Scientific and technical journal
«Technogenic and Ecological Safety»

RESEARCH ARTICLE
OPEN ACCESS

DETERMINATION OF QUANTITATIVE AND QUALITATIVE ASPECTS OF ENVIRONMENTAL POLLUTION BY THERMAL ENERGY FROM POWER PLANTS WITH RECIPROCATING INTERNAL COMBUSTION ENGINES

O. Kondratenko[1], V. Koloskov[1], H. Koloskova[2], O. Lytvynenko[1]
[1]National University of Civil Protection of Ukraine, Cherkasy, Ukraine
[2]National Aerospace University «Kharkiv Aviation Institute», Kharkiv, Ukraine

UDC 504.064.4 : 355.695.1 : 621.039.542.4 : 621.039.542.5 : 544-971 : 544.01
DOI: 10.52363/2522-1892.2025.1.1
Received: 15 March 2025
Accepted: 24 April 2025

Cite as: Kondratenko O., Koloskov V., Koloskova H., Lytvynenko O. (2025). Determination of quantitative and qualitative aspects of environmental pollution by thermal energy from power plants with reciprocating internal combustion engines. Technogenic and ecological safety, 17(1/2025), 3–17. doi: 10.52363/2522-1892.2025.1.1

Abstract

In the article, which shows the results of the authors' own research, the purpose of which was improving the method for taking into account the parameters of the emission of thermal energy in the environment as a pollutant during the criteria-based complex assessment of the ecological safety (ES) level of the exploitation of such power plants (PP), especially taking into account the realities of the functioning of the divisions and institutions of the SES of Ukraine and their units of fire-fighting and emergency rescue vehicles (FERV) in conditions of armed aggression and in the perspective of the post-war reconstruction of critical infrastructure and the economy of our country. Following tasks were consistently solved: development of a method for calculating the values of the complex fuel-ecological criterion taking into account thermal energy emissions in the environment during the operation of FERV with RICE; obtaining the set of initial data for carrying out a calculation study for the standardized steady ESC test cycle and the 2Ch10.5/12 autotractor diesel engine, calculated assessment of the values of the complex fuel-ecological criterion taking into account thermal energy emissions in the environment during the exploitation of FERV with RICE. Problem of the study is the imperfection of existing methods for criteria-based assessment of the ES level of the exploitation of the PP with RICE, especially considering the realities of the functioning of the institutions and divisions of the SES of Ukraine and their FERV units in conditions of armed aggression and in the perspective of the post-war reconstruction of the critical infrastructure and economic of our country. Idea of the study is to improve the methodology for determining the values of the K_{fe} criterion by expanding the ES factors taken into account by its mathematical apparatus, in particular, emissions of thermal energy into environment. Main task of the study is determination of quantitative and qualitative aspects of the effect of taking into account the emission of thermal energy in the environment during a complex criteria-based assessment of the ES level of the exploitation process of such PP, in particular FERV units, using the steady standardized ESC test cycle (in accordance with UNECE Regulations No. 49) based on the improved mathematical apparatus of the complex fuel-ecological criterion. Object of the study is ES of the exploitation process of PP with RICE, in particular FERV units, taking into account the negative technogenic impact of thermal energy on environmental components. Subject of the study is contribution to the numerical values of the indicators of the object of the study of the emission of thermal energy into the environment. Scientific novelty of the results obtained is the method for taking into account the emission of thermal energy into the environment from PP with RICE, in particular FERV units, in a complex criteria-based assessment of the indicators of the ES level during their exploitation has been further developed. Practical value of the results obtained is the results obtained are suitable for providing a quantitative and qualitative assessment of the studied effects and developing on this basis technical solutions and organizational measures to reduce or eliminate them by developing an appropriate environmental protection technology with executive devices on the methodological basis of the ES management system.

Key words: environmental protection technologies, ecological safety, power plants, firefighting and emergency-rescue vehicles, reciprocating internal combustion engines, thermal pollution, complex criteria-based assessment, armed aggression, post-war reconstruction.

Statement of the problem and analysis of the sources

The relevance of the study presented in this article due to the following considerations. To provide a complex assessment of the value of the indicators of the ecological safety (ES) level of the exploitation of power plants (PP) with diesel reciprocating internal combustion engines (RICE) [1], equipped with fuel tanks, which are essentially reusable containers (reservoirs) for storing chemically active, fire and explosive, toxic fluids, it is advisable to use the mathematical apparatus of the complex fuel-ecological criterion of Prof. Parsadanov K_{fe} (NTU «KhPI»), described in the monograph [2] and improved in the monograph [3].

The classifier of ES factors, the source of which is the RICE in the composition of the PP in the process of its exploitation, which is built on the hierarchical principle and developed in work [3], includes, in addition to emissions of legally regulated pollutants with the exhaust gases (EG) flow, the consumption of motor fuel as a non-renewable energy resource (product of mineral processing), as well as emissions of motor fuel vapors caused by manifestations of the phenomena of small (SBR) and large (LBR) breathing of reservoirs, namely, fuel tanks of the PP.

However, in the structure of ES factors taken into account by the original mathematical apparatus of the K_{fe} criterion, the first of the specified factors is taken into account indirectly (approaches to determining the importance of fuel consumption of RICE as an ES factor are given in [3]), and the second is not taken into account at all.

Taking into account the specified ES factor in combination with the existing ones fully corresponds to the concept of improving the mathematical apparatus of the K_{fe} criterion, formulated in the source [3], the goals of sustainable development specified in the Decree of

the President of Ukraine № 722/2019 dated September 30, 2019 «On the Goals of Sustainable Development of Ukraine for the Period until 2030» [4], and the contents of the Regulation on the Organization of Ecological Support of the State Emergency Service of Ukraine, approved by the Order of the State Emergency Service (SES) of Ukraine № 618 (on main activities) dated September 20, 2013 [5].

However, it is also known that reusable containers (tanks) for chemically active, fire and explosive, toxic liquid media, which are subjected to heavy and inertial mechanical loads of a permanent, pulsed or oscillatory nature, are a product of high-tech production and have a rather high cost [4].

At the same time, the consumption of motor fuel by RICE causes, in the sum of the effects, 100 % pollution of all components of the environment – atmosphere, hydrosphere and lithosphere, as well as the negative impact of a technogenic nature on the components of the biosphere in general and humans in particular, with thermal energy, which is the main effect of exothermic redox reactions in the engine combustion chamber. Part of this thermal energy enters the environment due to the heat exchange with the heated engine parts and radiation from them and with the gas flow, part is a product of the action of dissipative forces in the engine itself, and the rest is as an effect of the action of such forces in the PP during its operation. Taking into account such an impact as an ES factor of the process of exploitation of the PP with RICE in its criteria-based complex assessment is also an equally relevant scientific and technical task.

It should be noted that the RICE is a powerful source of environmental pollution by factors of various physical nature – this is a qualitative aspect of the relevance of the topic of this study, they collectively produce up to 75 % [2] of energy (mechanical and electrical) in the territory of our country in peacetime, and about 85–90 % [6] in times of armed aggression and in the perspective of the post-war reconstruction of the critical infrastructure and economy of our country – this is a quantitative aspect of the relevance of the topic of this study.

Purpose of the study. Improving the method for taking into account the parameters of the emission of thermal energy in the environment as a pollutant during the criteria-based complex assessment of the ES level of the exploitation of such PP, especially taking into account the realities of the functioning of the divisions and institutions of the SES of Ukraine and their units of fire-fighting and emergency rescue vehicles (FERV) in conditions of armed aggression and in the perspective of the post-war reconstruction of critical infrastructure and the economy of our country.

Problem of the study. The imperfection of existing methods for criteria-based assessment of the ES level of the exploitation of the PP with RICE, especially considering the realities of the functioning of the institutions and divisions of the SES of Ukraine and their FERV units in conditions of armed aggression and in the perspective of the post-war reconstruction of the critical infrastructure and economic of our country.

Idea of the study. To improve the methodology for determining the values of the K_{fe} criterion by expanding the ES factors taken into account by its mathematical apparatus, in particular, emissions of thermal energy into environment.

Main task of the study. Determination of quantitative and qualitative aspects of the effect of taking into account the emission of thermal energy in the environment during a complex criteria-based assessment of the ES level of the exploitation process of such PP, in particular FERV units, using the steady standardized ESC test cycle (in accordance with UNECE Regulations No. 49 [7]) based on the improved mathematical apparatus of the complex fuel-ecological criterion.

Object of the study. ES of the exploitation process of PP with RICE, in particular FERV units, taking into account the negative technogenic impact of thermal energy on environmental components.

Subject of the study. Contribution to the numerical values of the indicators of the object of the study of the emission of thermal energy into the environment.

The study was carried out on the example of a D21A1 autotrucktor diesel engine (2Ch10.5/12 according to ISO 3046-1:2002 «Reciprocating internal combustion engines. General technical conditions»), the technical description of which is given in the source [8].

Methods of the study. Analysis of specialized scientific and technical, reference, patent and regulatory literature, analysis of the results of bench engine tests using standardized steady test cycles, the position of the scientific discipline «Theory of Internal Combustion Engines» [9], improved mathematical apparatus of the complex fuel-ecological criterion of Prof. Parsadanov, the method of least squares.

Tasks of the study are the following points.

1. Development of a method for calculating the values of the complex fuel-ecological criterion taking into account thermal energy emissions in the environment during the operation of FERV with RICE;
2. Obtaining the set of initial data for carrying out a calculation study for the standardized steady ESC test cycle and the 2Ch10.5/12 autotractor diesel engine.
3. Calculated assessment of the values of the complex fuel-ecological criterion taking into account thermal energy emissions in the environment during the exploitation of FERV with RICE.

Scientific novelty of the results obtained is as follows.

The method for taking into account the emission of thermal energy into the environment from PP with RICE, in particular FERV units, in a complex criteria-based assessment of the indicators of the ES level during their exploitation has been further developed.

Practical value of the results obtained is as follows.

The results obtained are suitable for providing a quantitative and qualitative assessment of the studied effects and developing on this basis technical solutions and organizational measures to reduce or eliminate them by developing an appropriate environmental protection technology (EPT) with executive devices on the methodological basis of the ES management system (ESMS).

The results of the study were **used and implemented** in the educational process of a higher

education institution of the IV level of accreditation in the preparation of applicants for higher education at the third (educational and scientific) level in the specialty 183 (G2) «Environmental Protection Technologies».

The instrumental error of the known formulas for converting opacity indicators into toxicity indicators of EG flow of RICE as a metrological aspect of a complex criteria-based assessment in the development of executive devices of EPT is considered in work [10], the place of DPF with a liquid working body in the classification of technologies for protecting atmospheric air from the complex negative impact of PP with RICE is identified and described in work [11], the results of a criteria-based assessment of the efficiency of converting RICE of hybrid vehicles and other types of PP with RICE to biofuel consumption as one of the effective organizational and technical measures for the greening of such technical facilities are given in works [12, 13], a characteristic of the methodological principles of ensuring an acceptable level of RICE of transport as a component of Ukraine's national security during the period of armed aggression and as a prerequisite for a «green» transition in the period of post-war reconstruction is given in work [14], the main aspects of physical and mathematical modeling of processes in DPF in the practice of a complex criteria-based assessment of the ES level of the exploitation of transport vehicles with RICE is presented in the monograph [15], the criteria for assessing the efficiency of decarbonization of transport vehicles with RICE in the context of implementing the concept of sustainable development are presented in the work [16].

