПРОЦЕСУ ЕКСПЛУАТАЦІЇ ПОРШНЕВИХ ДВЗ»)

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(Двигуни внутрішнього згоряння)

CONTENTS

INTRODUCTION

Relevance of the study is conditioned by the following considerations. For implementation of assessment of magnitudes of indicators of ecological safety (ES) level of exploitation process of power plants (PP) with reciprocating internal combustion engines (RICE) which not equipped with carter venting system of carter gas (CG) suflation system its rationale to use the mathematical apparatus of complex fuel-ecological criterion K_{fe} of Professor I.V. Parsadanov (NTU «KhPI») which desctibed in monograph [2] and improved in monograph [1] that developed on the basis of provisions of the methodica [3] and has the alternative proposed in study [4].

In the classificator of ES factors that was built on hierarchical principle and proposed in the study [1] there are the emission of CG which is attributed to non legislative normalized. However in the structure of ES factors which takes into account in original mathematical apparatus of criterion K_{fe} exapt the full set of legislative normalized pollutants in exhaust gas (EG) flow and motor fuel consumption the worded above factor does no accounted at all as well as all other ES factors from the classicator what are the main disadvantage of the criterion. Taking into account such an ES factor in combination with the available ones corresponds to the concept of improvement of the mathematical apparatus of the K_{fe} criterion proposed in the source [1]. That is, the partial elimination of this disadvantage is proposed to be carried out by extending its functionality by new ES factors, which by their physical nature are emissions of pollutants in the gaseous state.

It should be noted, that RICE as the part of PP are powerful sources of pollution of environment by factors with different physical nature [1, 2, 4] – it is the quailtative aspect of relevance of the study and they produces more than 75 % of mechanical and electrical energy in Ukraine [2] – it is the quantitative aspect of relevance of the study.

But, the results of the analysis of the scientific and technical literature of studies about the extension of the range of ES factors which taken into account by the mathematical apparatus of K_{fe} criterion were not found, that's why carrying out of such research and analysis of its results are relevant task that has the signs of scientific novelty, and the results of which has the practical value.

Purpose of the study. Improving of the approach for determination of magnitudes of mass hourly emissions into environment of CG as pollutant.

Probleme of the study. Determination of fuel-ecological effect of taking into account the emissions of CG in complex criteria-based assessment of ES level of PP with RICE exploitation process described by standardized steady testing cycle ESC (UNECE Regulations No 49 [5]) based on improved mathematical apparatus of complex fuel-ecological criterion.

Object of the study. Ecological safety of exploitation process of PP with RICE.

Subject of the study. Contribution in indicators of object of the study of emissions of CG.

This study was carried out on example of autotractor diesel engine D21A1 (2Ch10.5/12 in accordance with ISO 3046-1:2002) technical description of which consists in source [6].

Methods of the study. Analysis of scientific-technical, normative and references literature, analysis of results of motor bench tests on standardized steady testing cycle, basics of scientific discipline «Theory of RICE» [7], improved mathematical apparatus of complex fuel-ecological criterion, least squares method.

Tasks of the study.

1. Developing of the methodica for calculated assessment of magnitudes of complex fuel-ecological criterion with taking into account of mass hourly emissions of CG as the pollutant.

2. Obtaining of initial data set for carring out of calculated assessment for standardized steady testing cycle ESC.

3. Implementation of calculated assessment of magnitudes of complex fuel-ecological criterion with taking into account of mass hourly emissions of CG as the pollutant and analysis on its results.

Scientafic novelty of results of the study.

For the first time it was proposed the approach for the taking into account of mass hourly emissions of carter gasas in complex fuel-ecological assessment of ecological safety level of exploitation process of vehicles with reciprocating ICE.

Practical value of results of the study.

Obtained results are useful for providing of qualitative and quantitative evaluation of studied effects in process of developing on this basis of constructive and organizational measures for reducing or nullification of this effects.

Results of the study **was used** in practice of scientific researches of Groupe of Piston Power Plants of Department of Hydrogenic Energy of A.M. Pidgorny Institute for Mechanical Enginireeng Problems of NAS of Ukraine and in education process of Department of Applied Mechanics and Environment Protection Technologies of National University of Civil Defence of Ukraine.

Results of the study was **presented** on International scientific and practical conference «Problems of technogenic and ecological safety: education, science and practice» (Kharkiv, National University of Civil Defence of Ukraine, 21 – 22 November, 2019), III International scientific and practical conference «Actual problems of energy and recource saving and ecology» (Odesa, Odesa National Academy of Building and Architecture, 11 – 12 December, 2019), International scientific symposium SDEV'2020 «Sustainable development – status and prospects» (19 – 22 February 2020, NU «Lviv Polytechnica», Lviv), XI International scientific and methodical conference «Safety of human in modern conditions» (Kharkiv, National Technical University «KhPI», 05 – 06 December, 2019) and International scientific and practical conference of young scientists «Problems and prospects of civil defence» (15 – 16 April 2020, National University of Civil Defence of Ukraine, Kharkiv) and **was published** in materials of conferences and also **was published** in Scientific Journal «Young Scientist» as the article.

General characteristic of the study. The study consists of title shit, contents, introduction, 2 chapters, conclusions, references, 4 appendics and annotation. Full volume of the study is 43 pages, 30 of which are the main text, including 22 drawings, no tables, references has 20 items on 2 pages, appendixes are of 11 pages.

1 METHODICA OF CALCULATED ASSESSMENT OF MAGNITUDES OF COMPLEX FUEL-ECOLOGICAL CRITERION WITH TAKING INTO ACCOUNT OF AEROSOL OF CARTER GASES

Among the specialists in the field of RICE, in particular their ecologization, it is known that during the operation of engines so-called CG are formed and emitted into environment, which are an aerosol [8 – 10], that is, a mixture of:

a) the dispersed medium, which is formed in different proportions (depending on the RICE operational regime and its current technical condition) the following components: a.1) vapor of motor oil stored in the sump of carter; a.2) gaseous constituents of EG and fresh charge air that have seeped into the carter through the gaps in the cylinder-and-piston groups and between the piston rings and the corresponding grooves in and piston head and tronk; a.3) engine fuel vapor that have entered the carter in the same way in the case of a damage of the fuel supply system and/or the engine ignition system (flashover);

b) the dispersed phase, which is formed by the following components: b.1) motor oil drops as the component of so-called oil mist which is generated in the cavities of the crankcase and cylinders under the pistons in the implementation of the principle of lubrication of cylinder-and-piston groups by the principle of spraying, as well as being ejected by the inertia forces from the gaps between the parts of the sliding bearings of details of the engine mechanisms or fed to the pistons cooling gallery of or on the surface of the piston bottom for their cooling by the oil nozzles and removed from such cavities of the pistons by self-discharge; b.2) drops of motor fuel condensed from the vapor in the carter; b.3) PM as a component of EG; b.4) water droplets and dust from air entering the carter of cold RICE from environment in open type carter ventilation systems.

However, the main components of CG should be recognized as the most significant in their composition – engine oil vapor, gaseous components of EG in combination with PM, fresh charge air and droplets of engine oil.

At the same time, many RICE of modern constructions use two constructive measures to neutralize the harmful components of CG emission: 1) dispersed phase of the aerosol, since it is mostly liquid particles of a sufficiently large fraction, separated from the dispersed medium in special devices called prompters, oil separators or separators; 2) dispersed medium of the aerosol, previously purified from the dispersed phase, is not emitted into the atmospheric air under the engine casing of PP, and sent or into the intake manifold and added to the fresh charge and combustible pollutants in their composition are oxidized in the combustion chamber of the engine, or into the exhaust manifold of engine equipped with aggregates of neutralizing pollutants in the EG flow.

Features of the CG emission process are the following: a) this is a periodic process, due to the fact that the driving force of such emissions is the CG excess pressure, the value of which gradually increases as the gas in the carter accumulates, which in the RICE regular operational mode reaches a certain critical value is digested through a shut-off valve that tuned to a certain value the pressure (from 0.7 to 1.5 kPa [8 – 10]) – PCV valve; b) this process may become salvo-like due to the ignition of the combustible components of CG in the carter cavity and on some RICE present shut-off bodies that tuned at certain values of the pressure generated during the flash – valves on the carter hatches, as on D100 family diesel engines [11] . This feature of the CG emission process will not be considered in this study.

Crankcase (carter) ventilation systems are divided into [9, 10]: 1) supply and exhaust; 2) closed and open.

In this study, we will assume that the diesel engine 2Ch10.5/12, on the example of which it was carried out, is equipped with an open intake system of carter ventilation, equipped with a prompter and a valve adjusted to the limit value of excess pressure in the carter equal to 0.5, 1.0 and 1.5 kPa, i.e. as a part of the CG emission, which is periodically discharged into the atmospheric air, there are only EG with PM, fresh charge air and vapor of motor oil, and the drops of motor oil, fuel and condensed water are separated from the flow by the prompter.

In order to allow for the taking into account of the magnitude of CG emissions in the complex criteria-based assessment of ES level of the process of accident-free exploitation of PP with RICE, the following approach is proposed, on the basis of which an appropriate methodology is constructed. An analysis of the mathematical apparatus of the K_{fe} criterion is given in Appendix A.

Fo carrying out of such assessment it is necessary in composition of considered in mathematical apparatus of the complex fuel-ecological criterion K_{fe} ES fastors to introduce the component A(CG)·G(CG) in formula (A.10) which then converted into the formula (1.1).

$$\sum_{m=1}^{h}(A_k \cdot G_k) = A(PM)\cdot G(PM) + A(NO_x)\cdot G(NO_x) + \\ + A(C_nH_m)\cdot G(C_nH_m) + A(CO)\cdot G(CO) + A(CG)\cdot G(CG), \text{ kg/h.} \quad (1.1)$$

For application of formula (1.1) it is require of information about the individual regime values of the mass hourly emission of CG G(CG) and the coefficient of its ponderability as the ES factor A(CG).

For determination of values of G(CG) it is proposed to determine the nature (form) of the distribution of the analogue value over the field of RICE operating regimes, the value of the value of G(CG) itself on the characteristic RICE operating regime and the conversion coefficient k_{CG}, which correlates the value of G(CG) and the magnitude of the analogue value. That is, formula (1.2) will hold.

$$G(CG) = p_i(n_{cs}; M_T)\cdot k_{CG}, \text{ kg/h.} \quad (1.2)$$

In this case, it is proposed to choose as the analogue value the avaraged indicator pressure in the cylinder p_i on the RICE steady operational regime, which is determined by the formulas (1.3) – (1.6) according to the provisions of the scientific discipline «Theory of ICE» [7, 12] which are reduced to formula (1.7).

$$p_i = N_i \cdot 30 \cdot \tau/(z \cdot V_h \cdot n_{cs}), \text{ Pa,} \quad (1.3)$$

$$N_i = N_e / \eta_m, \text{ W,} \quad (1.4)$$

$$N_e = \pi \cdot n_{cs} \cdot M_T / 30, \text{ W ,} \quad (1.5)$$

$$V_h = \pi \cdot D^2 \cdot S / 4, \text{ m}^3, \quad (1.6)$$

$$p_i = M_T \cdot \pi \cdot \tau/(z \cdot V_h \cdot \eta_m) = 6{,}047 \cdot 10^3 \cdot M_T / \eta_m, \text{ Pa.} \quad (1.7)$$

where N_i – RICE indicator power, W; $\tau = 4$ – number of strokes in RICE working process, strokes/cycle; $V_h = 1.039 \cdot 10^{-3}$ – working volume of RICE cylinder, м^3; $z = 2$ – number of RICE cylinders, items; n_{cs} – RICE crankshaft speed, rpm; M_T – RICE crankshaft torque, N·m; N_e – RICE effective power, W; η_m – RICE mechanical efficiency coefficient; $D = 105 \cdot 10^{-3}$ – diameter of RICE cylinder, m; $S = 120 \cdot 10^{-3}$ – stroke of RICE piston, m.

