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ASSESSMENT OF IMPROVEMENT OF ECOLOGICAL SAFETY OF POWER PLANTS BY ARRANGING THE SYSTEM OF POLLUTANT NEUTRALIZATION

S. Vambol
Doctor of Technical Sciences,
Professor, Head of Department*
E-mail: sergvambol@nuczu.edu.ua
V. Vambol
Doctor of Technical Sciences, Associate Professor
Department of Labour Protection and
Technogenic and Ecological Safety**
E-mail: violavambol@nuczu.edu.ua
O. Kondratenko
PhD, Associate Professor*
E-mail: kharkivjanyn@i.ua
Y. Suchikova
PhD, Associate Professor
Department of Vocational Education***
E-mail: yo_suchikova@bdpu.org
O. Hurenko
Doctor of Pedagogical Sciences,
Associate Professor, First Vice-Rector***
E-mail: oi_hurenko@bdpu.org
*Department of Applied Mechanics**
**National University of Civil Protection of Ukraine
Chernyshevska str., 94, Kharkiv, Ukraine, 61023
***Berdyansk State Pedagogical University
Schmidta str., 4, Berdyansk, Ukraine, 71100

Визначено фізичний зміст й числові значення коефіцієнта компонування фільтра твердих частинок у випускній системі дизельної установки для математичної моделі його ефективності роботи. Це дозволяє врахувати вплив температури відпрацьованих газів дизеля на вході у корпус фільтра, а також прогнозувати робочі характеристики фільтрів з урахуванням місця їх розміщення у випускному тракті. Описано методику отримання експериментальних даних на моторному випробувальному стенді з автотракторним дизелем та робочим діючим зразком фільтра твердих частинок, на основі математичної обробки яких отримані залежності значень коефіцієнта від конструктивних і режимних робочих параметрів випускної системи дизеля

Ключові слова: техногенно-екологічна безпека, дизель, фільтр твердих частинок, ефективність очищення, наноматеріали

Определены физический смысл и числовые значения коэффициента компоновки фильтра твердых частиц в выпускной системе дизельной установки для математической модели его эффективности работы. Это позволяет учесть влияние температуры отработавших газов дизеля на входе в корпус фильтра, а также прогнозировать рабочие характеристики фильтров с учетом места их размещения в выпускном тракте. Описана методика получения экспериментальных данных на моторном испытательном стенде с автотракторным дизелем та рабочим действующим образом фильтра твердых частиц, на основе математической обработки которых получены зависимости значений коэффициента от конструктивных и режимных рабочих параметров выпускной системы дизеля

Ключевые слова: техногенно-экологическая безопасность, дизель, фильтр твердых частиц, эффективность очистки, нано материалы

1. Introduction

The level of ecological safety (ES) of an urban system is obviously determined by the numeric values of certain parameters. These parameters characterize the levels of ecological safety of the individual components of such a system. In this case, the level of ES is formed in line with a synergetic principle, that is, it is not a simple algebraic sum of components. Among such components, special attention should be paid to the sources of factors of environmental hazard that have intensive, multi-faceted influence even during their normal (not in emergency) operation. In urbosystems, such sources include power plants (PP), equipped with pistol internal combustion engines (PICE), in particular automotive vehicles (AMV) and specialized equipment (SE).

The problem on making PICE in PP environmentally safe is tackled in a large number of fundamental scientific studies [1–7], which testifies to its relevance. The latter is proved by the information in analytical reviews based on the results of annual congresses of the Society of Automotive Engineers (SAE) [8–10].

The most effective, as well as radical, out of the known ways of solving this problem is a partial or total rejection from the use of PICE as sources of mechanical power for AMV and SE. The first principle is implemented in hybrid cars, the second – in electric vehicles. In this case, a substantial obstacle to the widespread introduction of the above technologies is insufficient level of research into and development of the elementary base, first of all, accumulators of electrical power, in particular, batteries and supercondensers [11–13].