The topic of this study corresponds to the content of the Resolution of the Cabinet of Ministers of Ukraine No. 476 dated April 30, 2024 «On approval of the list of priority thematic areas of scientific research and scientific and technical developments for the period until December 31 of the year following the termination or abolition of martial law in Ukraine» [17], the content of the Specialty Passport 21.06.01 «Ecological Safety», approved by the Resolution of the Presidium of the Higher Attestation Commission of Ukraine No. 33-07/7 dated July 4, 2001 [18].

In this study and in the perspective of further research, the results of the application of the 3D Geometry modeling online free system FreeCAD [19] and the Online free system for modeling the working processes of RICE using digital twins Blitz-PRO [20] were used.

In general, the aspiration of technologically advanced and at the same time environmentally conscious humanity is the integration and intensification of thermal processes to increase energy efficiency and mitigate environmental pollution for sustainable industrial development [21]. The use of thermal energy of space as a component of the concept of restoring the landscape of industrial facilities based on thermal sensing of the environment and stereoscopic vision is described in the work [22]. The assessment of the environmental impact of rooftop photovoltaic installations in terms of thermal energy transfer is performed in the work [23]. A comprehensive energy, exergy and ecological assessment of integrated photovoltaic/thermal systems with heat pipes using multi-objective optimization is described in the work [24]. Mitigation of urban heat island effects through leadership in the assessment of energy and ecological design and blue-green infrastructure is achieved in the work [25]. Supply chain management of an environmentally friendly production process based on thermal efficiency improvement and ecological impact assessment technology is proposed in the work [26]. Ecological and economic planning of an integrated wind-storage and thermal energy system based on priority ranking is proposed in the work [27]. Long-term monitoring of thermal pollution from the Baniyas PP in Syrian coastal waters using Landsat data is presented in the work [28]. An experimental study of the thermodynamic and ecological efficiency of a novel ocean thermal energy conversion – air conditioning system was conducted in the work [29]. A comparative study on improving the thermoecological performance of a hemispherical distiller using inexpensive materials for thermal energy storage was disclosed in the work [30].

A quantitative assessment of the ecological impact of thermal emissions from a lake water heat pump is provided in the study [31]. An assessment of the ecological performance of thermal PP according to a study on Italian EMAS-registered sites is provided in the study [32]. A multifaceted study of the integration of a multigenerational system and a landfill gas combustion process using environmentally friendly thermal design is proposed in the study [33]. The principle of «gear shifting» in thermal power generation as a basis for ensuring the displacement efficiency and ecological impact of wind and solar generation in China is demonstrated in the study [34]. Flexible biomass-based phase change materials of the L-N-Ti type for environmentally friendly thermal management are proposed in the study [35]. Identification of key ecological factors affecting the visitation of urban parks, such as thermal comfort and air quality, is carried out in the study [36]. Environmental reporting in Italian thermal PP and conclusions from the comprehensive analysis of EMAS ecological statements are illustrated in the study [37]. A multi-thermal recovery scheme for sustainable electricity and cooling production using a biomass-based multi-generation system and an ecological feasibility analysis and ANN-GA optimization are developed in the study [38]. An energy, economic and ecological life cycle analysis of a direct expansion photovoltaic-thermal pump system in China is performed in the study [39]. An energy, exergy, economic and ecological life cycle analysis of a new biogas-fired hybrid solid oxide fuel cell power generation system supported by a solar thermal energy storage as an innovative comprehensive technical solution is developed in the study [40].

The influence of environmental conditions on the thermal, emission and economic performance of a gas turbine using different fuels based on the results of an experimental study is described in the research [41]. A comprehensive assessment of the thermal characteristics, kinetics and ecological impact of fly ash from municipal solid waste incineration during thermal

treatment is investigated in the research [42]. From waste to energy is the principle on which a comprehensive understanding of thermochemical recycling methods for waste tire recycling is based, as shown in the research [43]. An experimental study and comparison of the performance of an integrated air conditioning system of a 1 kW class solar-ocean thermal energy conversion system based on energy, exergy, economic and ecological (4E) analysis is presented in the research [44]. The ecological impact of Indian coal-fired thermal PP and the associated human health risks to nearby residential communities are described in the research [45]. Optimization of hydrogen production and system efficiency by utilizing EG heat in a hydrogen-enriched RICE is presented in the research [46]. Waste heat recovery of combined RICE and reverse Brayton cycle for hydrogen and fresh water production in terms of optimization and comparison using the 4E method is presented in the research [47]. Comparative analysis of different heat transfer models, energy and exergy analysis for hydrogen-enriched RICE under different operating conditions is described in the research [48]. Performance analysis of RICE with thermochemical recovery and combined power generation system with high-temperature proton exchange membrane on fuel cells is presented in the research [49]. A new trend of deep utilization of RICE waste heat by using condensing economizers in waste heat boilers is presented in the research [50].

Artificial intelligence-based response surface methods for thermoeconomic optimization of the superstructure of waste heat recovery systems in a large-scale thermal PP are developed in the source [51]. A proposal for a new method for waste heat recovery from a thermal PP for a direct combustion double-effect absorption refrigeration unit is substantiated in the source [52]. A review of phase change materials for waste heat recovery in thermal PP is performed in the source [53]. A comparison of the profitability of thermal electricity production from spent diesel RICE using exergoeconomic analysis of optimization of two different scenarios of the organic Rankine cycle is shown in the source [54]. An effective topology of exhaust heat exchangers equipped with thermoelectric generators for diesel RICE is developed in the source [55]. Utilization of waste heat from diesel RICE for power increase and cooling is considered in the source [56]. A hollow fiber polymer heat exchanger for reducing CO_2 emissions from a vehicle with an RICE is described in the source [57]. A joint numerical and technical analysis and economic assessment of the use of small RICE in cogeneration plants is performed in the source [58]. A theoretical analysis and comparison of the Rankine cycle and various organic Rankine cycles as a waste heat recovery system for a large RICE on gaseous fuel is performed in the source [59]. The study of the characteristics of the influence of the heat-accumulating material on the thermodynamic process in heat accumulators installed in the waste heat recovery system of the RICE is shown in the source [60]. The study of the integration of hydrogen into a multi-cylinder diesel RICE with low heat dissipation using a ternary mixture is described in the source [61]. The use of acetylene in a multi-cylinder diesel RICE with low heat dissipation operating on a ternary mixture is proposed in the source [62].

This state of the problem determines the **relevance of the study** – improving of the method of complex criteria-based assessment of indicators of the ES level of the exploitation process of PP with RICE, including FERV used by the SES of Ukraine, especially in remote areas and frontline zones, in terms of taking into account such a factor of environmental hazard as thermal energy emissions, aimed at protecting the environment from technogenic impacts of such mobile sources of environment pollution. This is crucial both during armed aggression and for post-war reconstruction of critical infrastructure.

This area of research is fully characterized by the following 4 main points of justification of relevance.

1) In accordance with the Order of the SES of Ukraine № 618 dated 20/09/2013 «On Approval of the Regulations on the Organization of Ecological Support of the State Emergency Service of Ukraine» [5]: the results of research allow achieving the goal of ecological support of the SES of Ukraine as a set of organizational and technical measures, including those carried out by higher educational institutions, namely, achieving ecological safety of all types of activities of bodies and units of the SES of Ukraine, protection of personnel and employees, material and technical means under the influence of environmentally unfavorable anthropogenic and natural factors, as well as environmental protection in the places of deployment and location of bodies and units of the SES of Ukraine, in terms of fulfilling the task of scientific support of the main tasks of ecological support of the SES of Ukraine, providing an assessment of environmental damage from the activities of bodies and units of the SES of Ukraine, implementing measures to restore the environment, complying with maximum permissible standards for emissions of harmful substances into the atmosphere, implementing measures to reduce them, reducing the toxicity of exhaust gases from equipment.

2) In accordance with the Decree of the President of Ukraine № 722/2019 dated 30/09/2019 «On the Sustainable Development Goals of Ukraine for the period up to 2030» [4]: the results of research correspond to:

– Goal № 3 «ensure a healthy lifestyle and promote well-being for all at all ages»,

– Goal № 7 «ensure access to affordable, reliable, sustainable and modern energy sources for all»,

– Goal № 11 «ensure openness, security, livability and environmental sustainability of cities and other settlements»,

– Goal № 13 «take urgent measures to combat climate change and its consequences».

3) In accordance with the Resolution of the Cabinet of Ministers of Ukraine № 476 dated 04/30/2024 «On approval of the list of priority thematic areas of scientific research and scientific and technical developments for the period until December 31 of the year following the termination or abolition of martial law in Ukraine» [17]: the results of research correspond to the direction of:

– the section «Rational environmental management», namely «Modeling and forecasting of the state of the environment, technologies for overcoming negative impacts on it»,

– the section «Energy and energy efficiency», namely «Systems of generation and transportation of electric and thermal energy» and «Technologies for the development and use of new types of fuel, renewable and alternative energy sources and types of fuel»,

– the section «National security and defense», namely «Ecologically balanced energy security» and «Intelligent information and control technologies for diagnostics, operation and repair of military and special equipment».

4) In accordance with the Specialty Passport 21.06.01 «Ecological Safety», approved by the Resolution of the Presidium of the Higher Attestation Commission of Ukraine № 33-07/7 dated 04.07.2001 [18]: the results of research correspond to the directions:

– «Development of scientific methods for research of complex assessment and forecasting of the impact of technogenic pollution on the environment and humans»;

– «Improvement of existing, creation of new, environmentally safe technological processes and equipment that ensure the rational use of natural resources, compliance with the standards of harmful effects on the environment. Environmental audit, environmental management».

1 Analysis of scientific and technical, reference, normative, and patent literature

In previous studies of the authors of this article [13], issues were considered, including the development of new and improvement of existing complexes of measuring equipment for the experimental and computational studies specified in the purpose of this article. The results of the profile work [14] on the issues of experimental testing of technical-economic and ecological indicators of the PP with the RICE and their metrological features were also analyzed in detail there.

In modern researches, modeling is used in the development of engine test benches, for example, in the MATLAB/Simulink application [15], multi-parameter controllers are used as part of the bench [16], measurement of the RICE torque using an electronic control system for an electro-mechanical dynamometer [17] and a hydraulic dynamometer [18], analysis systems for nonlinear output feedback and periodic damping of disturbances [19], failure analysis systems for the bench control system [20], nonlinear observer and output feedback of the bench [21], a reference controller for a discrete-time model for the test bench [22], a nonlinear observer of the air-fuel ratio in a separate cylinder in real time [23], application of probabilistic cause-effect diagnostics [24], etc.

Some designs of engine test benches allow for specific studies, such as the aging processes of motor oil [25] and the effectiveness of additives in it [26], prediction of fuel efficiency indicators of RICE taking into account the consumption of motor oil for waste [27], aerodynamic indicators duringRICE testing [28], operating characteristics of solid-state catalytic converters [29], electrochemical sensors based on YSZ for RICE and engine bench [30].

There are studies comparing the results of experimental measurements of ecological excellence of RICE using on-board measuring equipment and an engine test bench [31], development of 1D Urea-SCR systems [32], ecological indicators of RICE of motor vehicles [33].