This choice of the analogue value was done due to the following considerations regarding the factors that determine the intensity of CG formation:

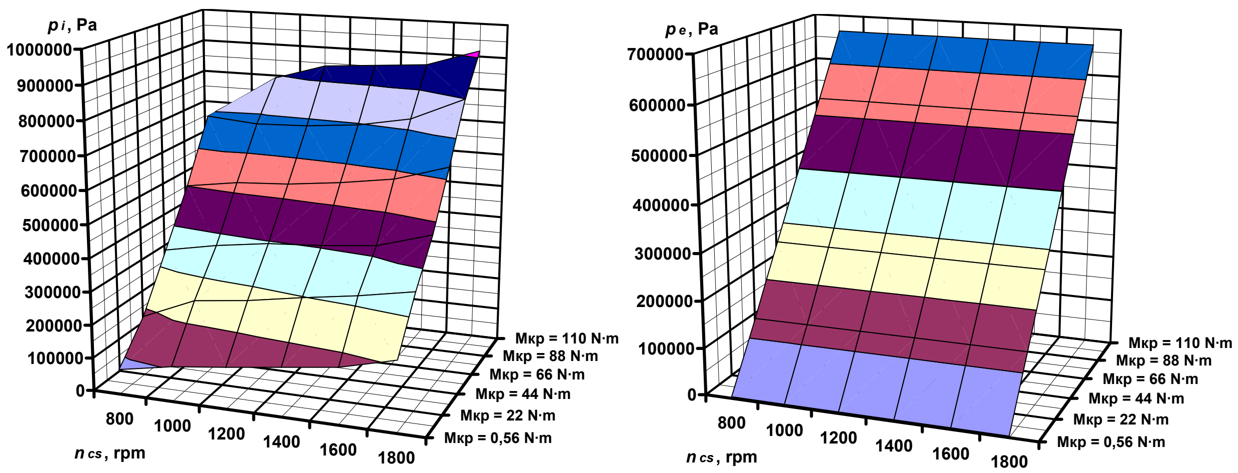
– the gaseous components of the CG aerosol, in particular the EG with PM and fresh charge air, seep into the carter through the gap between piston and cylinder sleeve and into locks of the piston rings under the action of the pressure difference between the working fluid in combustion chamber and in CG carter itself. The mean indicator pressure is, by definition, a conditional constant value of the working fluid pressure on the piston firing surface, which, when actuated on it, during one stroke of the piston from UDP to LDP, creates a mechanical work equal to the indicator work of the working fluid in the engine cylinder per working cycle. In this case, as can be seen from formula (1.7), the value of p_i is an average indicator of the pressure of the working fluid, which really develops in the RICE cylinder. We will also assume that the CG pressure in the carter is constant and equal to atmospheric p_0.

– motor oil vapor is more intensively incorporated into the CG aerosol, than, firstly, the movement of engine mechanism parts (first of all crank mechanism) is more intense and, accordingly, the process of creating a lubricating mist in the implementation of the principle of lubrication by spraying, and secondly, than the higher is the temperature of the engine parts cooled by the motor oil and, in fact, the oil itself. Both processes occur more intensively, the higher the RICE crankshaft speed n_{cs} and the higher the thermal energy released by the engine fuel during combustion (without taking into account mechanical losses in the engine), i.e. the greater the value of the diesel torque M_T. In this study, the impact of engine oil temperature in the carter on its evaporation is neglected.

The distribution of values of η_e, value of N_e and other performance indicators of a 2Ch10.5/12 autotractor diesel on regimes of a steady standardized test cycle ESC is shown in Fig. B.1 of Appendix B, and the magnitudes of values of p_i and p_e on the field of RICE operating regimes – on Fig. 1.1.

As for the value of k_{CG} coefficient then it is proposed to define it as the ratio of the magnitude of value of G(CG) to the value of p_i in any representative RICE operation regime, in particular the regime of maximal torque, i.e. by formula (1.8).

$$k_{CG} = G(CG) / \left. p_i \right|_{(n_{cs}=1200 rpm; M_T=110 N \cdot m)}, \text{ kg/(h·Pa)}. \qquad (1.8)$$



a b

Figure 1.1 – Distribution of magnitudes of values of mean indicator p_i (a) and mean effective pressure p_e (b) on the field of operating regimes of 2Ch10.5/12 diesel engine

The following approach is proposed in this study to determine the magnitude of mass hourly CG emission at a separate steady operational regime *G*(CG).

Since the EG with PM enters the carter under the influence of the pressure difference in carter and in combustion chamber, and it changes significantly at different strokes of the working process, through the gap between the piston and the cylinder liner, it is advisable to solve the task of gas flow movement between the two reservoirs thru a channel with constant life cross-section.

It should be noted that as the shape of the channel that connecting the cavities above and below the piston (the channel has the shape of a live cross-section in the form of a non-concentric ring with a cylinder diameter, i.e. D = 105 mm), changes in time due to the phenomenon of displacement of the piston under the influence of lateral force in the crankshaft mechanism and channel area vary as a function of the temperature of the parts between which it is formed, due to their thermal expansion. In addition, the gaseous fluid when moving through this channel is surrounded not by solid body walls but by layers of motor oil on these walls, which are in different condition along the length of the channel, because they are in different operating conditions, primarily in temperature. The length of the channel corresponds to the height of the piston, i.e. $L = S$ = 120 mm. Along its length, the canal also changes its live cross-section both in shape and size due to the features of the geometry of the outer surface of the head and trunk of the piston. One of the walls of the channel is rapidly moving relative to the other with acceleration.

According to the technical documentation for the 2Ch10.5/12 diesel engine, the gap in the cylinder-and-piston group in the cold state Δ should be no more than 0.2 mm, in the hot state – no more than 0.1 mm, and the gap size greater than 0.5 mm is a diagnostic feature of reaching the critical state by these parts [6, 8].

In the following calculations we will assume that the specified channel has invariable in space and time a live cross-section of circular shape, whose diameter *d* is defined by formula (1.9) and area *F* by formula (1.10). In the following calculations, we take the averaged by temperature and exploitation duration (taking into account the presence layers of motor oil on the surfaces of the piston and the cylinder liner and its thickness) the gap value Δ = 0.05 mm, then the value of the area $F = 8.2$ mm^2, and the diameter $d = 3.2$ mm.

The dependence of magnitdes of values of *F* and *d* from magnitde of the gap Δ is shown in Fig. 1.2. The calculation scheme of such a task is shown in Fig. 1.3.

$$F = 0{,}25 \cdot \pi \cdot \Delta \cdot (2 \cdot D - \Delta),\ \text{m}^2, \quad (1.9)$$

$$d = \sqrt{4 \cdot F / \pi},\ \text{m}. \quad (1.10)$$

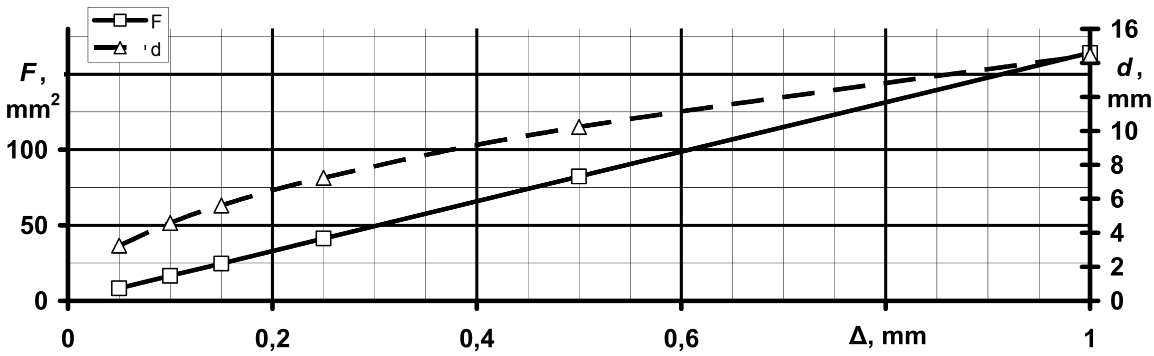


Figure 1.2 – Dependences of values of *F* and *d* from magnitde of the gap Δ

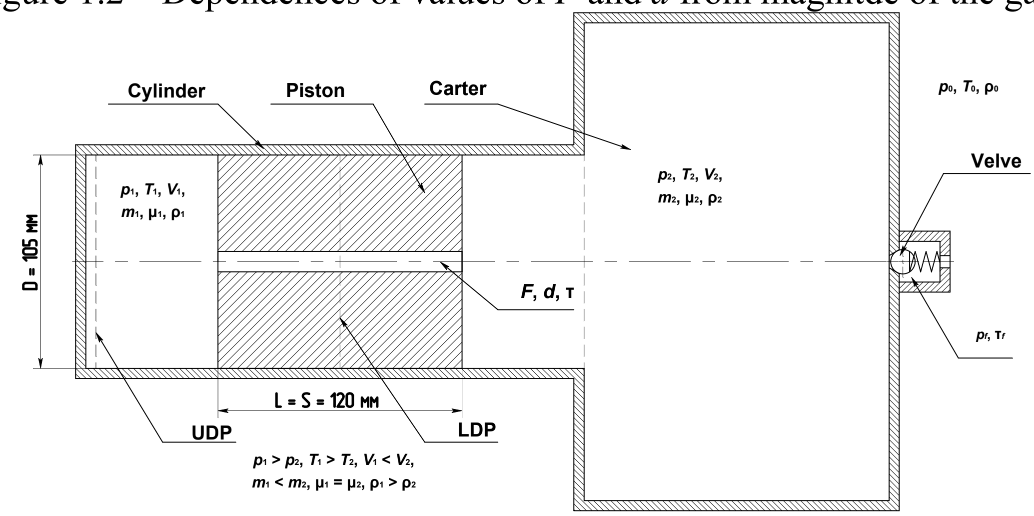


Figure 1.3 – Calculation scheme

To determine the values of initial data for the calculated assessment of values of G(CG), an approximate thermal calculation of working process of the diesel engine 2Ch10.5/12 was performed according to the methods [7, 12].

According to its results, the maximum value of the pressure of working fluid in the cylinder is reached at the combustion-expansion stroke of maximum torque regime (n_{cs} = 1200 rpm and M_T = 110 N·m), namely p_z = 8.0 MPa, and the maximum temperature of the working fluid in the combustion process T_z reaches 2800 K with degree of pressure increase during combustion λ = 1.7 (see formula (1.14)), with the coefficient of molecular change of the working fluid during combustion β = 1.08, and coefficient of previous expansion ρ = 1.8, coefficient of further expansion δ = 9.2. At the end of the combustion-expansion stroke, the pressure of the working fluid p_b is equal to 0.5 MPa (see formula (1.15)) and the temperature T_b = 1600 K (see formula (1.16)) with an average of the exponent of the adiabatic expansion n_p = 1.25. The volume of the compression chamber V_c is 0.067 liters (see formula (1.17)) and the total cylinder volume V_a = 1.106 liters (see formula (1.18)).

At the compression stroke, the pressure of the working fluid p_c reaches a maximum value of 4.7 MPa (see formula (1.11)), and the temperature of the working fluid at the end of the compression stroke T_c = 1000 K (see formula (1.12)) at a compression ratio ε = 16.5, the average value of the adiabatic compression ratio n_c = 1.37 and the pressure of the working fluid at the end of the inlet stroke p_a = 101325 Pa, the temperature of the working fluid at the end of the inlet stroke T_a = 350 K.

For a more accurate calculation of the value of G(CG), the average values of the pressure of the working fluid in the cylinder at the compression and combustion-expansion cycles were obtained, and the adiabats themselves are shown in Fig. 1.4,a. They are constructed according to formulas (1.19) and (1.20). The temperature curves shown in Figs. 1.4,b.

$$p_c = p_a \cdot \varepsilon^{n_c}\text{, MPa;} \quad (1.11)$$

$$T_c = T_a \cdot \varepsilon^{n_c - 1}\text{, K;} \quad (1.12)$$

$$p_z = p_c \cdot \lambda\text{, MPa;} \quad (1.13)$$

$$T_z = T_c \cdot \beta \cdot \rho / \lambda\text{, K.} \quad (1.14)$$

$$p_b = p_z \cdot / \delta^{n_p}\text{, MPa;} \quad (1.15)$$

$$T_b = T_z / \delta^{n_p - 1}, \text{ K}. \quad (1.16)$$

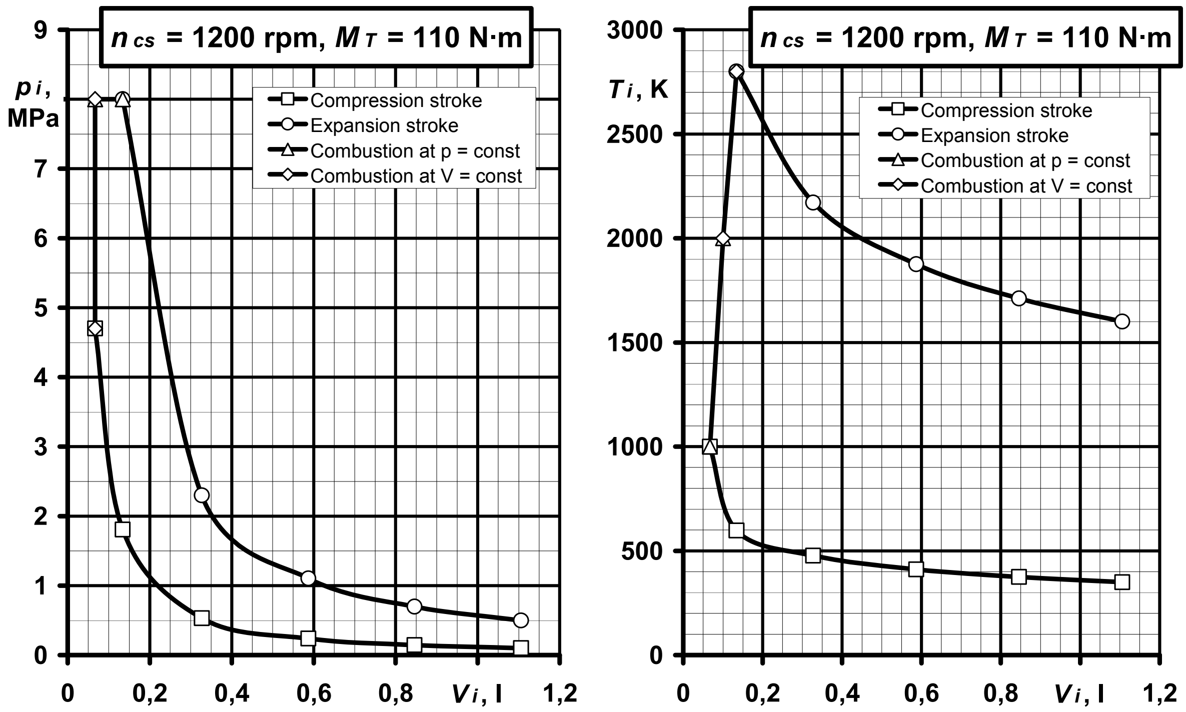
$$V_c = V_h / (\varepsilon - 1), \text{ m}^3. \quad (1.17)$$

$$V_a = V_h + V_c, \text{ m}^3. \quad (1.18)$$

$$p_{jc} = p_a / \left(V_j / V_a\right)^{n_c}, \text{ MPa}; \quad (1.19)$$

$$p_{jp} = p_b / \left(V_j / V_a\right)^{n_p}, \text{ MPa}; \quad (1.20)$$

$$\rho_j = m / V_j = \left(G_{cf} + G_{ca}\right) / V_j = \left(G_{fuel} + G_{air}\right) \cdot \tau / \left(n \cdot 120 \cdot V_j\right), \text{ kg/m}^3. \quad (1.21)$$



a b

Figure 1.4 – Indicator diagram (a) and operating temperature curve of working cycle (b) of diesel 2Ch10.5/12 at maximum torque regime