An analysis of articles [11–13] allows us to conclude that, in the short term, it is necessary to concentrate on studies into less radical ways of provision of the level of environmental safety of an urbosystem through harmonization of indicators of environmental safety of PICE with legislatively established standards, described for auto-tractor PICE, which equip AMV and SE of various purposes, in the UNECE Regulations No. 49 and 96 [14, 15]. According to data in [16], among such ways, the most effective is the neutralization of pollutants in the flow of exhaust gases (EG) of PICE, and among the means – diesel particulate matter filters (DPF). Modern ways and means of providing ES of motor vehicles based on elementary base from nanostructured semiconductors are an extremely promising direction for subsequent research, which, however, may be conducted sometime in the future.

Study [17] and the aforementioned emphasize the relevance of scientific-research work, aimed at creating fundamentally new and improvement of the known structures of DPF. Moreover, the peculiarities of their operation require further research.

2. Literature review and problem statement

As of 01.01.2016, norms of toxicity of AMV and SE with diesel PICE of standards of UNECE Regulations Nos. 49 and 96 of EURO V level have been put into effect on the territory of Ukraine. The norms of the same standards of EURO V level (as of 01.01.2016) are currently in force on the territory of the Russian Federation, and standards of EURO VI level (as of 01.09.2014 and 01.09.2015 for various types of AMV and SE) – on the territory of the European Union [14, 15, 17–19].

Authors of study [16] developed a system of management of ecological safety (SMES) of the process of operation of PP with PICE. Such PP, first of all, include the transportation AMV and SE that are on ready alert of the units of the State Emergency Service of Ukraine (SES), Armed Forces of Ukraine, the Ukrainian National Guard, the National Police of Ukraine, the State Border Guard Service of Ukraine, Security Service of Ukraine on other law enforcement agencies [20], as well as the mountain-rescue units [21]. Such SMES is structurally similar to:

– SMES of processes of dust and gas supression, which uses multi-phase disperse structures [22];

– SMES of processes of recycling of solid domestic wastes [23];

– SMES of the lifecycle of nano-structured semiconductor materials [11–13].

Developed SMES is constructed on the basis of the principles of multilevel decomposition, hierarchical structures, methodological approach and decimal division and includes several stages, each of which is divided into several levels.

The first stage of this SMES, termed “Source data for creating SMES”, includes two levels:

– Level 1, entitled “Identification of sources of factors of environmental hazard” and an analysis of the normative-legal framework”;

– Level 2, entitled “Classification of factors of environmental hazard with regard to their genesis and significance”.

Achieving these SMES levels resulted in updated classification of factors of environmental hazards, the source of which is PP with PICE, and the separation of particulate matters (PM) as one of the most dangerous legislatively normalized pollutants in EG of diesel engines. PM consist of uncombusted hydrocarbons of motor fuel and oil C_nH_m, adsorbed on surfaces of soot nuclei – porous amorphous carbon. By definition from [14, 15], PM are all substances, which settled on a special Teflon filter while passing through it of a specially prepared sample from EG, diluted with pure air, rather than water. In this case, it was found that up to 95 % of reduced toxicity of nitric oxide fall on nitrogen oxides NO_X and PM, in which, depending on the operation mode of the diesel engine, PM make up 20–45 % [16, 17].

The second phase of such SMES, entitled “Improved and new technologies for provision of ES, used by SMES”, consists of two levels:

– Level 3, entitled “Development of new and improvement of the known preparatory processes”;

– Level 4, entitled “Development of new and improvement of existing equipment for the implementation of technological processes”.

Results of implementation of levels of this stage are:

– new classifications of the ways and means of reducing the mass release of PM with EG flow from diesel engimes (primarily, DPF);

– implementation of the process of their regeneration;

– positioning of the design of DPF, developed by the authors, in these classifications.

Mathematical model of efficiency of the developed DPF was described in the previous part of research [17].

The purpose of DPF is the neutralization of PM in EG by removing them from the flow, accumulation in the filtration element (FE) and converting them into safe substances directly in FE or outside PP. When creating the above classifications, we applied the methods of literary-patent search, analysis and synthesis of information, and the principle of decimal division.

The third stage of SNES is named “Organization and execution of processes that provide a specified level of ES” and has two levels:

– Level 5, entitled “Organization and management of SMES”;

– Level 6, entitled “Production processes that provide a specified level of ES”.