2 Analysis of the criterial mathematical apparatus

The value of the K_{fe} criterion for the i-th steady regime of exploitation of the DRICE with the value of the weighting factor *WF* is determined by formula (2.1) [1–3], and the place in it of the mass hourly emissions of motor fuel vapors caused by the phenomena of LBR and SBR is proposed in this work to be determined by formula (2.2).

$$\begin{aligned} K_{fe} &= \eta_e \cdot (1-\beta) = \\ &= \frac{3600}{H_u \cdot g_e} \cdot \left(1 - \frac{Z_e(P_f)}{Z_f(P_f) + Z_e(P_f)}\right) = \\ &= \frac{3600 \cdot N_e(M_{кр}, n_{кв})}{H_u \cdot G_{fuel}} \times \\ &\times \frac{1}{1 + \sigma \cdot f \cdot \sum_{m=1}^{h} (A_k \cdot G_k) / G_{fuel}}, \text{‰}, \end{aligned} \quad (2.1)$$

$$\begin{aligned} \sum_{m=1}^{h} (A_k \cdot G_k) &= A(PM) \cdot G(PM) + \\ &+ A(NO_x) \cdot G(NO_x) + \\ &+ A(C_n H_m) \cdot G(C_n H_m) + \\ &+ A(CO) \cdot G(CO) + A(RB) \cdot G(RB) \end{aligned}, \text{ kg/h}, \quad (2.2)$$

where the index *i* denote the values for a separate representative regime of operation of the RICE on landfill in the model of its exploitation; H_u = 42.7 MJ/kg [2] – lower heat of combustion of motor fuel; N_e – effective power of the diesel engine, kW; G_{fuel} – mass hourly fuel consumption, kg/h; G_k – mass hourly emission of the *k*-th pollutant in the EG flow, kg/h; A_k – dimensionless indicator of the relative aggressiveness of the *k*-th pollutant in the EG flow (A_{NOx} = 41.1; A_{PM} = 200; A_{CnHm} = 3.16; A_{CO} = 1.0 [2]); h = 4 [2] – total number of pollutants in the TG flow; σ – dimensionless indicator of relative pollution safety in different territories (for automobile diesel σ = 1.0, for tractor σ = 0.25 [2]); f – dimensionless coefficient that takes into account the nature of dispersion of EG in atmospheric air (when operating diesel engines of various designations on the territory of Ukraine f = 1.0 [2]); δ = P_f – dimensional indicator that converts the point estimate into a cost estimate, $/kg; *WF* – relative share of diesel engine operation on the *i*-th polygon of exploatation model (weight factor); η_e – effective efficiency of diesel engine; β – coefficient of relative operational environmental monetary costs; Z_e and Z_f – monetary

costs for compensation of environmental damage and fuel, \$/(kW·h); g_e – specific effective mass hourly fuel consumption of the internal combustion engine, kg/(kW·h); M_T and n_{cs} – torque and crankshaft speed of the RICE, N·m and min^{-1}; P_f = 2.482 \$/kg – price per unit weight of motor fuel (at P_f = 57.0 UAH/l and exchange rate 42.0 UAH/\$); U_e – cost of compensation of environmental damage, \$/kg; g_{pr} – specific induced mass emission of pollutants in the EG flow, kg/(kW·h).

3 Development of the method for determining thermal energy emissions and considering that factor in the complex criteria-based assessment of ES level

The method proposed in the student competitive scientific paper for calculating the values of the complex fuel-ecological criterion, taking into account thermal energy emissions into the environment, consists in the fact that the formula (2.2), which is a component of the formula (2.1), the component $A_Q \cdot G_{fuel}$ has been introduced (see formula (3.1)), which is the product of the dimensionless ponderability coefficient of thermal energy emission A_Q as ES factor – qualitative indicator of such pollution, and quantitative indicator of pollution – mass hourly emission of thermal energy G_Q, which is determined by the value of the mass hourly consumption of motor fuel DRICE G_{fuel}, since the combustion of motor fuel is both a direct and indirect cause of the release of thermal energy during the operation of this type of heat engine.

$$\sum_{m=1}^{h}\left(A_k \cdot G_k\right) = A(PM)\cdot G(PM) + A(NO_x)\cdot G(NO_x) + A(C_nH_m)\cdot G(C_nH_m) + A(CO)\cdot G(CO) + A_Q \cdot G_Q \text{, kg/h.} \quad (3.1)$$

The value of the dimensionless ponderability coefficient of thermal energy emission A_Q as ES factor is proposed to define as part of the indicator of the importance of motor fuel consumption DRICE as ES factor A_{fuel}, the definition and meaning of which are given in the work [3], that is, by the formula (3.2).

$$A_Q = A_{fuel} \cdot k_E = A_{fuel} \cdot E_{RICE} / E_W, \quad (3.2)$$

where A_{fuel} = 38.4 is ponderability coefficient of the fuel component of the complex fuel-ecological criterion K_{fe}; k_E is energy coefficient; E_{RICE} – total amount of energy produced by DRICE, in the world energy balance, MJ; E_W – the total amount of energy produced by anthropogenic PP, in the world energy balance, MJ.

It is a well-known fact that in the early 2000s, approximately 80 % of the energy produced by all renewable energy sources in the world was generated by RICE [1], and today, given the higher level of use of alternative energy, caused by its rapid development, this share can be estimated at 75 % [2]. Therefore, in this study, the value of the energy coefficient was used k_E = 0.75. Then the value of the dimensionless ponderability coefficient A_Q is 28.8.

Structure of ponderability of criterion K_{fe} components taking into account thermal pollution of the environment, taking into account the ponderability of motor fuel consumption and excluding the figure shown in Fig. 3.1.

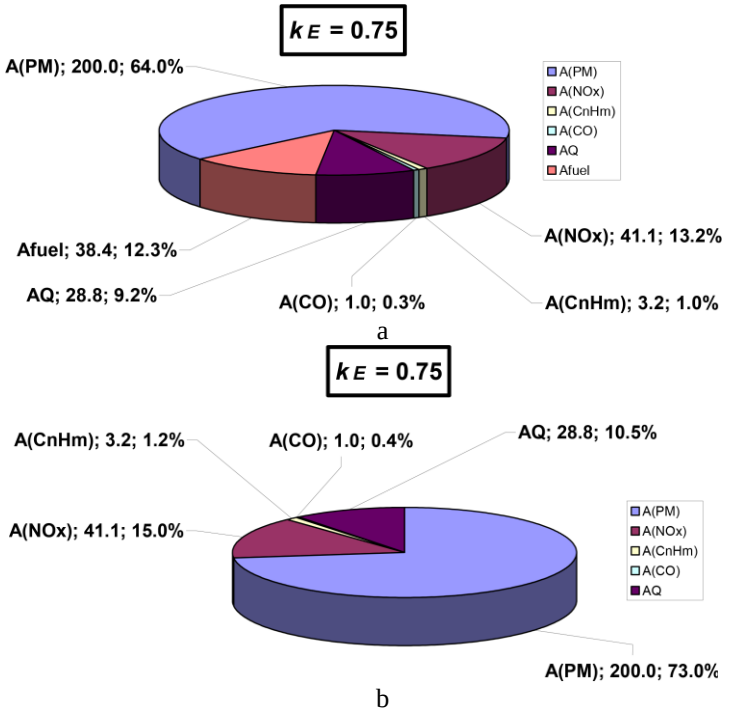

Figure 3.1 – Structure of ponderability of criterion K_{fe} components taking into account thermal pollution of the environment, taking into account the ponderability of motor fuel consumption (a) and without taking it into account (b)

Value of mass hourly emission of thermal energy by DRICE G_Q in the proposed method, it is correlated with the value of the mass hourly consumption of motor fuel as an indicator of thermal pollution of the environment by the formula (3.3).

$$G_Q = G_{fuel} \cdot (1 - \eta_e), \text{ kg/h}, \qquad (3.3)$$

where G_{fuel} – hourly fuel consumption RICE, kg/h; η_e – DRICE effective efficiency coefficient.

Distribution of values of a quantity G_Q in the field of operating regimes of a autotractor diesel engine 2Ch10,5/12 at k_E = 0.75 illustrated in Fig. 3.2, and according to the regimes of the standardized steady test cycle ESC – in Fig. 3.3.

Thus, in this section of the student competitive scientific work, a method has been developed for calculating the values of the complex fuel-ecological criterion of Prof. Parsadanov taking into account the emission of thermal energy into the environment, as well as a method for determining the values of such an emission and its importance as a ES factor. Distributions of the values of the emission of thermal energy as a field of operating regimes of a autotractor diesel engine 2Ch10,5/12 have been obtained, as well as according to the ESC standardized steady test cycle regimes.

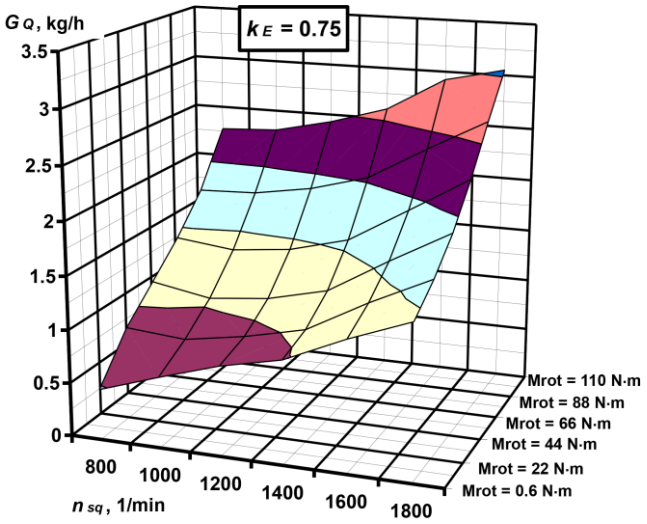

Figure 3.2 – Distribution of values of a quantity G_Q in the field of operating regimes of the autotractor diesel engine 2Ch10,5/12 at k_E = 0.75

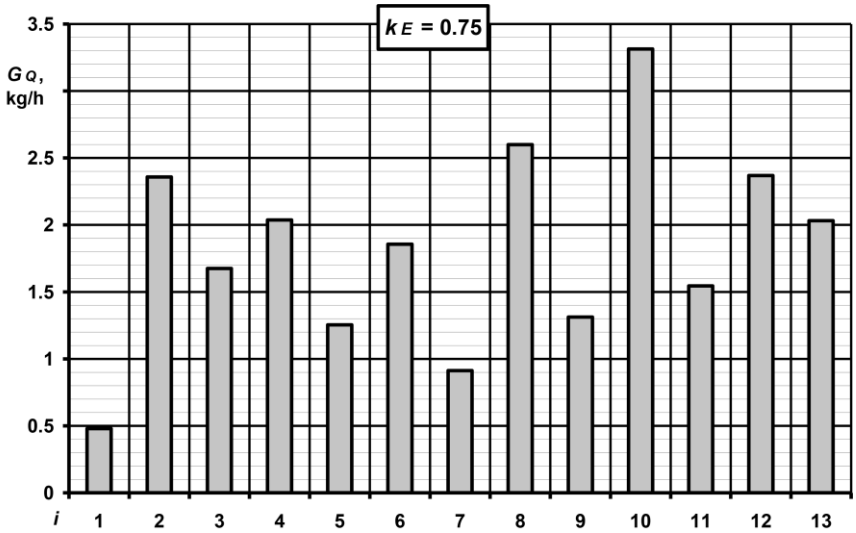

Figure 3.3 – Distribution of values of a quantity G_Q in the ESC standardized steady test cycle regimes for autotractor diesel 2Ch10,5/12 at k_E = 0.75

4 Results of criteria-based evaluation taking into account heat emissions and their analysis

4.1 Calculation study options

The study will consider the following variants: Variant A – «Reference» – without taking into account the emission of thermal energy. Variant B – «Pessimistic» – taking into account that all the energy from exothermic redox reactions, i.e. combustion of motor fuel in DRICE, will ultimately be converted into heat and given to the environment, and the share of RICE in the structure of the world balance of mechanical and electrical energy production will reach 100 %, i.e. k_E = 1.0. Variant C – «Current» is the same as Variant B, but with a current meaning k_E = 0.75.