Weighted average values of the pressure and temperature of the working fluid in the cylinder of 2Ch10.5/12 diesel engine at the maximum torque regime on the compression stroke are 1.253 MPa and 535 K, and at the combustion-expansion stroke are 3.434 MPa and 2160 K. At the specified RICE operational regime mass hourly fuel consumption G_{fuel} = 3.593 kg/h, air G_{air} = 72.317 kg/h, the coefficient of excess air α = 1.3, then the cycle fuel supply G_{cf} is 0.100 g/cycle, air G_{ca} = 2.009 g/cycle, which means that the weighted average mass of the working fluid in the cylinder m = = 2.109 g/cycle and density of the working fluid in the cylinder ρ is equal to 10.275 kg/m^3 (see formula (1.21) and Fig. 1.5).

For other operational regimes of the diesel engine it is necessary to determine a relation between the received average values of pressure on the compression and combustion-expansion cycles with the value of the mean indicator pressure.

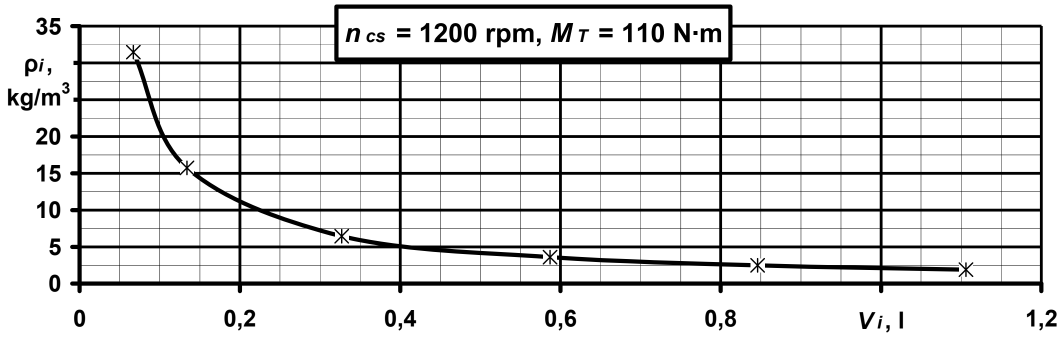


Figure 1.5 – Dependences of values of density of the working fluid in the cylinder ρ for 2Ch10.5/12 diesel engine at the maximum torque regime

The volume of CG in the cavity of the 2Ch10.5/12 diesel carter can be determined by its transverse and longitudinal section and the formula (1.22).

$$V_{CG} = V_0 - V_{CS} - V_{GDM} - 3 \cdot V_{MB} - 2 \cdot V_{CR} - \\ - V_{DM} - V_{BM} - V_h - 2 \cdot \mathrm{V}_P - V_{oil} - V_{OP}, \text{ m}^3, \quad (1.22)$$

where V_0 – overall volume of the carter cavity, m^3; V_{CS} – crankshaft volume, m^3; V_{GDM} – mechanism of gas distribution volume, m^3; V_{MB} – crankshaft main bearing volume, m^3; V_{CR} – connecting rod volume, m^3; V_{DM} – mechanism of drive of aggregates of engine systems volume, m^3; V_{BM} – Lanchesters mechanism (external balance of forces and moments of inertia of 1st order) volume, m^3; V_h – cylinder working volume, m^3; V_P – piston internal cavity volume, m^3; V_{oil} – storaged motor oil in carter cavity volume, m^3; V_{OP} – motor oil pump volume, m^3.

Volume of engine oil contained in diesel 2Ch10.5/12 is 7.0 liters, 5.0 liters of which is stored in the carter [6].

According to the data obtained from the reference literature and technical documentation to the diesel engine 2Ch10.5/12 and its drawings [6], we have the following approximate values of the quantities that contained in formula (1.22): $V_0 = 31.5 \cdot 10^{-3}$ m^3; $V_{CS} = 3.5 \cdot 10^{-3}$ m^3; $V_{GDM} = 0.75 \cdot 10^{-3}$ m^3; $V_{MB} = 1.05 \cdot 10^{-3}$ m^3; $V_{CR} = 0.4 \cdot 10^{-3}$ m^3; $V_{DM} = 1.75 \cdot 10^{-3}$ m^3; $V_{BM} = 0.3 \cdot 10^{-3}$ m^3; $V_h = 1.0 \cdot 10^{-3}$ m^3; $V_P = 0.25 \cdot 10^{-3}$ m^3; $V_{oil} = 5.0 \cdot 10^{-3}$ m^3; $V_{OP} = 0.25 \cdot 10^{-3}$ m^3.

Therefore, the value of $V_{CG} = 14.5 \cdot 10^{-3}$ m^3, i.e. the volume of CG is 46 % of the overall volume of the carter cavity.

Mass of CG in the carter cavity M_{CG} at a pressure of 101325 Pa and a temperature of 400 K, determined by the equation of Klaiperon–Mendeleev (see formula (1.23)) is 0.0128 kg. Then value of the CG density in the carter is ρ_{CG} = 0.883 kg/m^3.

$$M_{CG} = \mu_{CG} \cdot p_{CG} \cdot V_{CG} / (R \cdot T_{CG}), \text{ kg.} \qquad (1.23)$$

Next, to determine the value of G(CG), the proposed approach provides the following.

a) The value of the portion of CG Δm_{CG}, which is the sum of portions of EG Δm_{EG} and fresh charge air Δm_{air}, was successively received into the carter through the gap in the cylinder-and-piston group at combustion-expansion and compression strokes of working cycle, respectively (see formula (1.24)), and is supplied to the carter during a single RICE workind cycle in a its separate representative operation regime, increases the value of the mass of gases accumulated in the carter, whose thermodynamic equilibrium is described by the equation of of the ideal gas state Klaiperon-Mendeleev – i.e. formula (1.25). However, as is known, the molar mass of EG μ_{EG} is approximately equal to the molar mass of air μ_{air} = 29 g/mol, and therefore the molar mass of crankcase gases μ_{CG} is the same [7, 12].

$$\Delta m_{CG} = \Delta m_{EG} + \Delta m_{air}, \text{ kg/cycle;} \qquad (1.24)$$

$$p_{CG} \cdot V_{CG} = m_{CG} / \mu_{CG} \cdot R \cdot T_{CG}, \text{ J;} \qquad (1.25)$$

where p_{CG} – pressure of CG in cavity of carter, Pa; V_{CG} – volume of cavity of carter, m^3; m_{CG} – mass of CG in cavity of carter, kg; μ_{CG} – molar mass of CG in cavity of carter, g/mol; R = 8,314 J/(mol·K) – universal gas constant; T_{CG} – absolute temperature of CG in cavity of carter, K.

b) Intake of a portion of CG Δm_{CG} into the closed RICE carter cavity causes an increase in the pressure in it according to equations (1.26) – (1.28).

$$p_{CG} = m_{CG} \cdot R \cdot T_{CG} / (\mu_{CG} \cdot V_{CG}), \text{ Pa;} \qquad (1.26)$$

$$\Delta p_{CG} = (\partial p_{CG} / \partial m_{CG}) \cdot \Delta m_{CG}, \text{ Pa;} \qquad (1.27)$$

$$\frac{\partial p_{CG}}{\partial m_{CG}} = \frac{R \cdot T_{CG}}{\mu_{CG} \cdot V_{CG}} = \frac{8{,}314 \cdot 400}{29 \cdot 10^{-3} \cdot 14{,}5 \cdot 10^{-3}} = 6{,}651 \cdot 10^9 = const, \text{ Pa/kg.} \qquad (1.28)$$

c) Considering that the periodicity of intake of CG portion Δm_{CG} into the carter cavity is strictly predetermined by the cyclical type of operation of RICE itself, namely for each working cycle of one cylinder there is one portion of CG, such a cycle lasts two rotations of crankshaft, diesel 2Ch10.5/12 is four-stroke RICE and containes two cylinders, then it can be concluded that a portion of CG Δm_{CG} enters the carter at each crankshaft rotation, and the magnitudes of the mass of CG m_{CG} and their pressure p_{CG} changes discretely.

d) When pressure p_{CG} is reached the magnitude of pressure to which the PCV valve p_{CV} is ajusted up, the accumulated excess CG mass ΔM_{CG} is released in the environment, and the pressure in the carter cavity is reduced to the initial one.

Therefore, the value of the mass hourly emission of CG G(CG) is determined by the formula (1.29) and its components by the formulas (1.30) and (1.31).

$$G(CG) = \Delta M_{CG} / \tau_{CG} = N_{CG} \cdot \Delta m_{CG} / \tau_{CG} = \Delta m_{CG} \cdot 60 \cdot n_{cs}, \text{ kg/h}, \quad (1.29)$$

$$N_{CG} = \Delta M_{CG}(p_{PCV}) / \Delta m_{CG}(p_z; p_c), \text{ pieces}, \quad (1.30)$$

$$\tau_{CG} = \Delta M_{CG} / G(CG) = N_{CG} / (n_{cs} \cdot 60), \text{ h}, \quad (1.31)$$

where ΔM_{CG} – mass of CG emission, kg; τ_{CG} – time period during of which was accumulated mass of CG emission in RICE catrer cavity and causes the magnitude of CG overpressure p_{PCV}, h; N_{CG} – number of CG portion with mass Δm_{CG}, pieces; n_{cs} –crankshaft speed, rpm.

For the regime of maximal torque the duration of one working cycle is 0.05 s, for the regime of nominal effective power – 0.033 s, for the regime of minimal idle – 0.075 s. In this case duration of one stroke is 0.0125 s, 0.0083 s and 0.0188 s respectively.

In following calculations it was used the initial data set which was previously obtained experimentally as the result of processing of results of bench motor tests of 2Ch10.5/12 diesel engine and are given in Appendix B.

Thus, magnitude of value p_i at n_{cs} = 1200 rpm and M_T = 110 N·m is equal 841 kPa, magnitude of value G(CG) on the same rerime – 1.5 kg/h then magnitude of value coefficient $k_{CG} = 1.784 \cdot 10^{-3}$ kg/(h·Pa).

The distribution of mass hourly CG emission G(CG) in the field of operational regimes of 2Ch10.5/12 diesel engine is shown in Fig. 1.6. Figure 1.6 shows that the minimum magnitude of value of G(CG) is 0.05 kg/h reaches on the minimum idling regime, and the maximum magnitude of value of G(CG) = 1.65 kg/h – at the nominal effective power regime.

It should be noted that CG emission is estimated for different types of diesel RICE up to 20 g/h, the magnitude of 0.5 g/h is considered to be the desired value. On the regime of nominal effective power for diesel engine of modern construction and serviceable technical state with power 280 – 450 kW magnitude of such emission usually changes in range from 5 to 10 g/h (140 – 600 l/min), on the regime of minimal idle – from 0.7 to 5 g/h (40 – 120 l/min) and for diesel engines that have reached the critical (limit) of technical condition such emission can reach 1120 l/min [8].