Results of their implementation include researched, described and rationalized processes in FE of DPF and in the exhaust tract of PICE.

That means that this series of studies takes a defined place in the construction of operation process of PP with the piston ICE in SMES.

An analysis of up-to-date information from current scientific research suggests that temperature of EG in different sections of the exhaust tract of diesel PICE in general, and in particular in the units of the system of pollutant neutralization, exerts significant influence on the progress and results of operation processes in them. Thus, paper [24] describes the features of operation of DPF with ceramic FE of the cellular structure with longitudinal channels with gas-permiable walls with catalytic coating that are plugged in staggered order at decreased temperature of EG. Article [25] studies the effect of temperature of EG on efficiency of a selective absorber of nitrogen oxides; while article [26] explores its influence on efficiency of application of EG recirculation. Research [27] is devoted to the influence of EG temperature on operation processes in a catalytic oxidizing agent of uncombusted hydrocarbons with netlike-steel FE as parts of DPF. Paper [28] describes results of multi-zone mathematical modeling of relationships between temperature of EG, operation efficiency and hydraulic resistance of DPF. Articles [29, 31] analyse selection of temperature of EG in the process of regeneration of DPF, article [30] explores the influence of temperature of the combustible generator gas at the inlet to PICE on efficiency of its cleaning. Paper [32] examines the effect of temperature of EG on the process of standard passive regeneration of the first kind by the thermocatalytic method of DPF, and research [38] focuses on the specifics of operation of sensors of the system of electronic control over this process. The influence of the temperature of EG on the course of processes of chemical transformation of polycyclic aromatic hydrocarbons in EG for three types of diesel fuels of biological origin are given in paper [34], on other processes – in papers [39, 42].

The examined DPF has FE of non-conventional design that contains modules filled with granular natural zeolite in netlike holders and does not contain catalytic coatings. The relationship of the processes of oxidation of PM and reduction of nitrogen oxides in DPF with the use of zeolites with catalysts was studied in papers [33, 41], and in case of their different spatial structuring, it was explored in articles [37, 40]. The temperature of EG has a significant impact on the course of operation processes in DPF with non-conventional design, which is constructed by the triboelectric principle of self-powered operation, which is explored in paper [36].

In this case, the problem is the lack of description of the influence of processes, taking place in the EG flow in the exhaust tract of PICE, on the performance characteristics of the studied DPF. These processes include the following consecutive chain, determined by causal relations [16, 43]:

– cooling of EG flow due to heat exchange with unmoved details of the exhaust tract and radiation, expansion and slowdown of the viscous flow through linear and local losses of head;

– condensation of uncombusted hydrocarbons of motor fuel and lubricants on PM due to cooling of the EG flow;

– increase if dimensions of PM themselves at the expense of their coagulation due to the presence of adhesive properties of layers of hydrocarbons, adsorbed on soot cores.

The latter, obviously, should improve the efficiency of the process of cleaning of the EG flow from PM with the help of devices, built on inertial and filter methods. However, direct research into processes of condensation and coagulation in the flow of EG of diesel PICE still pose certain difficulties of technologically-methodological nature.

In the present study, we plan to perform assessment and mathematical description of the influence of length of the exhaust tract of the diesel engine between the exhaust collector and DPF on temperature of the EG flow. The influence of the length of the tract on the DPF efficiency may be regarded as a useful practical result of the studied effect. Assessment and a mathematical description will be carried out based on an analysis of experimentally obtained data.

It should also be noted that nanomaterials will gradually begin to occupy the niche of materials for DPF and unburned hydrocarbons, catalytic for oxidizers, in particular in the form of membranes from silicium carbide, as shown in paper [34].

3. The aim and tasks of the study

The aim of present study is to identify the impact of DPF lay-out along the exhaust tract of the diesel engine on the efficiency of EG cleaning from PM.

To achieve the specified aim, the following tasks were set:

– to describe prerequisites for the formation and the structure of the mathematical model of operation efficiency of a solid particle filter of diesel plants, as well as the methods of obtaining experimental source data for its creation;

– to improve the mathematical model of operation efficiency of the solid particle filter of diesel plants by taking into account the special features of its lay-out in the exhaust system of a diesel engine;

– to determine physical essense and definition of lay-out coefficient of such mathematical model;

– to evaluate effectiveness of taking of structural measures to improve the environmental safety of the operation process of power plants with the system of pollutant neutralization through the lay-out of its units.