4.2 Results of the calculation study

Fig. 4.1 and 4.2 show the distribution of the values of the criterion K_{fe} and effect δK_{fe} according to ESC test cycle regimes for autotractor diesel engines 2Ch10,5/12 for all studied variants for taking into account thermal energy emissions. Fig. 4.3 shows such data for average operational values of the criterion K_{fe} and effect δK_{fe} for all studied variants, taking into account thermal energy emissions. Fig. 4.4 illustrates graphs of the dependence of the average operational values of the criterion K_{fe} and values δK_{fe} for autotractor diesel engine 2Ch10,5/12 from the value of the energy coefficient k_E, which are described by the least squares method with polynomials of the second degree by the formulas (4.1)–(4.2).

$$K_{fe} = 1{,}931 \cdot 10^2 \cdot k_E^4 - 5{,}168 \cdot 10^2 \cdot k_E^3 + 5{,}143 \cdot 10^2 \cdot k_E^2 - 2{,}433 \cdot 10^2 \cdot k_E + 6{,}250 \cdot 10; \quad R^2 = 1{,}0 \text{ , ‰}, \tag{4.1}$$

$$\delta K_{fe} = 3{,}051 \cdot 10^2 \cdot k_E^4 - 8{,}203 \cdot 10^2 \cdot k_E^3 + 8{,}201 \cdot 10^2 \cdot k_E^2 - 3{,}893 \cdot 10^2 \cdot k_E + 3{,}015 \cdot 10^{-10}; \quad R^2 = 1{,}0 \text{ , \%}. \tag{4.2}$$

Thus, in this chapter of the student's competitive scientific work, the calculated assessment of the values of the complex fuel-ecological criterion has been carried out, taking into account thermal energy emissions into the environment during the exploitation of a PP with DRICE.

It has been established that the individual regime value of the motor fuel consumption as an equivalent of thermal energy emission into the environment during the exploitation of PP with DRICE is observed at the nominal power regime and is 3.3 kg/h, and the minimum is at minimum idle regime and is 0.5 kg/h.

It was also found that the average operational values of the criterion K_{fe} according to the ESC cycle for diesel engine 2Ch10,5/12 taking into account the emission of thermal energy into the environment during the exploitation of the PP with DRICE for the current version of the calculation study is 12.5 %, i.e. the effect of taking into account such a ES factor δK_{fe} is 80 %. For the pessimistic version of the calculation study, this effect is –89 %.

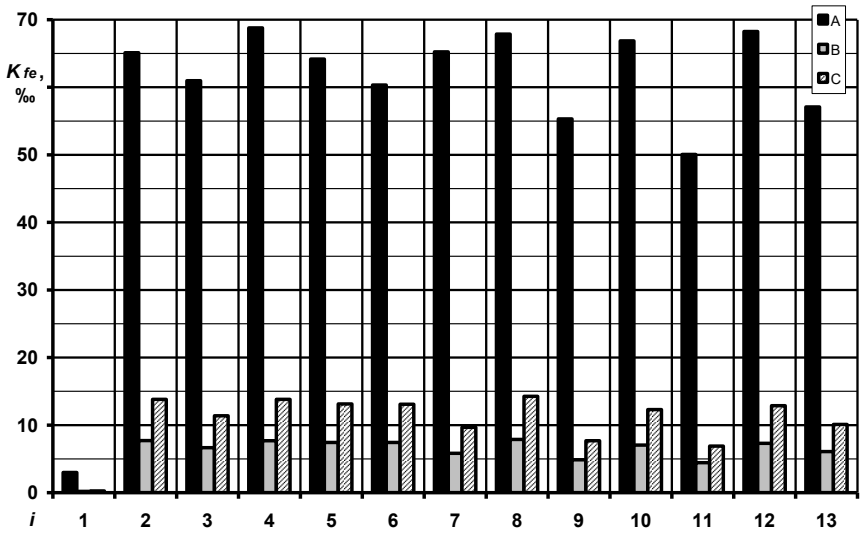

Figure 4.1 – Distribution of the criterion K_{fe} values according to ESC test cycle regimes for autotractor diesel engine 2Ch10,5/12 for all studied variants for taking into account thermal energy emissions

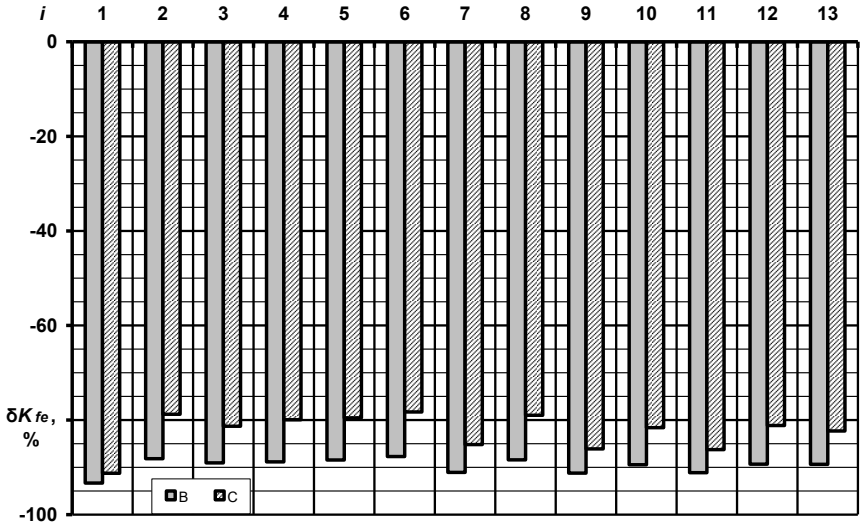

Figure 4.2 – Distribution of effect values δK_{fe} according to ESC test cycle regimes for autotractor diesel engine 2Ch10,5/12 for all studied variants for taking into account thermal energy emissions

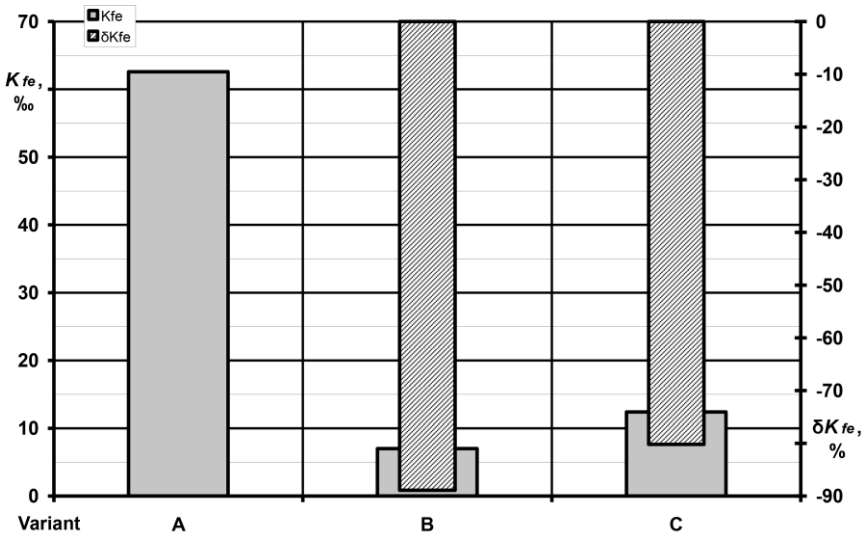

Figure 4.3 – Distribution of average operational values of the criterion K_{fe} and value δK_{fe} for autotractor diesel engine 2Ch10,5/12 and all studied variants for accounting for thermal energy emissions

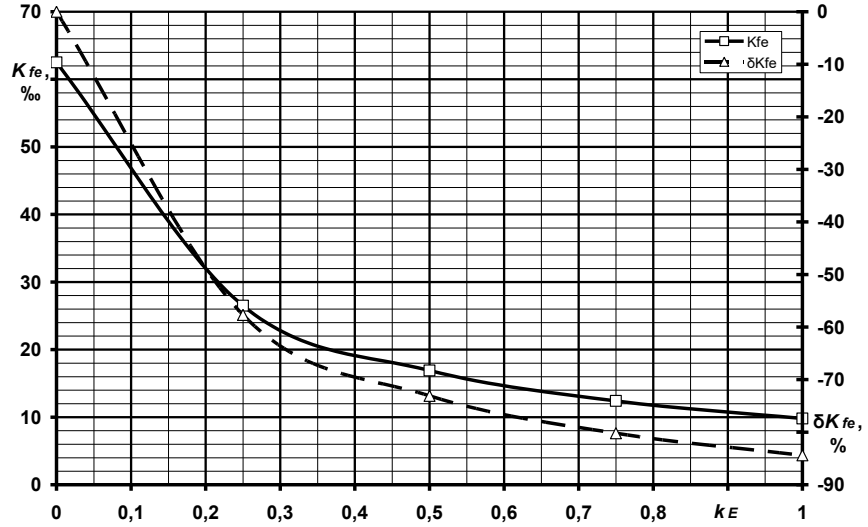

Figure 4.4 – Graphs of the dependence of the average operational values of the criterion K_{fe} and value δK_{fe} for autotractor diesel engine 2Ch10,5/12 on the value of the energy coefficient k_E

Acknowledgement

This study was carried out as part of the scientific and research work of the Department of Applied Mechanics and Environmental Protection Technologies (now – Environmental Protection Technologies) of the Faculty (now – Educational and Scientific Institute) of Technogenic and Ecological Safety (now – Management and Population Protection) of the National University of Civil Protection of Ukraine of State Emergency Service of Ukraine «Development of a methodology for complex assessment of the impact of exploitation and application of special equipment on the environment in conditions of military aggression» (State Registration № 0124U000374, 01.2024–12.2026).

At the same time, materials from the VCU library system were used, including electronic versions of journals and other materials, databases, interlibrary subscription as part of participation in Non-Resident Academic Associates program co-sponsored by the College of Humanities and Sciences at Virginia Commonwealth University (VCU) and the Davis Center for Eurasian Studies at Harvard University in 202–2025 academic year.

This study was carried out within the framework of the implementation of the educational component of the mastery of the educational and scientific program of higher education «Technogenic and ecological safety» for applicants for higher education of the third (educational and scientific) level in the specialty 183 «Environmental protection technologies» (corresponds to the Detailed branch according to the code of the International Standard Classification of Education ISCED-F 2013 0712 «Environmental Protection Technologies» in accordance with the Resolution of the Cabinet of Ministers of Ukraine dated July 7, 2021 № 762 «On Amendments to the List of Fields of Knowledge and Specialties in Which Applicants for Higher Education Study», as well as the specialty G2 «Environmental Protection Technologies» in accordance with the Resolution of the Cabinet of

Ministers of Ukraine № 1021 dated August 30, 2024 «On Amendments to the List of Fields of Knowledge and Specialties in Which Applicants for Higher and Professional Pre-Higher Education are Trained education») in the field of knowledge 18 «Production and Technology» (G Engineering, Production and Construction), in accordance with the Higher Education Standard, approved and put into effect by Order of the Ministry of Education and Science of Ukraine № 1427 dated 12/23/2021, as well as the Professional Standard for the group of professions «Teachers of Higher Education Institutions», approved by Order of the Ministry of Economic Development, Trade and Agriculture № 610 dated March 23, 2021, namely as the part of the lecture course «Environmental monitoring methods» (3 ECTS credits).

Conclusion

Thus, based on the results of the research, reflected in the sections of this work, the following general conclusions can be drawn.