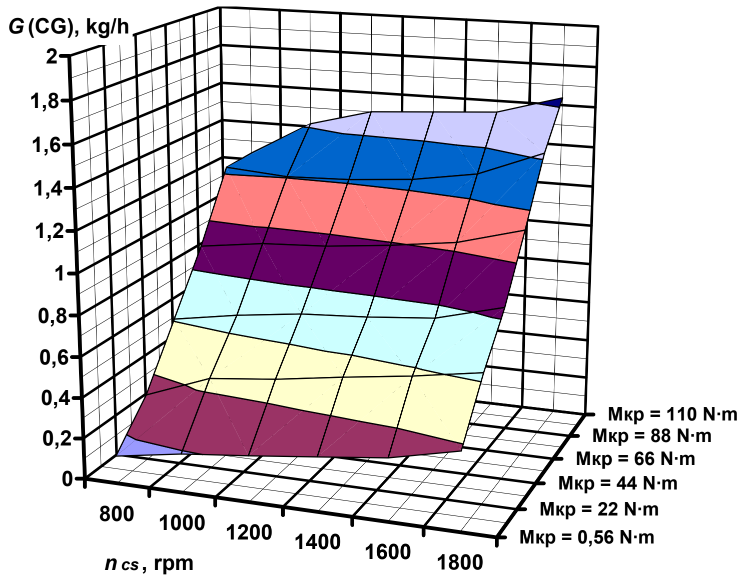


Figure 1.6 – Distribution of mass hourly CG emission G(CG) in the field of operational regimes of 2Ch10.5/12 diesel engine

So, for diesel engine D120 (2Ch10.5/12) in serviceable technical state that produced by Vladimir Tractor Plant when it operates on regimes of loading characteristic with crankshaft speed of regime of maximal torque mass hourly emission of CG is changes in range from 1200 to 1600 l/h an for loading characteristic with crankshaft speed of regime of nominal effective power – from 1000 to 1500 l/h [8].

In the same study [8] was proposed the empirical formula for approximate (with relative error about 16 %) assessment of volume consumption of CG Q for D120 diesel engine for regime of nominal effective power – the formula (1.32). Taking into account that the nominal effective power of the diesel engine 2Ch10.5/12, mounted on the engine test bench of the Hydrogen Energy Department of IPMash of

NAS of Ukraine, is 17.9 kW, that is 24.3 hp, Q = 1,215 m^3/h or 1215 l/h , 20.3 l/min and 0.338 l/s, which gives a mass hourly emission of G(CG) = 1.431 kg/h, due to the pressure of CG is 101325 Pa and their temperature of 300 K (27 °C).

$$Q = N_e / k, \text{ m}^3\text{/h}, \qquad (1.32)$$

where k = 20 hp·h/m^3 – proportionality coefficient.

Thus, it possible to conclude that obtained with using of proposed in this study approach and methodica magnitude of CG emission G(CG) = 1.5 kg/h (at magnitudes of CG dencity in normal conditions ρ(CG) = 1.178 kg/m^3 and CG molar mass μ(CG) = 29 g/mol) agrees well with experimental data from other researchers for this diesel.

About value of dimensionless index of the relative aggressiveness of CG as an pollutant A_{CG}, it is proposed to determine it as the weighted average value of values of all CG components – EG with PM A_{EG}, fresh air A_{air}, motor oil vapor A_{oil}, i.e. by formula (1.33).

$$A_{CG} = \left(A_{EG} \cdot G_{EG}^{CG} + A_{air} \cdot G_{air}^{CG} + A_{oil} \cdot G_{oil}^{CG}\right) / \, G_{CG}, \qquad (1.33)$$

where G_{EG}^{CG} – mass hourly emission of EG with PM in CG flow, kg/h; G_{air}^{CG} – mass hourly emission of air in CG flow, kg/h; G_{oil}^{CG} – mass hourly emission of motor oil vapor in CG flow, kg/h; G_{CG} – mass hourly emission of CG, kg/h.

Magnitude of indicator A_{air} is assumed to be zero, that is A_{air} = 0, magnitude of indicator A_{oil} is assumed to be equal magnitude for such indicator for motor fuel A_{fuel}, obtained in monograph [1], that is A_{fuel} = 38.4.

Magnitude of indicator A_{EG} it is proposed to determine it as the weighted average value of values of all legislative normalized pollutants in EG flow, namely A_{PM}, A_{NOx}, A_{CnHm} and A_{CO}, i.e. by formula (1.34).

$$A_{EG} = \frac{g_{prEG}}{G_{\Sigma k}} = \frac{A_{PM} \cdot G_{PM} + A_{NOx} \cdot G_{NOx} + A_{CnHm} \cdot G_{CnHm} + A_{CO} \cdot G_{CO}}{G_{PM} + G_{NOx} + G_{CnHm} + G_{CO}}, \qquad (1.34)$$

where g_{prEG} – total reduced emission of legislative normalized pollutants in EG flow, kg/h; $G_{\Sigma k}$ – total emission of legislative normalized pollutants in EG flow, kg/h.

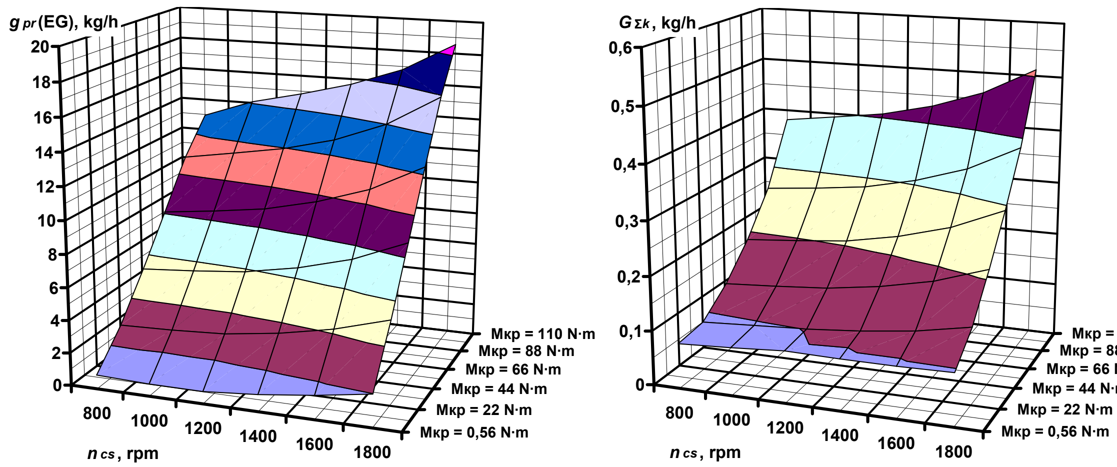
Distribution of values of total reduced emission of pollutants g_{prEG}, total emission of pollutants in the composition of EG $G_{\Sigma k}$ is shown in Fig. 1.7, and the index of relative aggressiveness of EG A_{EG} – in Fig. 1.8.

This approach is due to the fact that the environment damage from the emission of a particular pollutant is determined by the intensive (qualitative) and extensive (quantitative) aspects, namely: the intensive (qualitative) aspect is described by the value of the dimensionless index of the relative aggressiveness of k-th pollutant A_k; an extensive (quantitative) aspect is described by the value of the mass hourly emission of the k-th polyutant G_k.

Therefore, it is possible to distinguish the following degrees of danger of emission of a pollutant with the EG flow of diesel engine: a) critical – for the pollutants with high magnitude of both values of A_k and G_k; b) high – for pollutants with a high magnitude of value of A_k and a small magnitude of value of G_k; c) moderate – for pollutants with low magnitude of value of A_k and high magnitude of value of G_k; d) low – for pollutants with small magnitude of values of both A_k and G_k.

So, on Fig. 1.8 it can be seen that magnitude of value $G_{\Sigma k}$ averaged over the entire RICE operating regimes field is 0.221 kg/h, such magnitude of value g_{prEG} values is 8.213 kg/h and such magnitude of value A_{EG} values is 34.3.

The following considerations are proposed to determine the values of the mass hourly emissions in CG emission of EG with PM G_{EG}^{CG}, air of fresh charge G_{air}^{CG}, and motor oil vapor G_{oil}^{CG}.



a b

Figure 1.7 – Distribution of values of total reduced emission of pollutants g_{prEG} (a) total emission of pollutants in the composition of EG $G_{\Sigma k}$ (b) for 2Ch10.5/12 diesel engine and all field of its operational regimes

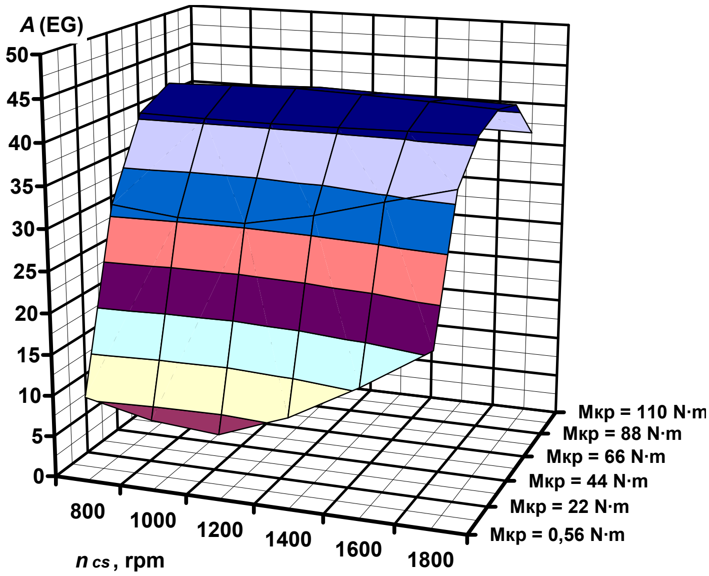


Figure 1.8 – Distribution of values of index of relative aggressiveness of EG A_{EG} for 2Ch10.5/12 diesel engine and all field of its operational regimes

Both EG with PM and air of fresh charge into CG composition are supplied from the cylinders of the diesel engine under the action of pressure difference in the under-piston and over-piston cavities at the combustion-expansion and compression cycles, the ratio of values G_{EG}^{CG} and G_{air}^{CG}, apparently, is determined by the ratio of the average pressures in the working fluid in RICE cylinder. For the maximum torque regime according to preliminary calculations, this ratio is 3.43 : 1.25.

The mass fraction of motor oil vapor in CG can be determined by its evaporation data as a function of its temperature. This property of this technical fluid characterizes the value of the saturated vapor pressure p_{sv}. We assume that the motor oil temperature in the carter of the diesel engine 2Ch10.5/12 at maximum torque regime T_{oil} is 400 K or 127 °C. In the full load range, the motor oil temperature of the engine varies from 80 to 150 °C.

For motor oil, the concepts of distillation temperatures of 10, 50 and 96 % are established, as well as for gasoline and diesel fuel, as well as the amount of evaporation at a certain temperature (usually 200 °C) for a certain time (usually 2 hours) by different methods according to GOST 32330-2013 and 32391-2013 [13, 14], which is from 10 to 25 % of the mass. The density of engine oils at a temperature of 20 °C ranges from 850 to 950 kg/m^3 [15]. Thus, according to GOST 2177-82 [16], the boiling point of 50 % of diesel fuel is 280 °C, and 96 % is 350 °C, the beginning of boiling is 170 °C, the end of distillation is 380 °C.

One of the main indicators of evaporation of motor oil is the pressure of saturated vapor p_{sv}, which is determined according to GOST 15823-70 [17]. According to this indicator, for motor oils, as for other petroleum products, it was build nomograms, which are graphs of dependences of the temperature of petroleum products t on the value of pressure p_{sv} (see Fig. B.3), which are compared with the Cox graph (see Fig. B.1) and the UOP nomogram (see Fig. B.2) [18, 19]. The graphs on the nomogram, based on the data from the source [19], are described by the method of least squares by polynomials in the form of formulas (1.35) and (1.36) (they have a p_{sv} value in kPa).

$$t_{motor\_oil} = 55.310 \cdot \ln(p_{sv}) + 75.5;\ R^2 = 0.973,\ °C, \tag{1.35}$$

$$t_{\text{diesel fuel}} = 53.439 \cdot \ln(p_{sv}) + 2.5;\ R^2 = 0.978,\ °C. \tag{1.36}$$

Fig. B.3 shows the graphs of dependence of the values of pressure p_{sv} on the temperature of the motor oil t. On Fig. 1.9 the same graphs for diesel fuel and motor oil in their operating temperature range.

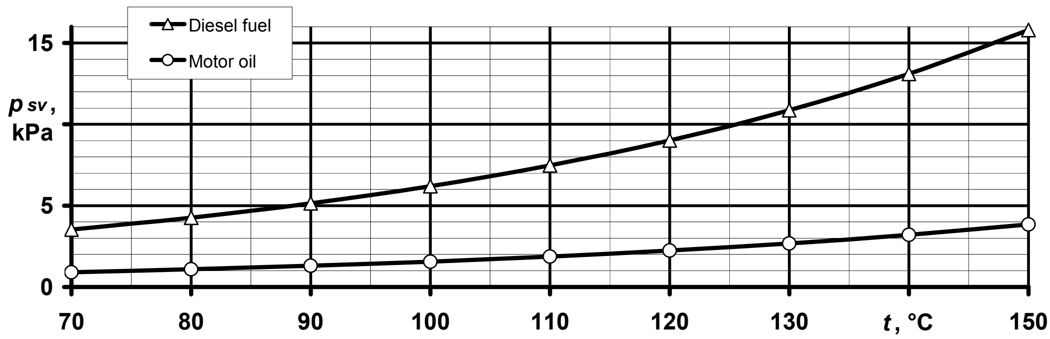


Figure 1.9 – Saturated vapor pressure nomograms for motor oil and diesel fuel in the operating temperature range (obtained on the basis of data from source [19])

Figure 1.9 shows that with increasing temperature from 70 to 150 °C, the evaporation of petroleum products increases by 4 times, and for diesel fuel the evaporation indicator is 3.5 times higher than for motor oil.