4. Determining a lay-out coefficient of particulate matter filter in exhaust system of a diesel plant for the mathematical model of its efficiency

4. 1. Prerequisites for the formation of mathematical model of operational efficiency of a particulate matter filter of the diesel plants

The authors developed DPF with FE of a new modular alternative design [16, 17]. Results of physical and mathematical modeling of the process of motion of the EG flow in DPF were obtained. Under real conditions of operation, engine testing of the present layout of such DPF on the bench, equipped with autotractor diesel engine 2Ch10.5/12, were carried out. Based on these results, a mathematical model of hydraulic resistance (HR) of such DPF was constructed and data to build a mathematical model of its efficiency, which is similar to it by structure, were obtained. Peculiarities and differences of these models are described in study [17].

Design features of the current mockup sample of DPF, engine testing bench, motor-free experimental plant, autotractor diesel engine 2Ch10.5/12, manufactured at Vladimir tractor factory (Russian Federation), composition and characteristics of measuring equipment of the bench, programs and methods of conducting such a study and test cycles are described in [14, 15, 17, 44].

4. 2. Mathematical model of operatinal efficiency of a particulate matter filter of the diesel plants

The developed mathematical model establishes relationships between performance characteristics of DPF and the mode, regulatory, and design parameters of the diesel engine and operational factors, described with the mathematical language. Such a model in subsequent studies will form the basis for scientific-research works on construction of the standard series of DPF of the known and new, traditional and non-traditional designs, which, in turn, is the first stage of their implementation in the full-scale production and operation with the purpose of provision of ES of environment of urban systems.

The mentioned mathematical model, described in [17] and based on the same principles as the mathematical model of hydraulic resistance of DPF from [45], takes the following form:

$$K_{CE} = K_{CE}(G_{PM})(g_{m\_EG}) \cdot k_L(t_{DPFint\max}) \cdot k_\tau(\tau_M; N_{ei}; WF_i) = \\ = K_{CE}(G_{PM})(n_{cs}) \cdot k_L(L_{exh}) \cdot k_\tau(\tau_M; N_{ei}; WF_i), \qquad (1)$$

$$K_{CE}(G_{PM})(g_{m\_EG}) = -0{,}332 \cdot g_{m\_EG}^2 + \\ +14{,}198 \cdot g_{m\_EG}^2 - 112{,}557; R^2 = 0{,}96756, \quad (2)$$

$$g_{m\_EG} = \\ = (1{,}558 \cdot 10^{-2} \cdot n_{cs} + 0{,}956) \cdot 20 / z_m \cdot 55 / S_{int} \ \text{kg/(s·m}^2\text{)}, \quad (3)$$

where $K_{CE}(G_{PM})(g_{m\_EG})$ and $K_{CE}(G_{PM})(n_{cs})$ are, respectively, coefficient of efficiency of cleaning of EG flow (as a phenomenon) from PM in the function of EG flow (as physical magnitude) and rotation frequency of crankshaft of the diesel engine, %; g_{m_EG} are the second mass consumption of EG through a unit of area of the inlet hole of FE module of DPF (EG flow), kg/(s·m²); G_{PM} is the mass exhaust of PM with EG flow, kg/h; k_L, k_τ are, respectively, lay-out coefficient and temporal coefficient of the model; t_{DPFint_max} is the maximum temperature of EG at the outlet into the case of DPF by external velocity characteristic (EVC), which is observed under the mode of maximum torque, °C; L_{exh} is the length of the exhaust tract of the diesel engine to the place where DPF is installed, m; τ_M is the operation time of the diesel engine under the mode of maximum torque, h; N_{ei} is the effective capacity of the diesel engine in the i-th operation mode, kW; WF_i is the weight factor of the i-th operation mode of diesel engine in the operation model; index i corresponds to the current operation mode of the diesel engine in operation model; z_m is the number of modules in FE, unit; S_{int} is the area of the inlet hole of module of FE, m²; n_{cs} is the rotation frequency of crankshaft, s⁻¹.