The method has been improved for the computational assessment of the values of the complex fuel-ecological criterion taking into account the emission of thermal energy in the environment, as well as a method for determining the values of such an emission itself and its weight as the ES factor. Distributions of the values of the emission of thermal energy have been obtained both in the field of operating regimes of the 2Ch10.5/12 autotractor diesel engine and in the regimes of the ESC test cycle.

The calculation evaluation of the values of the complex fuel-ecological criterion was carried out taking into account thermal energy emissions in the environment during the exploitation of the PP with the DRICE. It was established that the individual regime value of the motor fuel consumption as an equivalent of thermal energy emissions in the environment during the exploitation of the PP with the DRICE is observed at the nominal power regime and is 3.3 kg/h, and the minimum – at the minimum idle regime and is 0.5 kg/h. It was also found that for the average operational values of the K_{fe} criterion for the ESC cycle for the 2Ch10.5/12 diesel engine, taking into account thermal energy emissions in the environment during the exploitation of the PP with the DRICE for the current version of the calculation study is 12.5 ‰, i.e. the effect of taking into account such ES factor δK_{fe} is –80 %. For the pessimistic version of the calculation study, this effect is –89 %.

Analysis of the results of the performed study shows that taking into account the thermal energy emission of PP with RICE, including FERV units of divisions of SES of Ukraine and other special equipment of institutions of sector of safety and defense of Ukraine, in conditions of armed aggression is an urgent task in view of the need to ensure compliance with the requirements contained in the Order of the SES of Ukraine № 618 (on the main activity) dated 20/09/2013 «On approval of the Regulations on the organization of ecological support of the State Emergency Service of Ukraine» both during armed aggression and during the post-war reconstruction of the country's critical infrastructure and economy in the historical perspective of ensuring the goals of sustainable development, defined in the Decree of the President of Ukraine № 722/2019 dated 30/09/2019 «On the Goals of Sustainable Development of Ukraine for the period up to 2030».

REFERENCES

1. Kondratenko, O., Andronov, V., Koloskov, V., & Strokov, O. (2021). Development and Use of the Index of Particulate Matter Filter Efficiency in Environmental Protection Technology for Diesel-Generator with Consumption of Biofuels. *2021 IEEE KhPI Week on Advanced Technology*: Conference Proceedings (13–17 September 2021, NTU «KhPI», Kharkiv), 239–244. DOI: 10.1109/KhPIWeek53812.2021.9570034.
2. Parsadanov, I. V. (2003). *Pidvyshchennia yakosti i konkurentospromozhnosti dyzeliv na osnovi kompleksnoho palyvno-ekolohichnoho kryteriiu: monohrafiia* [*Improving the quality and competitiveness of diesel engines based on a complex fuel-ecological criterion: monograph*]. Kharkiv, Publ. Center of NTU «KhPI». [in Ukrainian]
3. Kondratenko, O. M. (2019). *Metrolohichni aspekty kompleksnoho kryterialnoho otsiniuvannia rivnia ekolohichnoi bezpeky ekspluatatsii porshnevykh dvyhuniv enerhetychnykh ustanovok : monohrafiia* [*Metrological aspects of a complex criteria-based assessment of the ecological safety level of the exploitation of reciprocating engines of power plants: monograph*]. Kharkiv, Publ. Stil-Izdat (FOP Brovin O.V.). [in Ukrainian]
4. *Pro Cili stalogo rozvy`tku Ukrayiny` na period do 2030 roku* [*On the Sustainable Development Goals of Ukraine for the period up to 2030*]. 722/2019 Decree of the President of Ukraine. (2019). URL: https://zakon.rada.gov.ua/laws/show/2697-19. [in Ukrainian]
5. *Pro zatverdzhennya Polozhennya pro organizaciyu ekologichnogo zabezpechennya DSNS Ukrayiny* [*On approval of the Regulations on the organization of environmental support of the State Emergency Service of Ukraine*]. 618 Order of the State Emergency Service of Ukraine. (2013). URL: https://zakon.rada.gov.ua/rada/show/v0618388-13#Text.
6. Kondratenko, O. M. (2021). *Naukovo-metodolohichni osnovy zakhystu atmosfernoho povitria vid tekhnohennoho vplyvu enerhoustanovok z porshnevymy dvyhunamy vnutrishnoho zghoriannia* [*Scientific and methodological foundations of protecting atmospheric air from the technogenic impact of power plants with internal combustion piston engines*]. Kharkiv, NUCP of Ukraine.
7. United Nations Economic and Social Council Economics Commission for Europe Inland Transport Committee Working Party on the Construction of Vehicles. (2013). *Uniform provision concerning the approval of compression ignition (C.I.) and natural gas (NG) engines as well as positive-ignition (P.I.) engines fueled with liquefied petroleum gas (LPG) and vehicles equipped with C.I. and NG engines and P.I. engines fueled with LPG, with regard to the emissions of pollutants by the engine*. Regulation 49.
8. ISO. (2002). ISO 3046-1:2002. *Reciprocating internal combustion engines – Performance*.
9. Marchenko, A. P., Parsadanov, I. V., Tovazhnyansky, L. L., & Shekhovtsov, A. F. (2004). *Dvyhuny vnutrishnoho zghoriannia: seriia pidruchnykiv u 6 tomakh. T.5. Ekolohizatsiia DVZ* [*Internal combustion engines: a series of textbooks in 6 volumes. Vol.5. Environmentalization of internal combustion engines*]. Kharkiv, Publ. Prapor.
10. Kondratenko, O. M., Andronov, V. A., Strokov, O. P., Babakin, V. M., & Krasnov, V. A. (2022). Instrumentalna pokhybka vidomykh formul pererakhunku pokaznykiv dymnosti u pokaznyky toksychnosti vidpratsovanykh haziv porshnevykh DVZ [Instrumental error of known formulas for converting opacity indicators into toxicity indicators of exhaust gases of reciprocating ICE]. *Technogenic and ecological safety*, 12(2/2022), 3–18. DOI: 10.52363/2522-1892.2022.2.1. [in Ukrainian]

11. Kondratenko, O. M., Krasnov, V. A., & Semykin, V. M. (2023). The place of DPF with a liquid working body in the classification of atmospheric air protection technologies from the complex negative influence of power plants with reciprocation ICE. *Technogenic and ecological safety*, 14(2/2023), 67–91. DOI: 10.52363/2522-1892.2023.2.8.

12. Kondratenko, O., Koloskov, V., Kovalenko, S., Derkach, Y., & Strokov, O. (2020). Criteria based assessment of efficiency of conversion of reciprocating ICE of hybrid vehicle on consumption of biofuels. *2020 IEEE KhPI Week on Advanced Technology, KhPI Week 2020, 05–10 October 2020*, Conference Proceedings. Kharkiv, 177–182. DOI: 10.1109/KhPIWeek 51551.2020.9250118.

13. Kondratenko, O., Mishchenko, I., Chernobay, G., Derkach, Yu., & Suchikova, Ya. (2018). Criteria based assessment of the level of ecological safety of exploitation of electric generating power plant that consumes biofuels. *2018 IEEE 3rd International Conference on Intelligent Energy and Power Systems (IEPS–2018)*: Book of Papers, 10–14 September, 2018. Kharkiv, 57-1–57-6. DOI: 10.1109/IEPS.2018.8559570.

14. Kondratenko, O., & Lytvynenko, O. (2024). *Exploring the digital landscape: interdisciplinary perspectives. Monograph. Chapter 5 «Artificial intelligence and innovative educational approaches in digital society». Subsection 5.6. Ecological safety of transport as a component of national security of Ukraine during armed aggression and as a prerequisite for a «green» transition during post-war reconstruction*. Katowice, The University of Technology in Katowice Press, 853–869. URL: http://www.wydawnictwo.wst.pl/uploads/files/f22f3113112eb3a985d36ee5fcdb6747.pdf. DOI: 10.54264/M036.

15. Kondratenko, O. M., Koloskov, V. Yu., Derkach, Y. F., & Kovalenko, S. A. (2020). *Fizy`chne i matematy`chne modelyuvannya procesiv u fil`trax tverdy`x chasty`nok u prakty`ci kry`terial`nogo ocinyuvannya rivnya ekologichnoyi bezpeky` : monografiya* [*Physical and mathematical modeling of processes in particulate filters in the practice of criteria-based assessment of the level of environmental safety: monograph*]. Kharkiv, Publ. Stil-Izdat (FOP Brovin O.V.), 522 p. [in Ukrainian]

16. Marchenko, A. P., & Parsadanov, I. V. (2024). Criteria for assessing the effectiveness of transport power plants decarbonisation in accordance with implementation of the sustainable development concept. *Internal Combustion Engines*, 1, 3–11. DOI: 10.20998/0419-8719.2024.1.01.

17. *Pro zatverdzhennya pereliku priory`tetny`x tematy`chny`x napryamiv naukovy`x doslidzhen` i naukovo-texnichny`x rozrobok na period do 31 grudnya roku, shho nastaye pislya pry`py`nennya abo skasuvannya voyennogo stanu v Ukrayini* [*On approval of the list of priority thematic areas of scientific research and scientific and technical developments for the period until December 31 of the year following the termination or abolition of martial law in Ukraine*]. 476 Decree of the Cabinet of Ministers of Ukraine. (2024). URL: https://zakon.rada.gov.ua/laws/show/476-2024-%D0%BF#Text. [in Ukrainian]

18. Specialty passport 21.06.01 «Ecological Safety», approved by the Decree of the Presidium of the Higher Attestation Commission of Ukraine 33-07/7. (2001). URL: https://zakon.rada.gov.ua/rada/show/va7_7330-01#Text.

19. 3D Geometry modelling online free system FreeCAD: official web-site. URL: https://www.freecad.org.

20. Online free system for modeling the working processes of reciprocating internal combustion engines using digital twins Blitz-PRO: official web-site. URL: http://blitzpro.zeddmalam.com/application/index/signin.

21. Kapustenko, P., Ocłoń, P., Picón-Núñez, M., Wang, B., & Varbanov, P. S. (2023). Integration and intensification of thermal processes to increase energy efficiency and mitigate environmental pollution for sustainable development of industry – PRES'22. *Thermal Science and Engineering Progress*, 45, 102148. DOI: 10.1016/j.tsep.2023.102148.

22. Huang, X., & Li, W. (2025) Landscape renewal design of industrial sites based on environmental thermal sensing and stereoscopic vision: Space thermal energy utilization. *Thermal Science and Engineering Progress*, 60, 103437. DOI: 10.1016/j.tsep.2025.103437.

23. Shan, M., Zhang, H., Wang, Y., Qiao, Z., Zuo, J., & Xu, Y. (2025). Estimating environmental impact of rooftop photovoltaic from the perspective of thermal power transmission, Environmental Impact Assessment Review, Vol. 112, 107848. DOI: 10.1016/j.eiar.2025.107848.

24. Ghasempour, R., Salehi, M., & Fakouriyan, S. (2024). Comprehensive energy, exergy, and environmental evaluation of integrated heat pipe photovoltaic/thermal systems using multi-objective optimization. *Applied Thermal Engineering*, 257(C), 124402. DOI: 10.1016/j.applthermaleng.2024.124402.

25. Kim, J., Lee, G., Park, S., & Kang, J. (2025). Mitigating urban heat island effects through leadership in energy and environmental design evaluation and blue-green infrastructure: Applying the hazard capacity factor design model for urban thermal resilience. *Sustainable Cities and Society*, 124, 106306. DOI: 10.1016/j.scs.2025.106306.

26. Liu, Y., & Wen, Z. (2024). Green manufacturing process supply chain management based on thermal efficiency improvement and environmental impact assessment technology. *Thermal Science and Engineering Progress*, 54, 102847. DOI: 10.1016/j.tsep.2024.102847.