From the worded above, it follows that the value of temperature of motor oil in the carter pan of the diesel engine 2Ch10.5/12 400 K (127 °C), taken for this calculation study, is saturated vapor pressure of this technical liquid of petroleum origin (M10G2 oil in summer and M8G2 in winter [6]) is 2.538 kPa according to the formula (1.37).

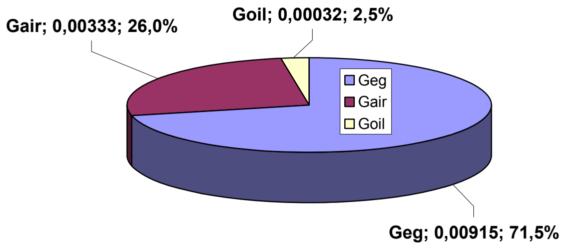
$$p_{sv} = \exp((t_{\text{motor oil}} - 75.5) / 55.310), \text{ kPa}. \quad (1.37)$$

Therefore, the value of G_{oil}^{CG} is proposed to be defined as the ratio of the value of saturated vapor pressure of motor oil p_{sv} at its temperature in RICE carter to the value of pressure of CG p_{CG}, i.e. by the formula (1.38), therefore, value of G_{oil}^{CG} is 2.5 % of the amount of CG, i.e. 0.00032 kg.

$$G_{oil}^{CG} = M_{CG} \cdot p_{sv} / p_{CG}, \text{ kg}. \quad (1.38)$$

Then the remaining 97.5 % of amount of CG is a mixture of EG with PM and fresh charge air, which ratio by weight are equal to 2.75 : 1, i.e. G_{EG}^{CG} = 0.00915 kg and G_{air}^{CG} = 0.00333 kg, so $G_{CG} = M_{CG}$ = 0.0128 kg. Then the value of A_{CG} obtained by the formula (1.33) is 25.5.

Fractional contribution of values G_{oil}^{CG}, G_{EG}^{CG} and G_{air}^{CG} in the total value of G_{CG} is illustrated in Fig. 1.10,a. The fractional contribution of values A_{EG}, A_{air} and A_{oil} to the total value A_{CG} is illustrated in Fig. 1.10,b. Fractional contribution of value A_{CG} to the structure of the ponderability of ES factors in the mathematical apparatus of K_{fe} criterion is illustrated in Fig. 1.11.



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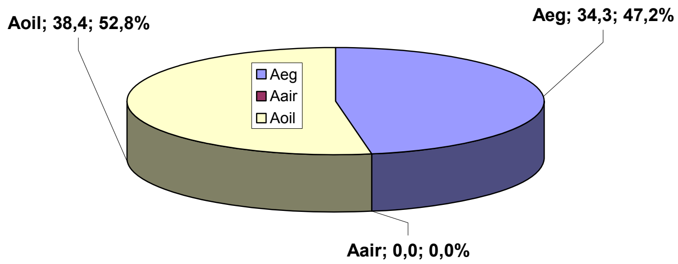


b

Figure 1.10 – Fractional contribution of values G_{oil}^{CG}, G_{EG}^{CG} and G_{air}^{CG} in the total value of G_{CG} (a) and values A_{EG}, A_{air} and A_{oil} to the total value A_{CG} (b)

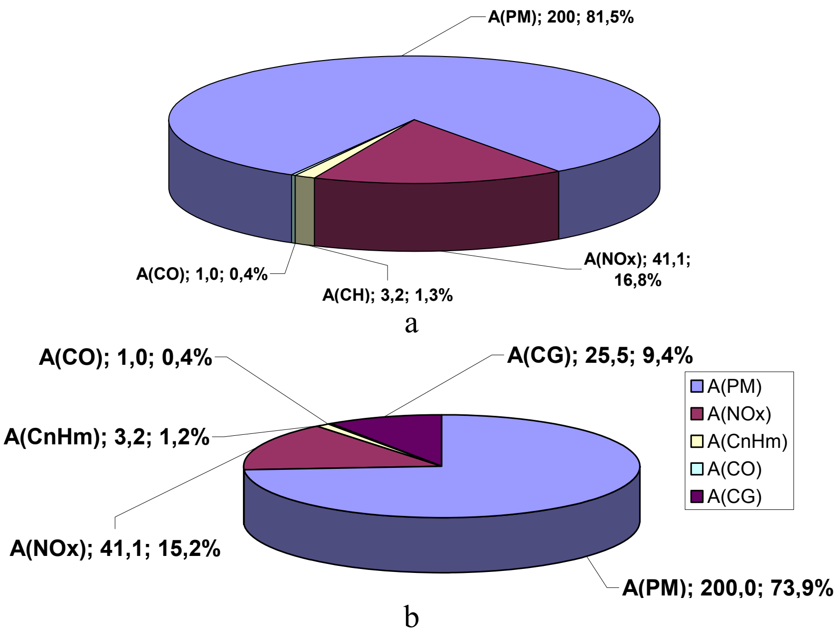


Figure 1.11 – Fractional contribution of value A_{CG} to the structure f the ponderability of ES factors in the mathematical apparatus of K_{fe} criterion

Thus, in this section of the study it was proposed the approach and methodica for calculated assessment of magnitudes of fuel-ecological criterion of Professor I.V. Parsadanov with taking into account of mass hourly emissions of carter gases as pollutant from reciprocating ICE which not equipped with carter venting system of carter gas suflation system.

It was detected that for autotractor diesel engine 2Ch10.5/12 maximal magnitude of mass hourly emission of aerosol of CG reaches on the regime of nominal effective power and equals 1.62 kg/h and is 35 % of magnitude of mass hourly fuel consumption and also 1.5 % of magnitude of mass hourly EG consumption.

It was also determined that magnitude of dimensionless indexes of aggresivenes of EG has uneven distribytion on RICE operational regimes field and for diesel engine 2Ch10.5/12 reaches maximum on regime of maximal crankshaft torque and the its avareged magnitude is 34.3.

In this case magnitude of dimensionless indexes of aggresivenes of aerosol of CG avareged on RICE operational regimes field for diesel engine 2Ch10.5/12 equals 25.5.

2 RESULTS OF CRITERIA-BASED CALCULATED ASSESSMENT AND THEIR ANALYSIS

Variants of the calculated study are following.

Variant A – Reference – without taking into account of emission of CG, that is $G(\text{CG}) = G(\text{CG})_b = 0$ kg/h and $k_{TS} = 0.0$.

Variant B – Desirable – emission of CG corresponds to recommended (see source [8]) for diesel RICE of moderm construction in serviceable technical state, that is $G(\text{CG}) = G(\text{CG})_{D21A1} \cdot 0.05$ and $k_{TS} = 0.05$.

Variant C – Basic – emission of CG corresponds to typical for 2Ch10.5/12 diesel engine in serviceable technical state, $G(\text{CG}) = G(\text{CG})_{D21A1} \cdot 1.0$ and $k_{TS} = 1.0$.

Variant D – Critical – emission of CG corresponds to predicted for diesel RICE in critical technical state, $G(\text{CG}) = G(\text{CG})_{D21A1} \cdot 2.0$ and $k_{TS} = 2.0$.

In this case it can be proposed the coefficient of RICE technical state that described by formula (2.1).

$$k_{TS} = G(\text{CG})_{CTS} \,/\, G(\text{CG})_{GTS}, \quad (2.1)$$

where $G(\text{CG})_{CTS}$ – magnitude of mass hourly emission of CG for actual RICE technical state, kg/h; $G(\text{CG})_{GTS}$ – magnitude of mass hourly emission of CG for serviceable RICE technical state in beginning of uts exploitation process, kg/h.

So, for desirable RICE technical state $k_{TS} = 0.05$, for actual technical state of 2Ch10.5/12 diesel engine $k_{TS} = 1.0$ (by definition) and for RICE critical technical state $k_{TS} = 2.0$.

Results of the calculated study are illustrated on Fig. 2.1 – 2.6.

Sertain interest are ratio between individual regime magnitudes of CG emission $G(\text{CG})$ and magnitudes of EG emission G_{EG} – $\delta G(\text{CG})$ and also fuel consumption G_{fuel} – $\delta G_g(\text{CG})$. Distribution of magnitudes of values of $G(\text{CG})$, $\delta G(\text{CG})$, $\delta G_g(\text{CG})$ on regimes of testing cycle ESC for 2Ch10.5/12 diesel engine are presented on Fig. 2.1 and 2.2. Such distribution for magnitudes of criterion K_{fe} and value of its changing δK_{fe} (as indicator of obtained effect from taking into account the CG emissions) for all variants of calculated study are illustrated on Fig. 2.3 and 2.4. Middle exploitational magnitudes of criterion K_{fe} and value of δK_{fe} are showed on Fig. 2.5.

Based on results of the study was obtained graphics of dependences of middle exploitational magnitudes of criterion K_{fe} and value of δK_{fe} from magnitude of coefficient of RICE technical state k_{TS} that for diesel engine 2Ch10.5/12 showed on Fig. 2.6. These graphics was described by polinomas of 2nd rank using the least squares method – see formulas (2.2) and (2.3).

$$K_{fe} = 16{,}012 \cdot k_{TC}^2 - 56{,}253 \cdot k_{TC} + 61{,}192, ‰, R^2 = 0{,}998; \quad (2.2)$$

$$\delta K_{fe} = 25{,}675 \cdot k_{TC}^2 - 90{,}026 \cdot k_{TC} - 2{,}290, ‰, R^2 = 0{,}998. \quad (2.3)$$

On Fig. 2.1 can be seen that for all variants of the study the magnitude of CG emission reaches maximum on regime of maximal crankshaft torque (№ 2) and minimum – on regime of minimal idle (№ 1), so changes in 12.5 times.

On Fig. 2.2 can be seen that for all variants of the study the magnitude of CG emission is in renge from 0.1 to 4.0 % of EG emission and from 2.5 to 87 % of fuel comsumption.

On Fig. 2.3 can be seen that for regime of nominal effective power (№ 10) magnitude of criterion K_{fe} for the reference variant (A) equals 77 ‰, for the desirable variant (B) – 65 ‰, for the basic variant (C) – 24 ‰ and for the critical variant (D) – 15 ‰.

On Fig. 2.4 can be seen that maximal magnitude of relative changing of criterion K_{fe} on regimes of ESC testing cycle which also are in RICE external speed characteristics reaches on regime of maximal crankshaft torque (№ 2) and equals –10 % for variant B, –65 % for variant C and –82 % for variant D.

On Fig. 2.5 can be seen that middle exploitation magnitude of criterion K_{fe} for variant A is 63 ‰, for variant B – 56 ‰ (that is, on 11 % less than for variant A), for variant C – 22 ‰ (that is, on 65 % less than for variant A), for variant D – 13 ‰ (that is, on 79 % less than for variant A).

On Fig. 2.6 can be seen that dependences $K_{fe} = f(k_{TS})$ and $\delta K_{fe} = f(k_{TS})$ has non linear characters, namely is the polinomas of 2nd rank. When magnitude of coefficient k_{TS} increases in range from 0.0 to 2.0 then middle exploitation magnitude of criterion K_{fe} decreases in range from 63 to 13 ‰ (that is, in 4.8 times), and magnitude of value δK_{fe} increases in range from 0.0 to 79 %.

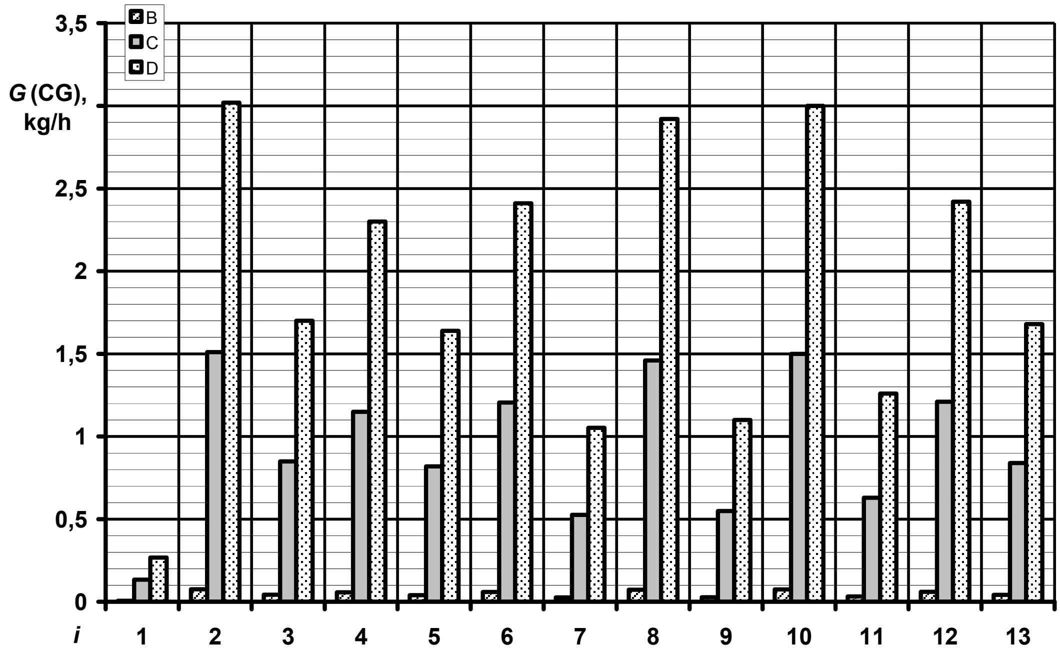
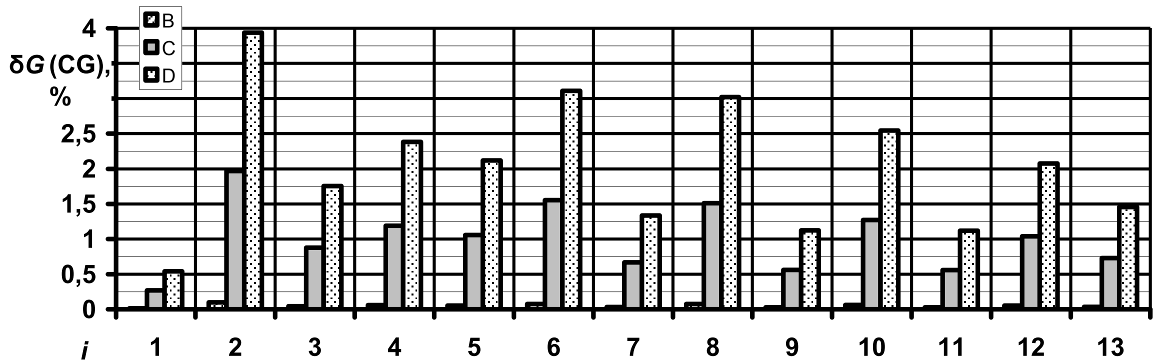