Magnitudes G_{PM} in kg/h and $K_{CE}(G_{PM})$ in % are determined by formulas (4) and (5).

$$G_{PM} = \Big(2{,}3 \cdot 10^{-3} \cdot N_D + 5 \cdot 10^{-5} \cdot N_D^2 + \\ +0{,}145 \cdot \frac{C_{CH} \cdot 4{,}78 \cdot 10^{-7} \cdot (G_{air} + G_{fuel})}{0{,}7734 \cdot G_{air} + 0{,}7239 \cdot G_{fuel}} + \\ +0{,}33 \cdot \left(\frac{C_{CH} \cdot 4{,}78 \cdot 10^{-7} \cdot (G_{air} + G_{fuel})}{0{,}7734 \cdot G_{air} + 0{,}7239 \cdot G_{fuel}} \right)^2 \Big) \times \\ \times \frac{(0{,}7734 \cdot G_{air} + 0{,}7239 \cdot G_{fuel})}{1000}, \quad (4)$$

$$K_{CE}(G_{PM}) = (G_{PMICE} - G_{PMDPF}) \cdot 100 / G_{PMICE}, \quad (5)$$

where indexes of ICE and DPF refer to the cases of lack and existence of DPF in the exhaust tract of a diesel motor.

4. 3. Physical essence and definition of a lay-out coefficient of a particulate matter filter in the exhaust system of diesel plants

The coefficient that is being developed and researched establishes the relationships between the temperature of EG flow at the inlet to the housing of DPF and efficiency of cleaning EG flow from PM with the filter. It is determined by the place, where it is installed along the exhaust tract of the diesel engine (the course of processes of extenstion of EG flow and EG heat exchange with the medium in the exhaust tract) and growing in size of PM through condensation of C_nH_m on PM and coagulation of PM in EG flow. Herein lies the unsolved problem of the research and its scientific novelty.

Materials of research [11, 44] contain sufficient experimentally obtained information to describe the relationship between indicators of operation efficiency of the studied DPF, with the most important design parameters of the diesel engine, AMV and SE and the performance factors.

5. Results of examining a lay-out coefficient of particulate matter filter in the exhaust system of diesel plant

Approaches to the solution of the set problems of the research and its results are given in studies [17, 45]. The aforementioned engine tests were carried out at several stages, the results of the first of which formed the basis of the mathematical model itself. In the course of implementation of the first stage, we experimentally compared characteristics of performance of two types of experimental samples of FE during the operation of the auto tractor diesel engine 2Ch10.5/12 in the modes of external velocity characteristic (EVC), at which they were mounted in the housing of DPF directly behind the exhaust collector of the diesel engine (L_{exh}=0 m).

Advantages of the chosen approach to comparative studies with the use of EVC, peculiatiries of characteristics themselves and the way of their construction are presented in [17]. The value of the coefficient of luminous flux damping N_D in % was obtained as a result of direct single measurement by the smoke density indicator INFRAKAR-D. The value of volumetric concentration of C_nH_m in EG C_{CH} in mln⁻¹ was obtained by the five-compoment gas analyzer AUTOTEST-02.03. The magnitude of G_{PM} in kg/h was calculated using known conversion formula (4) from [46].

The second stage of the engine experimental research was carried out for the purpose of detection and estimation of the influence of temperature of dispersed medium of aerosol "EG of the diesel engine – PM" t_{EG} on efficiency of cleaning from disperse phase by means of the researched DPF.

There was made an assumption that when the value of t_{EG} decreases, the value of $K_{CE}(G_{PM})$ is to increase under other equal conditions. Such an effect might be expected due to the above reasons, which may be described in more detail as follows.