27. Zhu, Y., Yao, Sh., Zhang, Y., & Cao, M. (2024). Environmental and economic scheduling for wind-pumped storage-thermal integrated energy system based on priority ranking. *Electric Power Systems Research*, 231, 110353. DOI: 10.1016/j.epsr.2024.110353.

28. Khatib, A., Al-Araj, B., & Salhab, Z. (2024). Long-term monitoring of thermal pollution from Baniyas power plant in the Syrian coastal water using Landsat data. *Remote Sensing Applications: Society and Environment*, 36, 101287. DOI: 10.1016/j.rsase.2024.101287.

29. Zhou, Y., Gao, W., Zhang, Y., Tian, Z., Wang, F., & Gao, R. (2024). Experimental investigation on thermodynamic and environmental performance of a novel ocean thermal energy conversion (OTEC)-Air conditioning (AC) system. *Energy*, 313, 133760. DOI: 10.1016/j.energy.2024.133760.

30. Sharshir, S. W., Sharaby, M. R., El-Naggar, A. A., Ismail, M., Abd EL-Gawaad, N. S., Al-Dossari, M., El-Samadony M. O. A., & Yuan, Zh. (2025). Augmentation of thermo-environmental performance of hemispherical distiller utilizing low-cost thermal energy storage materials: A comparative study. *Journal of Energy Storage*, 113, 115619. DOI: 10.1016/j.est.2025.115619.

31. Luo, J., Xin, Sh., Huang, Y., Hu, Q., Wang, J., & Zhang, Ch. (2025). Quantitative Evaluation of Environmental Influence of Heat Emission from Lake Water Heat Pump. *International Journal of Refrigeration*, 175, 288–298. DOI: 10.1016/j.ijrefrig.2025.03.027.

32. Castelluccio, S., Orlandella, I., Fiore, S., & Comoglio, C. (2025). Evaluating the environmental performances of thermal power plants: A study on EMAS registered Italian sites. *Journal of Cleaner Production*, 490, 144677. DOI: 10.1016/j.jclepro.2025.144677.

33. Qiu, Y., Ahmad, S. F., & Song, R. (2025). Multi-facet investigation of integrating a multigeneration system and landfill gas-based combustion process using an environmentally friendly thermal design arrangement. *Journal of Environmental Chemical Engineering*, 13(1), 115241. DOI: 10.1016/j.jece.2024.115241.

34. Zhu, Z., Xu, Zh., Zhang, B., & Li, X. (2025). Shifting gears in thermal power: Displacement efficiency and environmental impact of wind and solar generation in China. *Resources, Conservation and Recycling*, 212, 107916. DOI: 10.1016/j.resconrec.2024.107916.

35. Zhang, S., Zhao, G., Li, Zh., Hu, J., Zhao, Zh., Yao, J., Cheng, N., & Zhang, Zh. (2025). Flexible biomass-based phase change materials: L-N-Ti for environmentally friendly thermal management. *Solar Energy Materials and Solar Cells*, 285, 113552. DOI: 10.1016/j.solmat.2025.113552.

36. Rao, F., Xiao, P., Zhang, Y., & Lai, D. (2024). Unravelling key environmental factors influencing urban park visits: Thermal comfort and air quality. *Urban Climate*, 57, 102096. DOI: 10.1016/j.uclim.2024.102096.

37. Castelluccio, S., Fiore, S., & Comoglio, C. (2024). Environmental reporting in Italian thermal power plants: insights from a comprehensive analysis of EMAS environmental statements. *Journal of Environmental Management*, 359, 121035. DOI: 10.1016/j.jenvman.2024.121035.

38. Zihao, M., Farouk, N., Singh, P. K., Abed, A. M., Samad, S., Babiker, S. G., Shernazarov, I., Hendy, A., Almadhor, A., Bouallegue, B., & Afzal, A. R. (2025). Multi-thermal recovery layout for a sustainable power and cooling production by biomass-based multi-generation system: Techno-economic-environmental analysis and ANN-GA optimization. *Case Studies in Thermal Engineering*, 65, 105589. DOI: 10.1016/j.csite.2024.105589.

39. Liu, L., Liu, W., Yao, J., Jia, T., Zhao, Y., & Dai, Y. (2024). Life cycle energy, economic, and environmental analysis for the direct-expansion photovoltaic-thermal heat pump system in China. *Journal of Cleaner Production*, 434, 139730. DOI: 10.1016/j.jclepro.2023.139730.

40. Ran, P., Ou, Y. F., Zhang, Ch. Y., & Chen, Y. T. (2024). Energy, exergy, economic, and life cycle environmental analysis of a novel biogas-fueled solid oxide fuel cell hybrid power generation system assisted with solar thermal energy storage unit. *Applied Energy*, 358, 122618. DOI: 10.1016/j.apenergy.2024.122618.

41. Alomar, O. R., Ali, B. M., Ali, O. M., & Mustafa, A. N. (2024). Impacts of environmental conditions on thermal, emissions and economic performance of gas turbine using different types of fuels: An experimental investigation. *Results in Engineering*, 24, 103402. DOI: 10.1016/j.rineng.2024.103402.

42. Zhao, Ch., Zhao, Y., Lin, K., Wang, Zh., & Zhou, T. (2023). Comprehensive assessment of thermal characteristics, kinetics and environmental impacts of municipal solid waste incineration fly ash during thermal treatment. *Process Safety and Environmental Protection*, 175, 619–631. DOI: 10.1016/j.psep.2023.05.074.

43. Wang, Sh., Cheng, M., Xie, M., Yang, Y., Liu, T., Zhou, T., Cen, Q., Liu, Z., & Li, B. (2025). From waste to energy: Comprehensive understanding of the thermal-chemical utilization techniques for waste tire recycling. *Renewable and Sustainable Energy Reviews*, 211, 115354. DOI: 10.1016/j.rser.2025.115354.

44. Zhang, Y., Chen, Y., Qiu, X. Ch., Tian, Zh., Peng, H., & Gao, W. (2024). Experimental study and performance comparison of a 1 kW-class solar-ocean thermal energy conversion system integrated air conditioning: Energy, exergy, economic, and environmental (4E) analysis. *Journal of Cleaner Production*, 451, 142033. DOI: 10.1016/j.jclepro.2024.142033.

45. Vig, N., Ravindra, Kh., & Mor, S. (2023). Environmental impacts of Indian coal thermal power plants and associated human health risk to the nearby residential communities: A potential review. *Chemosphere*, 341, 140103. DOI: 10.1016/j.chemosphere.2023.140103.

46. Shahid, M. I., Farhan, M., Rao, A., Salam, H. A., Chen, T., Xiao, Q., Li, X., & Ma, F. (2025). Optimization of hydrogen production and system efficiency enhancement through exhaust heat utilization in hydrogen-enriched internal combustion engine. *Energy*, 319, 135051. DOI: 10.1016/j.energy.2025.135051.

47. Zoghi, M., Hosseinzadeh, N., Gharaie, S., & Zare, A. (2025). Waste heat recovery of a combined internal combustion engine and inverse brayton cycle for hydrogen and freshwater outputs: 4E optimization and comparison. *Energy Nexus*, 17, 100356. DOI: 10.1016/j.nexus.2024.100356.

48. Shahid, M. I., Rao, A., Farhan, M., Liu, Y., & Ma, F. (2024). Comparative analysis of different heat transfer models, energy and exergy analysis for hydrogen-enriched internal combustion engine under different operation conditions. *Applied Thermal Engineering*, 247, 123004. DOI: 10.1016/j.applthermaleng.2024.123004.

49. Leng, Sh., Xu, Sh., Li, Ch., Ha, Ch., Liu, Z., Qin, J., Wang, Z., Wang, J., Chen, Zh., & Liao, M. (2025). Performance analysis of an internal combustion engine with thermochemical recovery and high temperature proton exchange membrane fuel cell combined power generation system. *Fuel*, 384, 133913. DOI: 10.1016/j.fuel.2024.133913.

50. Kornienko, V., Radchenko, M., Radchenko, R., Pavlenko, A., & Radchenko, A. (2025). A new trend in combustion engine's deep waste heat recovery by application of condensing economizers in exhaust boilers. *Applied Thermal Engineering*, 261, 125150. DOI: 10.1016/j.applthermaleng.2024.125150.

51. de Araújo, L. R., Morawski, A. P., Barone, M. A., Rocha, H. R. O., Donatelli, J. L. M., & Santos, J. J. C. S. (2022). Response surface methods based in artificial intelligence for superstructure thermoeconomic optimization of waste heat recovery systems in a large internal combustion engine. *Energy Conversion and Management*, 271, 116275. DOI: 10.1016/j.enconman.2022.116275.

52. Dadpour, D., Deymi-Dashtebayaz, M., Hoseini-Modaghegh, A., Abbaszadeh-Bajgiran, M., Soltaniyan, S., & Tayyeban, E. (2022). Proposing a new method for waste heat recovery from the internal combustion engine for the double-effect direct-fired absorption chiller. *Applied Thermal Engineering*, 216, 119114. DOI: 10.1016/j.applthermaleng.2022.119114.

53. Omara, A. A. M. (2021). Phase change materials for waste heat recovery in internal combustion engines: A review. *Journal of Energy Storage*, 44(B), 103421. DOI: 10.1016/j.est.2021.103421.

54. Asadi, M., Deymi-Dashtebayaz, M., & Rad, E. A. (2022). Comparing the profitability of waste heat electricity generation of internal combustion engines: An exergoeconomic analysis through optimization of two different organic Rankine cycle scenarios. *Applied Thermal Engineering*, 211, 118443. DOI: 10.1016/j.applthermaleng.2022.118443.

55. Fini, A. T., Hashemi, S. A., & Fattahi, A. (2022). On the efficient topology of the exhaust heat exchangers equipped with thermoelectric generators for an internal combustion engine. *Energy Conversion and Management*, 268, 115966. DOI: 10.1016/j.enconman.2022.115966.

56. Alklaibi, A. M., & Lior, N. (2021). Waste heat utilization from internal combustion engines for power augmentation and refrigeration. *Renewable and Sustainable Energy Reviews*, 152, 111629. DOI: 10.1016/j.rser.2021.111629.

57. Vančura, J., Kroulíková, T., Bartuli, E., Kůdelová, T., & Vondruš, J. (2025). Polymeric hollow fibre heat exchanger for reducing vehicle CO_2 pollution. *Applied Thermal Engineering*, 270, 126180. DOI: 10.1016/j.applthermaleng.2025.126180.

58. Arbabi, P., Abbassi, A., Mansoori, Z., & Seyfi, M. (2017). Joint numerical-technical analysis and economical evaluation of applying small internal combustion engines in combined heat and power (CHP). *Applied Thermal Engineering*, 113, 694–704. DOI: 10.1016/j.applthermaleng.2016.11.064.

59. Shu, G., Wang, X., & Tia, H. (2016). Theoretical analysis and comparison of rankine cycle and different organic rankine cycles as waste heat recovery system for a large gaseous fuel internal combustion engine. *Applied Thermal Engineering*, 108, 525–537. DOI: 10.1016/j.applthermaleng.2016.07.070.

60. Raznoshinskaia, A. V. (2015). The Research of Influence Characteristics of Heat-storage Material on Thermodynamic Process in Heat Storage, Installed in System of Waste-heat Recovery of Internal Combustion Engines. *Procedia Engineering*, 129, 140–144. DOI: 10.1016/j.proeng.2015.12.022.