Figure 2.1 – Distribution of magnitudes of value of G(CG) on regimes of testing cycle ESC for 2Ch10.5/12 diesel engine



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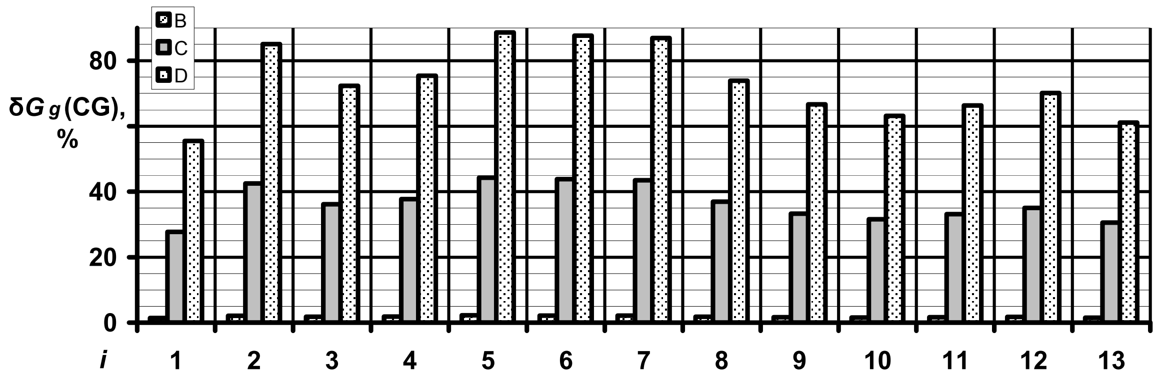

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Figure 2.2 – Distribution of magnitudes of values of δG(CG), δG(CG) on regimes of testing cycle ESC for 2Ch10.5/12 diesel engine

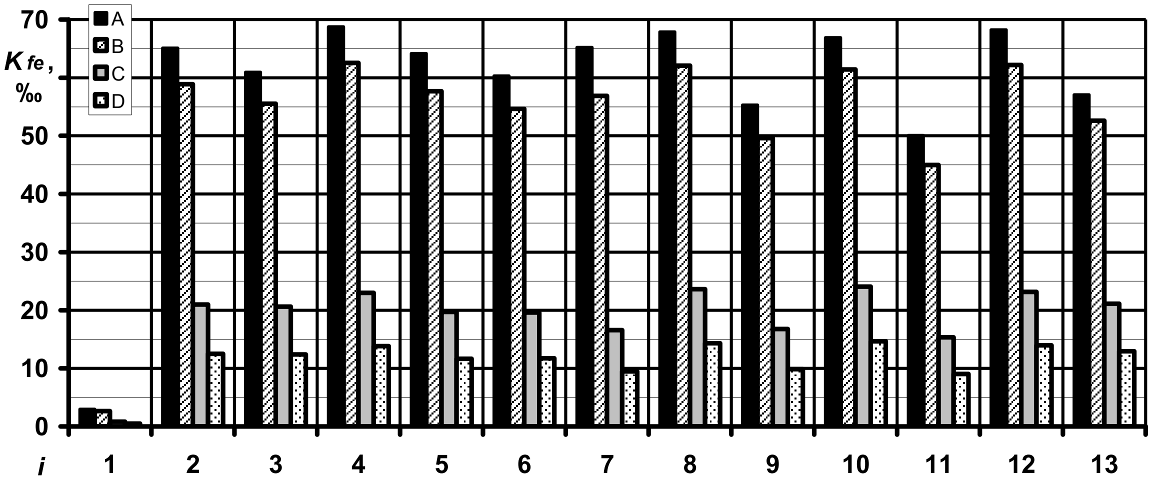

Figure 2.3 – Distribution of magnitudes of magnitudes of criterion K_{fe} for all variants of calculated study on regimes of testing cycle ESC for 2Ch10.5/12 diesel engine

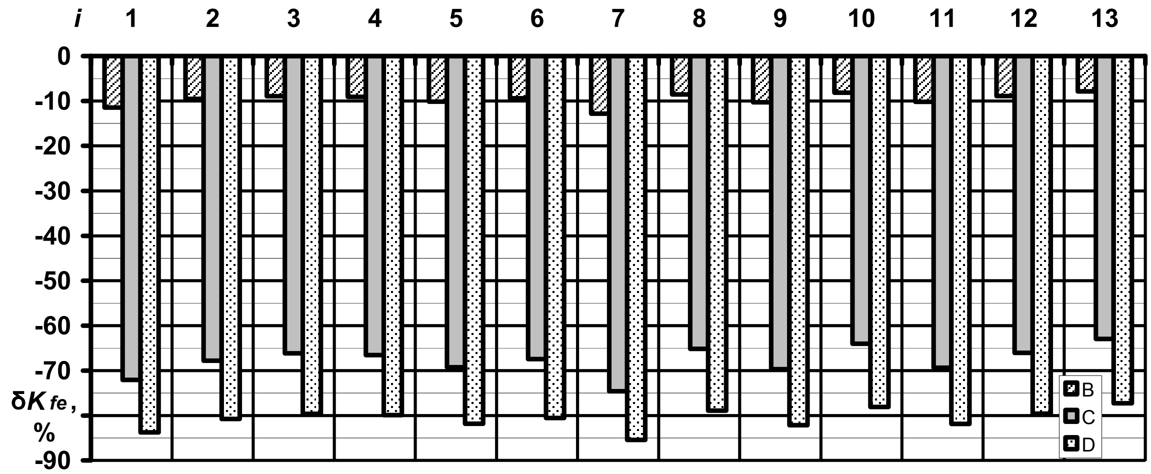

Figure 2.4 – Distribution of magnitudes of magnitudes of value of δK_{fe} for all variants of calculated study on regimes of testing cycle ESC for 2Ch10.5/12 diesel engine

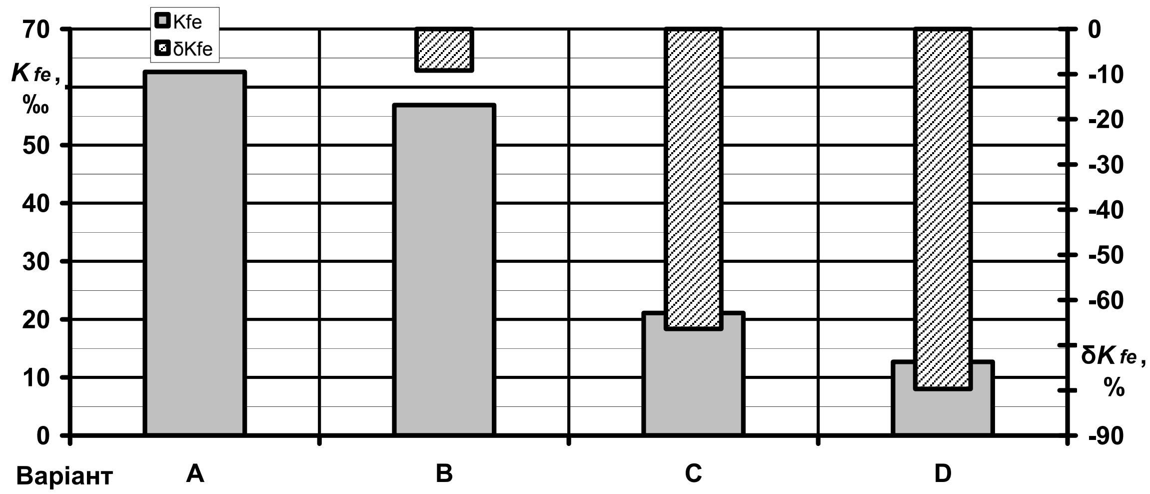

Figure 2.5 – Middle exploitational magnitudes of criterion K_{fe} and value of δK_{fe} for all variants of calculated study for 2Ch10.5/12 diesel engine

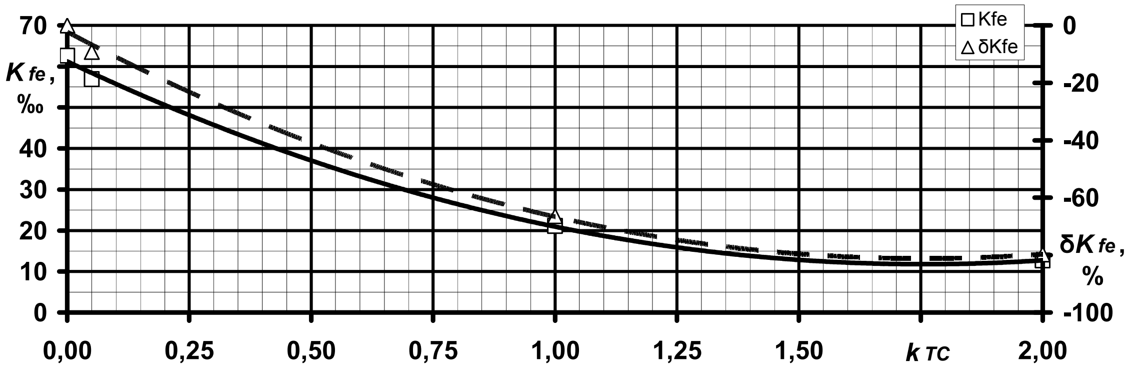

Figure 2.6 – Graphics of dependences of middle exploitational magnitudes of criterion K_{fe} and value of δK_{fe} from magnitude of coefficient of RICE technical state k_{TS} that for diesel engine 2Ch10.5/12

Thus, in this chapter of the study based on obtained from analysis of data of bench motor tests of 2Ch10.5/12 diesel engine initial data set for standardized steady testing cycle ESC it was carried out the calculated assessment of magnitudes of complex fuel-ecological criterion with taking into account of mass hourly emissions of aerosol of CG from reciprocating ICE which not equipped with carter venting system of carter gas suflation system on example of diesel engine 2Ch10.5/12.

It was determined that middle exploitational value of the criterion on the standardized steady testing cycle ESC (UNECE Regulations № 49) the taking into account of mass hourly emissions of aerosol of CG for diesel engine 2Ch10.5/12 that is in serviceable desired technical condition has the noticeable impact (up to 11 %), in serviceable actual technical condition has the significant impact (up to 65 %), in serviceable extreme technical condition has the critical impact (up to 80 %).

The identified dependencies are described by formulas using the least squares method.

CONCLUSSIONS

Thus, according to the analysis of the results of the study it can be formulated the following conclusions.

1. It was proposed the approach and methodica for calculated assessment of magnitudes of fuel-ecological criterion of Professor I.V. Parsadanov with taking into account of mass hourly emissions of carter gases as pollutant from reciprocating ICE which not equipped with carter venting system of carter gas suflation system.

Essence of the proposed approach is to obtain the values of the mass hourly emissions of aerosol of CG as the product of magnitudes of value-analog (namely, average indicator pressure in combustion chamber of diesel engine on selected steady operational regime) and proposed conversion coefficient, magnitude of which was obtained from results of solution of task about movement of gaseous fluid in the gap betwin the cylinder and piston. The driving force of the process is the difference in pressure in the combustion chamber and the carter obtained by the results of the calculation of the indicator diagram.

Magnitude of ponderability of such a pollutant it proposes to obtaine as the averaged on the RICE field of operational regimes magnitude of weighted average magnitude of dimensionless indexes of aggresivenes of components of aerosol of CG. Weight factors of such components was obtained as result of analysis of component composition of CG depending on their temperature and motor oil evaporation according to Cox schedule and UOP nomogram for petroleum products.

In the same way, the dimensionless index aggressiveness of EG of the diesel engine as a constituent of the aerosol of CG was also obtained.

2. It was obtained the initial data set to perform a calculated study for a standardized steady testing cycle ESC on the basis of the analysis of data of bench motor tests of a autotractor diesel engine 2Ch10.5/12 carried out at the motor test bench of the Piston Power Plant Laboratory of the Hydrogen Energy Department of IPMach of NAS of Ukraine with the participation of the science advisor of the study.