Firstly, the place of mounting of the current DPF mock-up immediately after outlet flange of the exhaust collector of the diesel engine is characterized by value L_{exh}=0 m and t_{EG}=605 °C, as well as maximum velocity of EG flow through FE. In this case, the processes that determine dimensions of PM (condensation of C_nH_m on soot core, coagulation of PM themselves), which are in the logarithmic dependence on t_{EG} [47], under these conditions are far from being completed. In the exhaust collector of the diesel engine, according to presented in [16, 43, 46, 47], they have dimensions of about 5 nm (at t_{EG}=600 °C), in the cross-section of the exhaust tract at the inlet to the EG silencer – around 0.1 μm (at t_{EG}=350...400 °C), and in the cross-section at the outlet of the exhaust system of AMV, they exceed 3...5 microns (t_{EG}=200 °C and less). That is, in function of $t_{EG,}$ there is a decrease in dimensions of PM and a change in their composition (calculation, chemical, dimensional, by weight, by area of adsorbing surface), structure and geometric shapes (complex branching).

In FE of the studied mock-up operating sample of DPF, the number of modules z_m=20 units, while by preliminary estimations for the diesel engine 2Ch10.5/12, with operation volume of 2.0 dm³, the rational value z_m should be 30...50 units. This provides a greater degree of extension of EG flow at the inlet to FE and a corresponding decrease in the velocity of motion of EG in FE.

At these dimensions of the experimental sample, soot capacity, that is, the dynamics of filling of PM over time, is also limited. Then the change in time of living cross-sections of randomly placed random-shape channels between the granules of fill from natural zeolite in netlike holders is also limited.

The state of fill (fractions, temperature, way of briquetting and compacting), obviously, also has to make some impact on K_{CE} [45]. Detection and assessment of such effects require additional research.

In the experiment, the change in value t_{EG} was achieved by extending the exhaust tract between the flanges of the exhaust collector and the case of the experimental sample with pieces of flexible heat-resistant pipeline by magnitude L_{exh}=1.5, 5.0 and 8.0 m. In this case, the EG flow was cooled naturally due to the processes of heat exchange with the environment and extension. For each new position of the researched experimental sample, EVC was recorded, which was later compared with such characteristic for L_{exh}=0 m, obtained in the first stage of experimental research.

It should be noted that in the course of experimental verification, these assumptions were proved. $K_{CE}(G_{PM})$ increased from 40.1 % at L_{exh}=0 m to 86.8 % at L_{exh}=8,0 m under the mode of maximum torque of the diesel engine. Under this mode, there is a global maximum of mass emission of PM and $K_{CE}(G_{PM})$. However, the limit to the value of L_{exh}=5,0 m is rational, because, in practice, larger values are difficult to achieve even for heavy-duty AMV and SE, in this case, $K_{CE}(G_{PM})$=77.4 % [44, 45].

Along with this, we also observed a decrease in EG of experimental sample and a difference in temperature of EG on the sample, the physical nature of these processes is interpreted in [45].

In the same study, the relationships between magnitudes were found:

a) temperature of EG in the place of mounting of the operating mock-up of DPF in the absence of t_{EG}, at temperature at the inlet to the housing of DPF t_{DPFint} and temperature of EG at the outlet from the housing of DPF t_{DPFint};

b) hydraulic resistance of DPF t_{DPFint}, a part of the exhaust tract of the diesel engine, which is located behind the housing of DPF ΔP_{exh}, housing of DPF without FE of ΔP_{DPFh} in qualitative terms are conserved for all values of L_{exh}.

Magnitudes t_{EG} also depend linearly on magnitude L_{exh}, and magnitudes t_{DPFint}, t_{DPFout}, Δt_{DPF} – nonlinearly (polynomials of the second power).

The maximum temperature of EG at the inlet to DPF t_{DPFint} and magnitude L_{exh} may be connected by the following dependence, obtained by description of the experimental data by the method of least squares (R^2 = 0.986) [45]:

$$t_{DPFint\,max} = 2{,}176 \cdot L_{exh}^2 - 61{,}272 \cdot L_{exh} + 591{,}2 \ \ ^\circ C. \qquad (4)$$

Results of this phase of engine tests are shown in Fig. 1, 2.