61. Pandey, K. K. (2024). Study on the integration of hydrogen in a multi-cylinder low heat rejection diesel engine using a ternary blend. *Atmospheric Pollution Research*, 15(10), 102250. DOI: 10.1016/j.apr.2024.102250.

62. Pandey, K. K. (2024). Application of acetylene in multi-cylinder low heat rejection diesel engine fueled with ternary blend. *Energy*, 311, 133368. DOI: 10.1016/j.energy.2024.133368.

Кондратенко О. М., Колосков В. Ю., Колоскова Г. М., Литвиненко О. О.

ВИЗНАЧЕННЯ КІЛЬКІСНИХ І ЯКІСНИХ АСПЕКТІВ ЗАБРУДНЕННЯ ДОВКІЛЛЯ ТЕПЛОВОЮ ЕНЕРГІЄЮ ВІД ЕНЕРГОУСТАНОВОК З ПОРШНЕВИМ ДВИГУНОМ ВНУТРІШНЬОГО ЗГОРЯННЯ

У статті наведено результати власних досліджень авторів, метою яких було удосконалення методики врахування параметрів викидів теплової енергії в навколишнє середовище як полютанта при комплексному критеріальному оцінюванні рівня екологічної безпеки (ЕБ) експлуатації таких енергоустановок (ЕУ), особливо з урахуванням реалій функціонування підрозділів і органів ДСНС України та їх одиниць пожежної та аварійно-рятувальних транспортних засобів (ПАРТ) в умовах збройної агресії та в перспективі післявоєнної відбудови критичної інфраструктури та економіки нашої країни. Послідовно вирішувалися наступні задачі: розробка методики розрахунку значень комплексного паливно-екологічного критерію з урахуванням викидів теплової енергії в навколишнє середовище при експлуатації ЕУ з ПДВЗ; отримання комплексу вихідних даних для проведення розрахункового дослідження для стандартизованого стаціонарного випробувального циклу ESC та автотракторного дизеля 2Ч10.5/12, розрахункова оцінка значень комплексного паливно-екологічного критерію з урахуванням викидів теплової енергії в навколишнє середовище при експлуатації ЕУ з ПДВЗ. Проблемою дослідження є недосконаліть існуючих методів критеріальної оцінки рівня ЕБ експлуатації ЕУ з ПДВЗ, особливо з огляду на реалії функціонування

установ і підрозділів ДСНС України та їх одиниць ПАРТ в умовах збройної агресії та в перспективі післявоєнної відбудови критичної інфраструктури та економіки нашої країни. Ідея дослідження полягає в удосконаленні методики визначення значень критерію K_{fe} шляхом розширення числа чинників ЕБ, що враховуються його математичним апаратом, зокрема, викидів теплової енергії в навколишнє середовище. Основним завданням дослідження є визначення кількісних та якісних аспектів ефекту врахування викидів теплової енергії в навколишнє середовище при комплексному критеріальному оцінюванні рівня ЕБ процесу експлуатації таких ЕУ, зокрема одиниць ПАРТ, з використанням стаціонарного стандартизованого випробувального циклу ESC (відповідно до Правил ЄЕК ООН № 49) на основі вдосконаленого математичного апарату комплексного паливно-екологічного критерію. Об'єктом дослідження є ЕБ процесу експлуатації ЕУ з ПДВЗ, зокрема одиниць ПАРТ, з урахуванням негативного техногенного впливу теплової енергії на компоненти навколишнього середовища. Предметом дослідження є внесок у числові значення показників об'єкта дослідження викидів теплової енергії в навколишнє середовище. Наукова новизна отриманих результатів полягає в тому, що набув подальшого розвитку метод врахування викидів теплової енергії в навколишнє середовище від ЕУ з ПДВЗ, зокрема одиниць ПАРТ, у комплексному критеріальному оцінюванні показників рівня ЕБ під час їх експлуатації. Практична цінність отриманих результатів полягає в тому, що отримані результати придатні для кількісної та якісної оцінки досліджуваних впливів і розробки на цій основі технічних рішень і організаційних заходів щодо їх зменшення або усунення шляхом розробки відповідної технології захисту навколишнього середовища з виконавчими пристроями на методологічній основі системи управління ЕБ.

Ключові слова: технології захисту навколишнього середовища, екологічна безпека, енергоустановки, пожежна та аварійно-рятувальна техніка, поршневі двигуни внутрішнього згоряння, теплове забруднення, комплексне критеріальне оцінювання, збройна агресія, повоєнна відбудова.

ЛІТЕРАТУРА

1. Development and Use of the Index of Particulate Matter Filter Efficiency in Environmental Protection Technology for Diesel-Generator with Consumption of Biofuels / O. Kondratenko, V. Andronov, V. Koloskov, O. Strokov. *2021 IEEE KhPI Week on Advanced Technology*: Conference Proceedings (13–17 September 2021, NTU «KhPI», Kharkiv). Харків: НТУ «ХПІ», 2021. С. 239–244. DOI: 10.1109/KhPIWeek53812.2021.9570034.

2. Парсаданов І. В. Підвищення якості і конкурентоспроможності дизелів на основі комплексного паливно-екологічного критерію: монографія. Харків: Центр НТУ «ХПІ», 2003. 244 с.

3. Кондратенко О. М. Метрологічні аспекти комплексного критеріального оцінювання рівня екологічної безпеки експлуатації поршневих двигунів енергетичних установок : монографія. Харків: Стиль-Издат (ФОП Бровін О.В.), 2019. 532 с.

4. Указ Президента України «Про Цілі сталого розвитку України на період до 2030 року» від 30.09.2019 р. № 722/2019. URL: https://zakon.rada.gov.ua/laws/show/722/2019#Text (дата звернення 10.03.2025).

5. Наказ Державної служби України з надзвичайних ситуацій «Про затвердження Положення про організацію екологічного забезпечення ДСНС України» від 20.09.2013 р. № 618 (за основною діяльністю). URL: https://zakon.rada.gov.ua/rada/show/v0618388-13#Text (дата звернення 10.03.2025).

6. Кондратенко О. М. Науково-методологічні основи захисту атмосферного повітря від техногенного впливу енергоустановок з поршневими двигунами внутрішнього згоряння: дис. д-ра техн. наук: спец 21.06.01 – екологічна безпека [Рукопис]. Харків: НУЦЗ України, 2021. 465 с.

7. Uniform provision concerning the approval of compression ignition (C.I.) and natural gas (NG) engines as well as positive-ignition (P.I.) engines fueled with liquefied petroleum gas (LPG) and vehicles equipped with C.I. and NG engines and P.I. engines fuelled with LPG, with regard to the emissions of pollutants by the engine: regulation United Nations Economic and Social Council Economics Commission for Europe Inland Transport Committee Working Party on the Construction of Vehicles of 26 January 2013 year Regulation No. 49, Revision 6, Geneva, UNECE, 2013.

8. ISO 3046-1:2002. Reciprocating internal combustion engines – Performance. ISO, 2022.

9. Двигуни внутрішнього згоряння: серія підручників у 6 томах. Т.5. Екологізація ДВЗ / А. П. Марченко, І. В. Парсаданов, Л. Л. Товажнянський, А. Ф. Шеховцов; за ред. А. П. Марченко та А. Ф. Шеховцова. Харків: Прапор, 2004. 360 с.

10. Інструментальна похибка відомих формул перерахунку показників димності у показники токсичності відпрацьованих газів поршневих ДВЗ / О.М. Кондратенко та ін. *Техногенно-екологічна безпека*. № 12(2/2022). С. 3–18. DOI: 10.52363/2522-1892.2022.2.1.

11. Kondratenko O. M., Krasnov V. A., Semykin V. M. The place of DPF with a liquid working body in the classification of atmospheric air protection technologies from the complex negative influence of power plants with reciprocation ICE. *Technogenic and ecological safety*. 2023. No. 14(2/2023). P. 67–91. DOI: 10.52363/2522-1892.2023.2.8.

12. Criteria based assessment of efficiency of conversion of reciprocating ICE of hybrid vehicle on consumption of biofuels / O. Kondratenko, et al. *2020 IEEE KhPI Week on Advanced Technology, KhPI Week 2020*. 05–10 October 2020. Conference Proceedings. Kharkiv, Ukraine, 2020. P. 177–182. DOI: 10.1109/KhPIWeek 51551.2020.9250118.

13. Criteria based assessment of the level of ecological safety of exploitation of electric generating power plant that consumes biofuels / O. Kondratenko et al. *2018 IEEE 3rd International International Conference on Intelligent Energy and Power Systems (IEPS–2018)*: Book of Papers. 10–14 September, 2018. Kharkiv: Ukraine, 2018. P. 57-1–57-6. DOI: 10.1109/IEPS.2018.8559570.

14. Kondratenko O., Lytvynenko O. *Exploring the digital landscape: interdisciplinary perspectives. Monograph. Chapter 5 «Artificial intelligence and innovative educational approaches in digital society». Subsection 5.6. Ecological safety of transport as a component of national security of Ukraine during armed aggression and as a prerequisite for a «green» transition during post-war reconstruction*. Katowice: The University of Technology in Katowice Press, 2024. P. 853–869. DOI: 10.54264/M036.

15. Фізичне і математичне моделювання процесів у фільтрах твердих частинок у практиці критеріального оцінювання рівня екологічної безпеки : монографія / О. М. Кондратенко, В. Ю. Колосков, Ю. Ф. Деркач, С. А. Коваленко. Харків: Стиль-Издат (ФОП Бровін О.В.), 2020. 522 с.

16. Marchenko A. P., Parsadanov I. V. Criteria for assessing the effectiveness of transport power plants decarbonisation in accordance with implementation of the sustainable development concept. *Internal Combustion Engines*. 2024. No. 1. P. 3–11. DOI: 10.20998/0419-8719.2024.1.01.

17. Постанова Кабінету Міністрів України «Про затвердження переліку пріоритетних тематичних напрямів наукових досліджень і науково-технічних розробок на період до 31 грудня року, що настає після припинення або скасування воєнного стану в Україні» від 30.04.2024 р. № 476. URL: https://zakon.rada.gov.ua/laws/show/476-2024-%D0%BF#Text (дата звернення 10.03.2025).

18. Паспорт спеціальності 21.06.01 «Екологічна безпека», затверджений постановою Президії ВАК України № 33-07/7 від 04.07.2001 р. URL: https://zakon.rada.gov.ua/rada/show/va7_7330-01#Text (дата звернення 10.03.2025).

19. 3D Geometry modelling online free system FreeCAD: official web-site. URL: https://www.freecad.org (дата звернення 10.03.2025).

20. Online free system for modeling the working processes of reciprocating internal combustion engines using digital twins Blitz-PRO: official site. URL: http://blitzpro.zeddmalam.com/application/index/signin (дата звернення 10.03.2025).

21. Integration and intensification of thermal processes to increase energy efficiency and mitigate environmental pollution for sustainable development of industry – PRES'22 / P. Kapustenko et al. *Thermal Science and Engineering Progress*. 2023. Vol. 45. Art. 102148. DOI: 10.1016/j.tsep.2023.102148.

22. Huang X., Li W. Landscape renewal design of industrial sites based on environmental thermal sensing and stereoscopic vision: Space thermal energy utilization. *Thermal Science and Engineering Progress*. 2025. Vol. 60. Art. 103437. DOI: 10.1016/j.tsep.2025.103437.

23. Estimating environmental impact of rooftop photovoltaic from the perspective of thermal power transmission / M. Shan et al. *Environmental Impact Assessment Review*. 2025. Vol. 112. Art. 107848. DOI: 10.1016/j.eiar.2025.107848.