It was detected that for autotractor diesel engine 2Ch10.5/12 maximal magnitude of mass hourly emission of aerosol of CG reaches on the regime of nominal effective power and equals 1.62 kg/h and is 35 % of magnitude of mass hourly fuel consumption and also 1.5 % of magnitude of mass hourly EG consumption.

It was also determined that magnitude of dimensionless indexes of aggresivenes of EG has uneven distribytion on RICE operational regimes field and for diesel engine 2Ch10.5/12 reaches maximum on regime of maximal crankshaft torque and the its avareged magnitude is 34.3.

In this case magnitude of dimensionless indexes of aggresivenes of aerosol of CG avareged on RICE operational regimes field for diesel engine 2Ch10.5/12 equals 25.5.

3. It was carried out the calculated assessment of magnitudes of complex fuel-ecological criterion with taking into account of mass hourly emissions of aerosol of CG from reciprocating ICE which not equipped with carter venting system of carter gas suflation system on example of diesel engine 2Ch10.5/12.

It was determined that middle exploitational value of the criterion on the standardized steady testing cycle ESC (UNECE Regulations № 49) the taking into account of mass hourly emissions of aerosol of CG for diesel engine 2Ch10.5/12 that is in serviceable desired technical condition has the noticeable impact (up to 11 %), in serviceable actual technical condition has the significant impact (up to 65 %), in serviceable extreme technical condition has the critical impact (up to 80 %).

The identified dependencies are described by formulas using the least squares method.

A SWOT-analysis of results of the study was carried out, the results of which are contained in Appendix D.

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APPENDIX A. ANALYSIS OF MATHEMATICAL APPARATUS OF COMPLEX FUEL AND ECOLOGICAL CRITERION

Magnitudes of the criterion K_{fe} for *i*-th steady operational regime of RICE with weight factor *WF* are determinates by formula (A.1) [2, 3], other its components are determinates by formulas (A.2) – (A.11) and its middle exploitation magnitude can be obtained by formula (A.12) (see monograph [1]).

$$K_{fe} = \eta_e \cdot (1-\beta) = \frac{3600}{H_u \cdot g_e} \cdot \left(1 - \frac{Z_e(P_f)}{Z_f(P_f) + Z_e(P_f)}\right) \cdot 10^3, ‰; \tag{A.1}$$

$$\eta_e = 3600/(H_u \cdot g_e); \tag{A.2}$$

$$\beta = Z_e / Z_{fe}; \tag{A.3}$$

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

$$N_e = M_{кр} \cdot n_{кв} / 9550, \text{ kW}; \tag{A.5}$$

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

$$Z_e = g_e \cdot U_{ei}, \text{\$/(kW·h)}; \tag{A.7}$$

$$U_{ei} = \delta \cdot \sigma \cdot f \cdot g_{pri}, \text{\$/kg}; \tag{A.8}$$

$$g_{pri} = \sum_{k=1}^{m} \left(A_k \cdot G_{ki} / G_{fueli}\right); \tag{A.9}$$

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

$$g_e = G_{fuel} / N_e, \text{ kg/(kW·h)}; \tag{A.11}$$

$$K_{fe} = \sqrt[7]{\sum_{i=1}^{n}\left(K_{fei}^7 \cdot WF_i\right) / \sum_{i=1}^{n}(WF_i)}; \sum_{i=1}^{n}(WF_i) = 1.0, ‰. \tag{A.12}$$

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 МДж/кг [2] – 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(NO_x) = 41.1; *A*(PM) = 200; A(C_nH_m) = 3.16; *A*(CO) = 1.0 [2]); *h* = 4 [2] – 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 [2]); *f* – dimensionless coefficient that takes into account the character of dispersion of EG in atmosphere (for Ukraine *f* = 1.0 [2]); δ = 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.

For the use of formula (A.10), which is part of formula (A.1), it is necessary to have a ponderability of value G(k) compared to the ponderability of the emission of the reference polutant G(CO). Such ponderability is determined by the dimensionless indicator of relative aggressiveness of the k-th polutant A_k, which according to the method [9] is determined by formulas (A.13) and (A.14).

$$A_k = a_k \cdot \alpha_k \cdot \beta_k \cdot \delta_k , \quad \text{(A.13)}$$

$$a_k = \sqrt{\frac{MPC_{ad}(CO) \cdot MCP_{ot}(CO)}{MCP_{ad}(k) \cdot MCP_{ot}(k)}} , \quad \text{(A.14)}$$

where 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 etalonic (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 maximal one-time, mg/m^3.

Source [1] contains information about the components of formula (A.10), obtained from the analysis of the contents of the source [4], and is illustrated in Fig. 1.11.

APPENDIX B. OBTAINING OF INITIAL DATA SET FOR CARRYING OUT OF CALCULATED STUDY FOR STANDARDIZED STEADY TESTING CYCLE ESC

Standardized steady testing cycle ESC (European Steady Cycle) described in standard [5] is used for developing of programs of testing of RICE of passager vehicles and containes 13 steady operational regimes.

The parameters of the ESC cycle regimes for the 2Ch10.5/12 diesel according to [5] are determined by formula (B.1).

$$n_k = n_{lo} + G \cdot \left(n_{hi} - n_{lo}\right), \text{ rpm}; \quad (\text{Б.1})$$

where where n_{lo} – low crankshaft speed i.e. its minimal magnitude at 50 % of RICE nominal effective power, rpm; n_{hi} – high crankshaft speed i.e. its minimal magnitude at 75 % of RICE nominal effective power, rpm; if k = A than C= 0.25; if k = B than C = 0.50; if k = C than C = 0.75.

For 2Ch10.5/12 diesel engine maximal power is 21 kW and reaches at M_T = = 110 N·m and $n_{кв}$ = 1800 rpm. Basing on results of motor bench tests of that engine we get following data: n_{lo} = 1000 rpm, n_{hi} = 2000 rpm, than: n_A = 1250 rpm, n_B = = 1500 rpm, n_C = 1750 rpm. So $M_{крA\max}$ = 108 N·m, $M_{крB\max}$ = 102 N·m, $M_{крC\max}$ = 93 N·m, than: $N_{eA\max}$ = 14.136 kW, $N_{eB\max}$ = 16.021 kW, $N_{eC\max}$ = 17.042 kW.

For 2Ch10.5/12 diesel engine distribution of magnitudes of operational indicators on regimes of testing cycle ESC illustrated: coordinates of regimes of its field – M_T i n_{cs}; effective power N_e and weight factor WF of regimes; mass hourly fuel consumption G_{fuel} and effective efficiency coefficient η_e – on Fig. B.1; mass hourly emissions of pollutants in EG flow – particulate matter G(PM), nitrogen oxides $G(NO_x)$, unburned hydrocarbons $G(C_nH_m)$ and carbon dioxide G(CO) – on Fig. B.2.

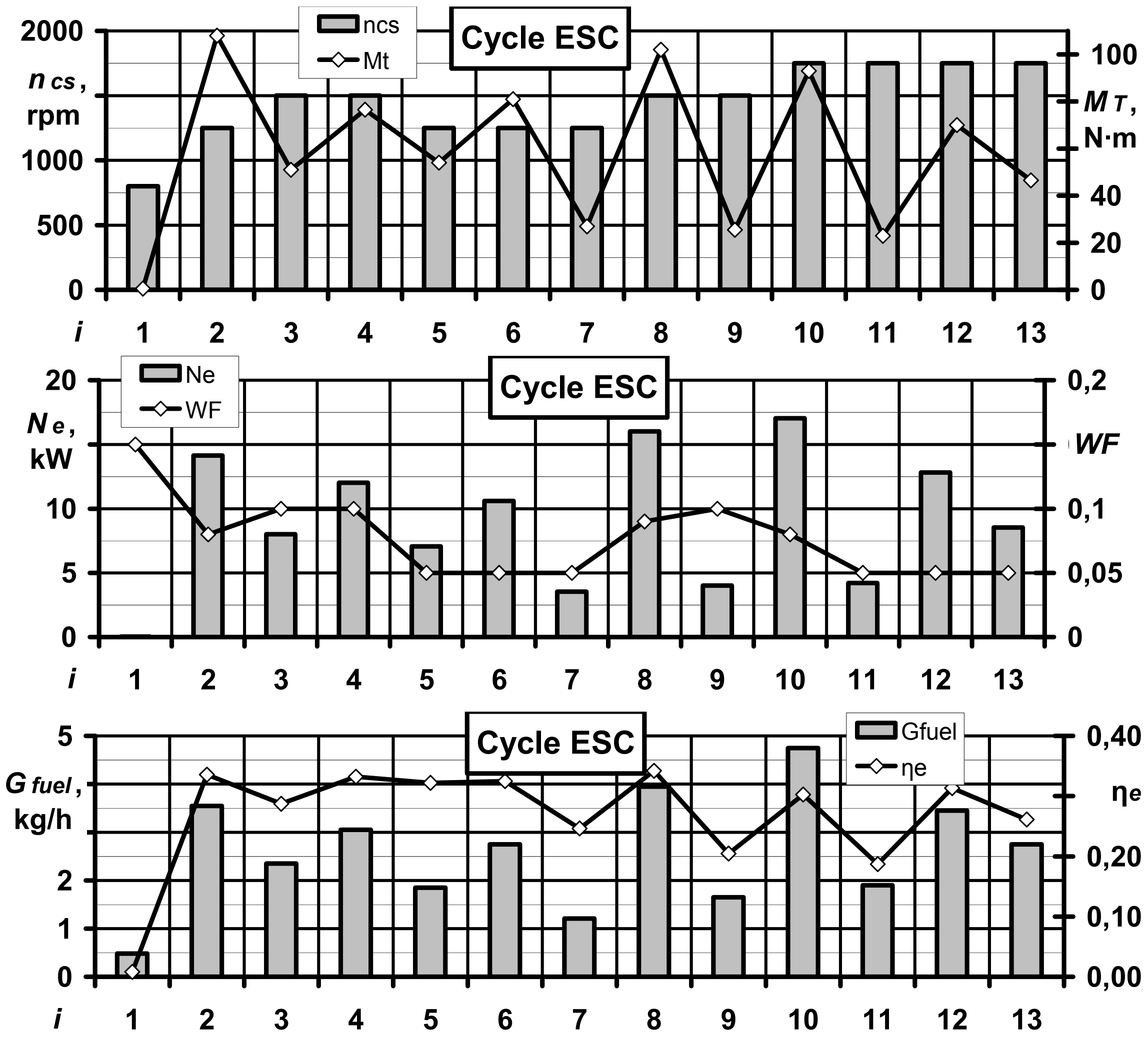


Figure B.1 – Distribution of magnitudes of technical-economical indicators of operation of 2Ch10.5/12 diesel engine on regimes of testing cycle ESC

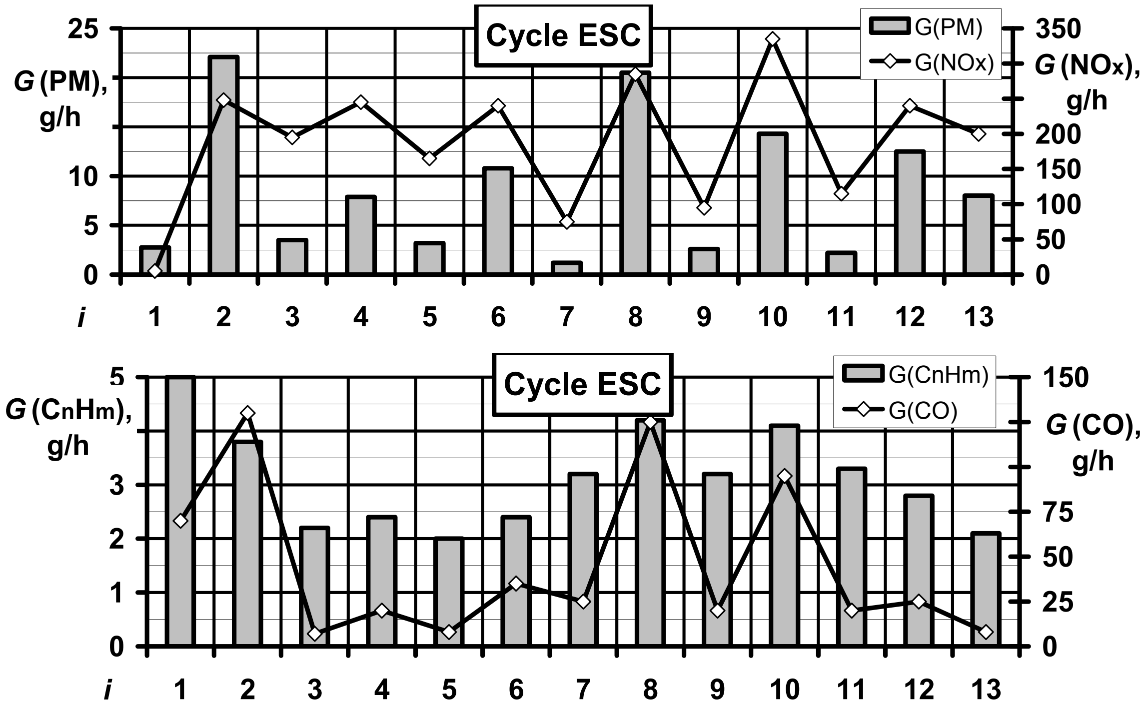


Figure B.2 – Distribution of magnitudes of ecological indicators of operation of 2Ch10.5/12 diesel engine on regimes of testing cycle ESC