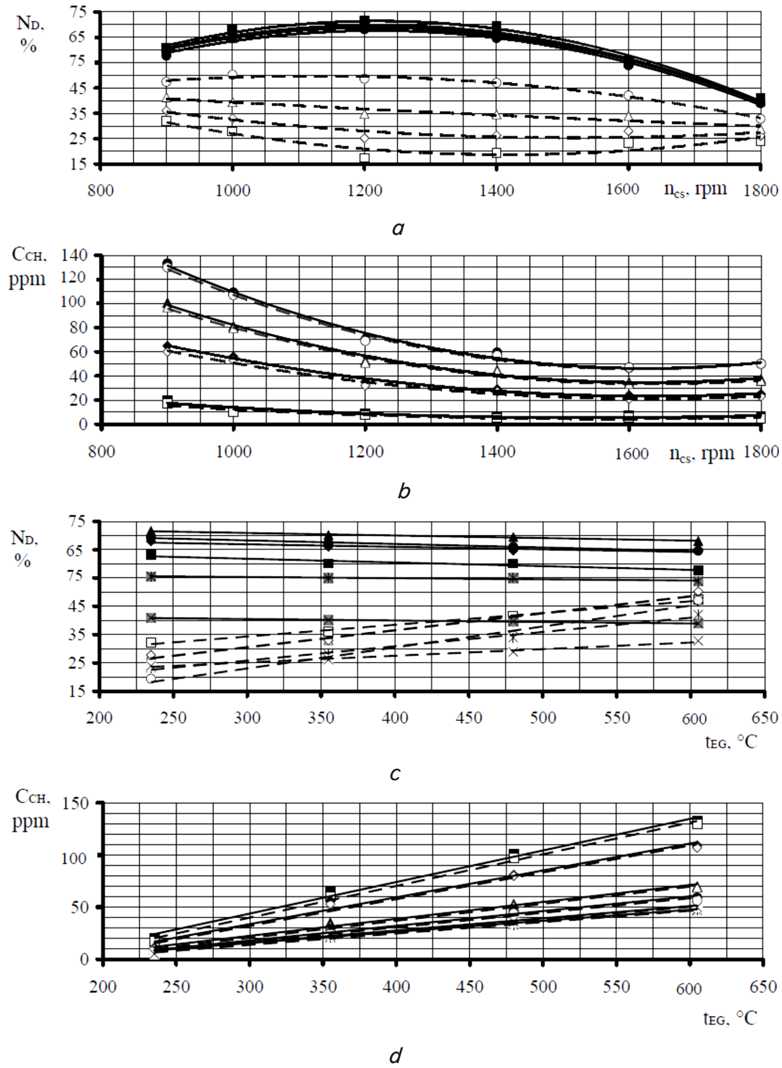


Fig. 1. External velocity characteristics of the diesel engine 2Ch10.5/12 for different places where DPF is installed: *a* – the dependence of coefficient of luminous flux damping N_D on rotation frequency of the crankshaft of the diesel engine; *b* – dependence of volumetric concentration of C_nH_m in EG on rotation frequency of the crankshaft of the diesel engine; *c* – dependence of coefficient of luminous flux damping N_D on temperature of dispersed medium of aerosol "Diesel EG-PM"; *d* – dependence of volumetric concentration of C_nH_m in EG on temperature of dispersed medium of aerosol "Diesel EG-PM". For *a*–*d*: ■, □ – t_{EG}=235 °C (L_{exh}=8.0 m); ◆, ◊ – t_{EG} = 355 °C (L_{exh}=5.0 m); ▲, Δ – t_{EG} = 480 °C (L_{exh}=1.5 m);●, ○ – t_{EG}=605 °C (L_{exh}=0.0 m); ■, ◆, ▲, ● – without DPF; □, ◊, Δ, ○ – with DPF; for d: ■, ◆, ▲, ● – $K_{CE}(G_{PM})$; □, ◊, Δ, ○ – $K_{CE}(N_D)$; □, ◊, Δ, ○ – $K_{CE}(C_{CH})$

Fig. 1 shows experimentally obtained dependences of magnitudes N_D, C_{CH}, in the course of operation of the diesel engine D21A1 under modes of EVC (that is, in function n_{cs}) for different fixed values of L_{exh} (that is, in function t_{DPFint}) under condition of existence (designated by index of DPF) or absence (designated by index ICE) in the exhaust tract of DPF.