24. Ghasempour R., Salehi M., Fakouriyan S. Comprehensive energy, exergy, and environmental evaluation of integrated heat pipe photovoltaic/thermal systems using multi-objective optimization. *Applied Thermal Engineering*. 2024. Vol. 257, Part C. Art. 124402. DOI: 10.1016/j.applthermaleng.2024.124402.

25. Mitigating urban heat island effects through leadership in energy and environmental design evaluation and blue-green infrastructure: Applying the hazard capacity factor design model for urban thermal resilience / J. Kim, G. Lee, S. Park, J. Kang. *Sustainable Cities and Society*. 2025. Vol. 124. Art. 106306. DOI: 10.1016/j.scs.2025.106306.

26. Liu Y., Wen Z. Green manufacturing process supply chain management based on thermal efficiency improvement and environmental impact assessment technology. *Thermal Science and Engineering Progress*. 2024. Vol. 54. Art. 102847. DOI: 10.1016/j.tsep.2024.102847.

27. Environmental and economic scheduling for wind-pumped storage-thermal integrated energy system based on priority ranking / Y. Zhu, Sh. Yao, Y. Zhang, M. Cao. *Electric Power Systems Research*. 2024. Vol. 231. Art. 110353. DOI: 10.1016/j.epsr.2024.110353.

28. Khatib A., Al-Araj B., Salhab Z. Long-term monitoring of thermal pollution from Baniyas power plant in the Syrian coastal water using Landsat data. *Remote Sensing Applications: Society and Environment*. 2024. Vol. 36. Art. 101287. DOI: 10.1016/j.rsase.2024.101287.

29. Experimental investigation on thermodynamic and environmental performance of a novel ocean thermal energy conversion (OTEC)-Air conditioning (AC) system / Y. Zhou et al. *Energy*. 2024. Vol. 313. Art. 133760. DOI: 10.1016/j.energy.2024.133760.

30. Augmentation of thermo-environmental performance of hemispherical distiller utilizing low-cost thermal energy storage materials: A comparative study / S. W. Sharshir et al. *Journal of Energy Storage*. 2025. Vol. 113. Art. 115619. DOI: 10.1016/j.est.2025.115619.

31. Quantitative Evaluation of Environmental Influence of Heat Emission from Lake Water Heat Pump / J. Luo et al. *International Journal of Refrigeration*. 2025. Vol. 175. P. 288–298. DOI: 10.1016/j.ijrefrig.2025.03.027.

32. Evaluating the environmental performances of thermal power plants: A study on EMAS registered Italian sites / S. Castelluccio, I. Orlandella, S. Fiore, C. Comoglio. *Journal of Cleaner Production*. 2025. Vol. 490. Art. 144677. DOI: 10.1016/j.jclepro.2025.144677.

33. Qiu Y., Ahmad S. F., Song R. Multi-facet investigation of integrating a multigeneration system and landfill gas-based combustion process using an environmentally friendly thermal design arrangement. *Journal of Environmental Chemical Engineering*. 2025. Vol. 13, Issue 1. Art. 115241. DOI: 10.1016/j.jece.2024.115241.

34. Shifting gears in thermal power: Displacement efficiency and environmental impact of wind and solar generation in China / Z. Zhu, Zh. Xu, B. Zhang, X. Li. *Resources, Conservation and Recycling*. 2025. Vol. 212. Art. 107916. DOI: 10.1016/j.resconrec.2024.107916.

35. Flexible biomass-based phase change materials: L-N-Ti for environmentally friendly thermal management / S. Zhang et al. *Solar Energy Materials and Solar Cells*. 2025. Vol. 285. Art. 113552. DOI: 10.1016/j.solmat.2025.113552.

36. Unravelling key environmental factors influencing urban park visits: Thermal comfort and air quality / F. Rao, P. Xiao, Y. Zhang, D. Lai. *Urban Climate*. 2024. Vol. 57. Art. 102096. DOI: 10.1016/j.uclim.2024.102096.

37. Castelluccio S., Fiore S., Comoglio C. Environmental reporting in Italian thermal power plants: insights from a comprehensive analysis of EMAS environmental statements. *Journal of Environmental Management*. 2024. Vol. 359. Art. 121035. DOI: 10.1016/j.jenvman.2024.121035.

38. Multi-thermal recovery layout for a sustainable power and cooling production by biomass-based multi-generation system: Techno-economic-environmental analysis and ANN-GA optimization / M. Zihao et al. *Case Studies in Thermal Engineering*. 2025. Vol. 65. Art. 105589. DOI: 10.1016/j.csite.2024.105589.

39. Life cycle energy, economic, and environmental analysis for the direct-expansion photovoltaic-thermal heat pump system in China / L. Liu et al. *Journal of Cleaner Production*. 2024. Vol. 434. Art. 139730. DOI: 10.1016/j.jclepro.2023.139730.

40. Energy, exergy, economic, and life cycle environmental analysis of a novel biogas-fueled solid oxide fuel cell hybrid power generation system assisted with solar thermal energy storage unit / P. Ran, Y. F. Ou, Ch. Y. Zhang, Y. T. Chen. *Applied Energy*. 2024. Vol. 358. Art. 122618. DOI: 10.1016/j.apenergy.2024.122618.

41. Impacts of environmental conditions on thermal, emissions and economic performance of gas turbine using different types of fuels: An experimental investigation / O. R. Alomar, B. M. Ali, O. M. Ali, A. N. Mustafa. *Results in Engineering*. 2024. Vol. 24. Art. 103402. DOI: 10.1016/j.rineng.2024.103402.

42. Comprehensive assessment of thermal characteristics, kinetics and environmental impacts of municipal solid waste incineration fly ash during thermal treatment / Ch. Zhao et al. *Process Safety and Environmental Protection*. 2023. Vol. 175. P. 619–631. DOI: 10.1016/j.psep.2023.05.074.

43. From waste to energy: Comprehensive understanding of the thermal-chemical utilization techniques for waste tire recycling / Sh. Wang et al. *Renewable and Sustainable Energy Reviews*. 2025. Vol. 211. Art. 115354. DOI: 10.1016/j.rser.2025.115354.

44. Experimental study and performance comparison of a 1 kW-class solar-ocean thermal energy conversion system integrated air conditioning: Energy, exergy, economic, and environmental (4E) analysis / Y. Zhang et al. *Journal of Cleaner Production*. 2024. Vol. 451. Art. 142033. DOI: 10.1016/j.jclepro.2024.142033.

45. Vig N., Ravindra Kh., Mor S. Environmental impacts of Indian coal thermal power plants and associated human health risk to the nearby residential communities: A potential review. *Chemosphere*. 2023. Vol. 341. Art. 140103. DOI: 10.1016/j.chemosphere.2023.140103.

46. Optimization of hydrogen production and system efficiency enhancement through exhaust heat utilization in hydrogen-enriched internal combustion engine / M. I. Shahid et al. *Energy*. 2025. Vol. 319. Art. 135051. DOI: 10.1016/j.energy.2025.135051.

47. Waste heat recovery of a combined internal combustion engine and inverse brayton cycle for hydrogen and freshwater outputs: 4E optimization and comparison / M. Zoghi, N. Hosseinzadeh, S. Gharaie, A. Zare. *Energy Nexus*. 2025. Vol. 17. Art. 100356. DOI: 10.1016/j.nexus.2024.100356.

48. Comparative analysis of different heat transfer models, energy and exergy analysis for hydrogen-enriched internal combustion engine under different operation conditions / M. I. Shahid et al. *Applied Thermal Engineering*. 2024. Vol. 247. Art. 123004. DOI: 10.1016/j.applthermaleng.2024.123004.

49. Performance analysis of an internal combustion engine with thermochemical recovery and high temperature proton exchange membrane fuel cell combined power generation system / Sh. Leng et al. *Fuel*. 2025. Vol. 384. Art. 133913. DOI: 10.1016/j.fuel.2024.133913.

50. A new trend in combustion engine's deep waste heat recovery by application of condensing economizers in exhaust boilers / V. Kornienko et al. *Applied Thermal Engineering*. 2025. Vol. 261. Art. 125150. DOI: 10.1016/j.applthermaleng.2024.125150.

51. Response surface methods based in artificial intelligence for superstructure thermoeconomic optimization of waste heat recovery systems in a large internal combustion engine / L. R. de Araújo et al. *Energy Conversion and Management*. 2022. Vol. 271. Art. 116275. DOI: 10.1016/j.enconman.2022.116275.

52. Proposing a new method for waste heat recovery from the internal combustion engine for the double-effect direct-fired absorption chiller / D. Dadpour et al. *Applied Thermal Engineering*. 2022. Vol. 216. Art. 119114. DOI: 10.1016/j.applthermaleng.2022.119114.

53. Omara A. A. M. Phase change materials for waste heat recovery in internal combustion engines: A review. *Journal of Energy Storage*. 2021. Vol. 44, Part B. Art. 103421. DOI: 10.1016/j.est.2021.103421.

54. Asadi M., Deymi-Dashtebayaz M., Rad E. A. Comparing the profitability of waste heat electricity generation of internal combustion engines: An exergoeconomic analysis through optimization of two different organic Rankine cycle scenarios. *Applied Thermal Engineering*. 2022. Vol. 211. Art. 118443. DOI: 10.1016/j.applthermaleng.2022.118443.

55. Fini A. T., Hashemi S. A., Fattahi A. On the efficient topology of the exhaust heat exchangers equipped with thermoelectric generators for an internal combustion engine. *Energy Conversion and Management*. 2022. Vol. 268. Art. 115966. DOI: 10.1016/j.enconman.2022.115966.

56. Alklaibi A. M., Lior N. Waste heat utilization from internal combustion engines for power augmentation and refrigeration. *Renewable and Sustainable Energy Reviews*. 2021. Vol. 152. Art. 111629. DOI: 10.1016/j.rser.2021.111629.

57. Polymeric hollow fibre heat exchanger for reducing vehicle CO_2 pollution / J. Vančura et al. *Applied Thermal Engineering*. 2025. Vol. 270. Art. 126180. DOI: 10.1016/j.applthermaleng.2025.126180.

58. Joint numerical-technical analysis and economical evaluation of applying small internal combustion engines in combined heat and power (CHP) / P. Arbabi, A. Abbassi, Z. Mansoori, M. Seyfi. *Applied Thermal Engineering*. 2017. Vol. 113. P. 694–704. DOI: 10.1016/j.applthermaleng.2016.11.064.

59. Shu G., Wang X., Tia H. Theoretical analysis and comparison of rankine cycle and different organic rankine cycles as waste heat recovery system for a large gaseous fuel internal combustion engine. *Applied Thermal Engineering*. 2016. Vol. 108. P. 525–537. DOI: 10.1016/j.applthermaleng.2016.07.070.

60. Raznoshinskaia A. V. The Research of Influence Characteristics of Heat-storage Material on Thermodynamic Process in Heat Storage, Installed in System of Waste-heat Recovery of Internal Combustion Engines. *Procedia Engineering*. 2015. Vol. 129. P. 140–144. DOI: 10.1016/j.proeng.2015.12.022.

61. Pandey K. K. Study on the integration of hydrogen in a multi-cylinder low heat rejection diesel engine using a ternary blend. *Atmospheric Pollution Research*. 2024. Vol. 15, Issue 10. Art. 102250. DOI: 10.1016/j.apr.2024.102250.

62. Pandey K. K. Application of acetylene in multi-cylinder low heat rejection diesel engine fueled with ternary blend. *Energy*. 2024. Vol. 311. Art. 133368. DOI: 10.1016/j.energy.2024.133368.