APPENDIX C. CHARACTERISTICS OF VAPORIZATION OF PETROLEUM PRODUCTS

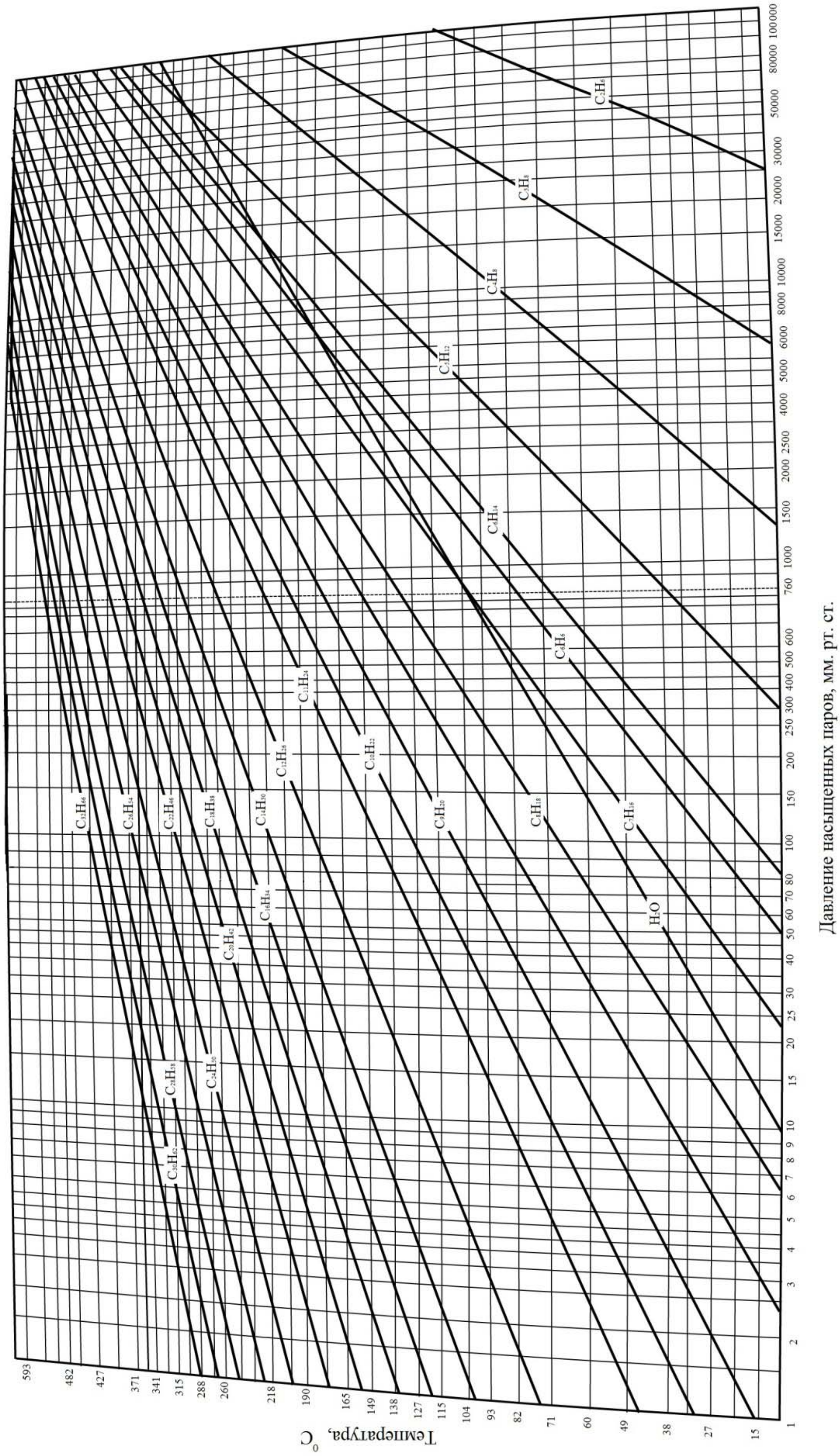


Figure B.1 – Cox's schedule [19]
(in the original language)

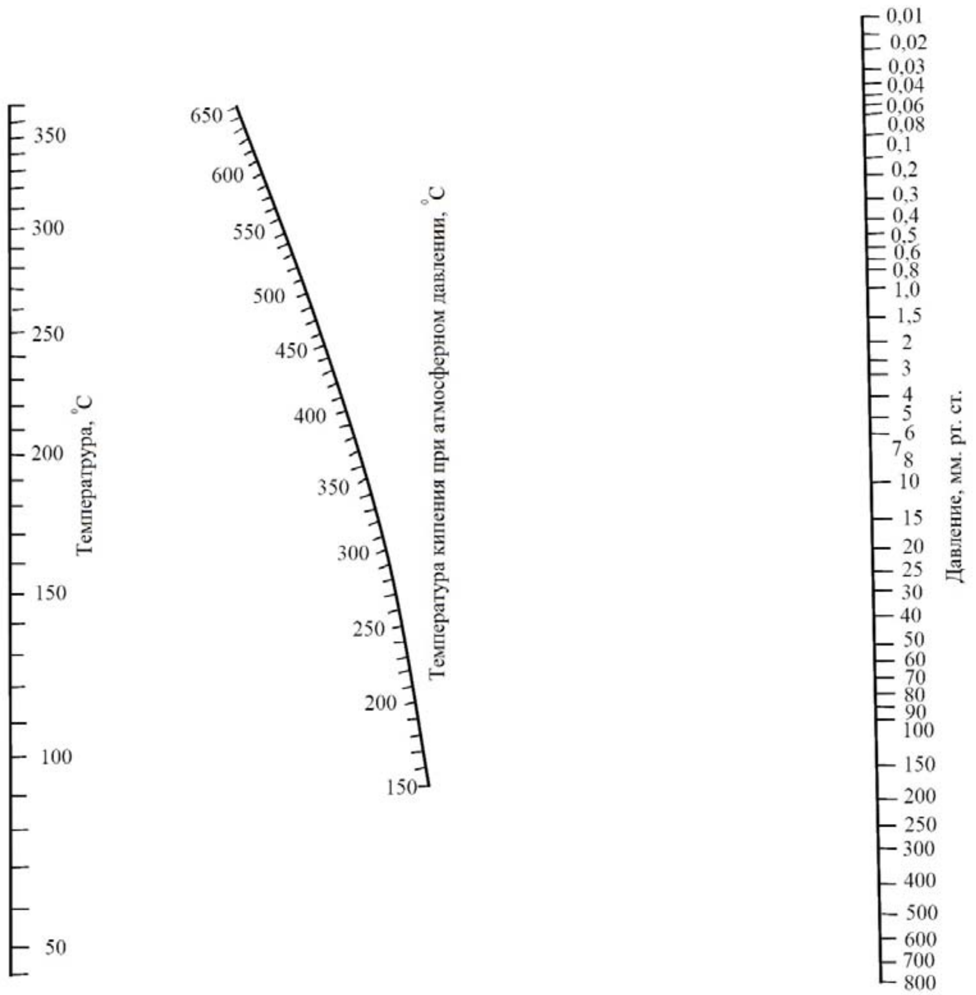
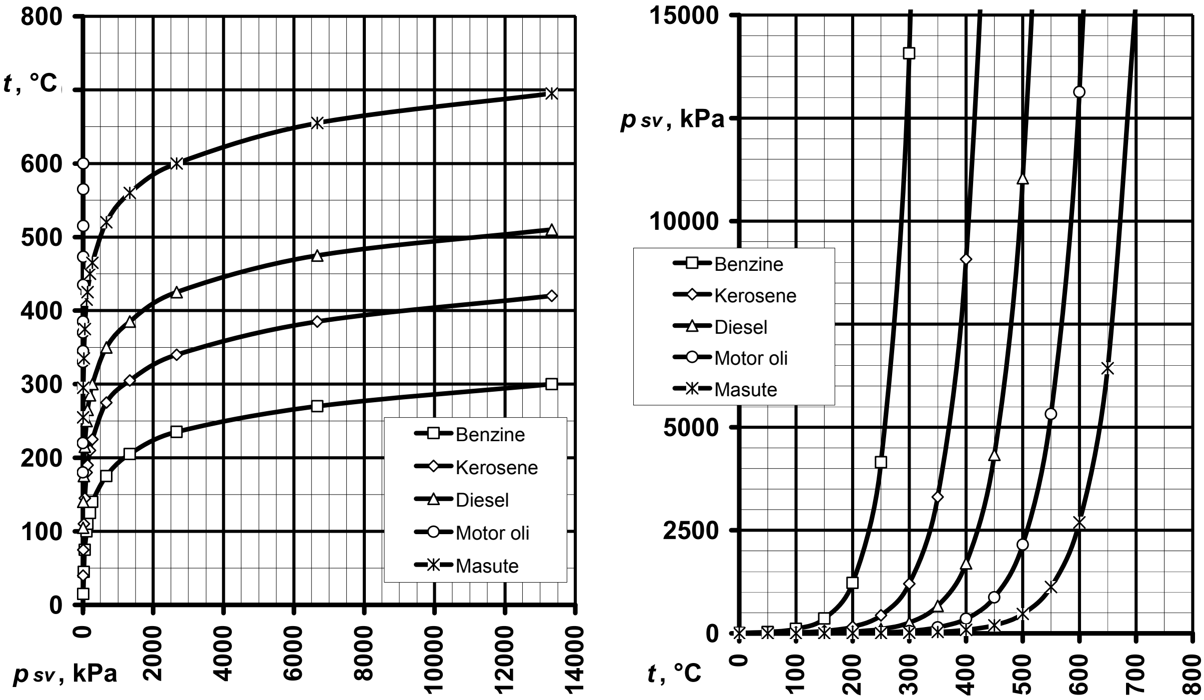


Figure B.2 – Nomogram UOP [19] (in the original language)



a b

Figure B.3 – Nomograms of saturation vapor pressure of petroleum products (a, b) (obtained on the basis of data from source [19])

APPENDIX D. SWOT-ANALYSIS OF RESULTS OF THE STUDY

Strengths (***S***). Results of the study presented in this manuscript are distinguished by the following advantages. The proposed approach to the criteria-based assessment of ES level of the PP with RICE accident-free exploitation process, with taking into account the emissions of aerosol of carter gases, allows to provide quantitative and qualitative assessment of effectiveness of use of systems that reduce or negate the causes of such emissions, and justify the need for their development and implementation.

Weaknesses (***W***). Results of this study have two major drawbacks. Monetary assessment of environmental damage from the identified effects as well as economic effect of overcoming them have not been given, nor have the analysis of features of constructive solutions of known or proposed new or improved measures for reducing the mentioned emissions been proposed.

Opportunities (***O***). Results of the study open up the following possibilities for their further practical application, and also outline the directions of further research, which is expressed in the realization of the next degree of approximation in the implementation of the specified criteria-based assessment and gradual consideration of all ES factors, which are inherent in the specified exploitation process, which are listed in the developed hierarchical classifier.

Threats (***T***). Results of this study, which form the basis of the developed list of recommendations for their practical application, are at the same time a source of the following risks. The optional character of implementation and consideration the results of criteria-based assessment in general and the results of this study, and the absence of an appropriate legislative framework in particular.

The following *strategies* are formed.

SO-strategy, that aims to further enhance strengths through the use of opportunities. Further research is being undertaken to expand the number of ES factors taken into account until the content of the hierarchical classifier is exhausted.

ST-strategy, that aimed at eliminating threats through the use of strengths. It envisages bringing the degree of perfection and versatility of the mathematical apparatus and the method of criteria-based assessment of the ES level of PP with RICE exploitation process to a state in which it will be possible to consolidate the procedure of such assessment at the legislative level and to create an appropriate program complex for this.

WO-strategy, that aims to strengthen the weaknesses by leveraging opportunities. Includes in the improvement (modernization and addition) of the mathematical apparatus of the applied criterion in terms of calculating its components having monetary equivalents, taking into account the actual fluctuation of the rate of the basic reserve world freely convertible currencies and the phenomenon of inflation.

WT-strategy, that aimed at strengthening the weaknesses that are still present by avoiding threats. It is proposed to overcome the formulated drawbacks by developing a draft normative document that will include an improved methodology for the use of modernized criterion mathematical apparatus as well as requests for financing an environmental program for the implementation of this type of environmental activity (in accordance with the «List of activities related to nature conservation measures», approved by the Cabinet of Ministers of Ukraine Decree No. 1147 of 17.09. 1996) from the State or Regional or Environmental Fund in accordance with the «Regulations on the State Fund for Environmental Protection», approved by the Cabinet of Ministers of Ukraine of 07.05.1998 No. 634 and the «Procedure for Planning and Financing of Environmental Measures», approved by the Order of the Ministry of Ecology and Natural Resources of Ukraine No. 194 of 12.06.2015.