Fig. 2 shows dependences of magnitudes G_{PM} of the diesel engine 2Ch10.5/12 and $K_{CE}(N_D)$, $K_{CE}(C_{CH})$ and $K_{CE}(G_{PM})$ by EVC modes on values n_{cs} and t_{EG} for different fixed values of L_{exh}, obtained by calculation. Fig. 2, *d* also shows dependence of magnitude L_{exh} on t_{DPFint}, which corresponds to formula (4).

The curves, given in Fig. 1, 2, are described by polynomials of the first and second power by the method of least squares (R^2=0.997...0.960) [17, 45] and take the following form.

$$y = a\cdot x^2 + b\cdot x + c, \quad (5)$$

where y is the experimentally obtained indicators of operational efficiency of the diesel engine or DPF; x is the influence factor, in this case – n_{cs}, min^{-1}, at n_{cs}=[800, 1800] min^{-1}; a, b, c are the coefficients of approximating polynomial.

The magnitudes of coefficients of approximating polynomials a, b and c for different magnitude y at different fixed values of magnitude L_{exh} (or $t_{DPFint\ max}$) in function of magnitude x are reduced to Table 1. At different fixed values of magnitude $t_{EG,}$ they are given in Table 2.

Therefore, we obtained approximated dependences of source data for the formation of values of a lay-out coefficient of DPF in the exhaust system of the diesel plant for the mathematical model of its operational effectiveness on the chosen influencing factors.

Table 1

Parameters of approximating polynomials

y	[y]	a	b	c	a	b	c
$x=n_{cs}$, $[x]=min.^{-1}$		$[y]/[x]^2$	[y]/[x]	[y]	$[y]/[x]^2$	[y]/[x]	[y]
At fixed values		L_{exh}=0,0 m ($t_{DPFint\ max}$=605 °C)			L_{exh}=1,5 m ($t_{DPFint\ max}$=480 °C)		
N_{D_ICE}	kW	$-8.697\cdot10^{-5}$	0.212	–61.6	$-8.634\cdot10^{-5}$	0.210	–58.6
N_{D_DPF}	kW	$-3.678\cdot10^{-5}$	8.289	3.1	$2.527\cdot10^{-6}$	$-1.882\cdot10^{-2}$	55.7
C_{CH_ICE}	ppm	$1.615\cdot10^{-4}$	–0.525	473.3	$1.221\cdot10^{-4}$	–0.397	357.1
C_{CH_DPF}	ppm	$1.610\cdot10^{-4}$	–0.521	466.6	$1.155\cdot10^{-4}$	–0.378	342.0
G_{PM_ICE}	kg/h	$-4.910\cdot10^{-8}$	$1.331\cdot10^{-4}$	$-6.6\cdot10^{-2}$	$-5.020\cdot10^{-8}$	$1.362\cdot10^{-4}$	$-6.7\cdot10^{-2}$
G_{PM_ICE}	kg/h	$-1.860\cdot10^{-8}$	$5.165\cdot10^{-5}$	$-2.1\cdot10^{-2}$	$-1.270\cdot10^{-9}$	$5.400\cdot10^{-6}$	$-4.6\cdot10^{-3}$
$K_{CE}(N_D)$	%	$-5.560\cdot10^{-5}$	0.146	–68.3	$-9.720\cdot10^{-5}$	0.256	–119.4
$K_{CE}(C_{CH})$	%	$-6.575\cdot10^{-6}$	$1.502\cdot10^{-2}$	–6.1	$4.981\cdot10^{-6}$	$-1.195\cdot10^{-2}$	9.8
$K_{CE}(G_{PM})$	%	$-8.060\cdot10^{-5}$	0.211	–99.2	$-1.197\cdot10^{-4}$	0.314	–142.2
At fixed values		L_{exh}=5.0 m ($t_{DPFint\ max}$=355 °C)			L_{exh}=8.0 m ($t_{DPFint\ max}$=235 °C)		
N_{D_ICE}	kW	$-8.968\cdot10^{-5}$	0.218	–63.2	$-9.391\cdot10^{-5}$	0.229	–68.4
N_{D_DPF}	kW	$2.669\cdot10^{-5}$	$-8.098\cdot10^{-2}$	86.8	$4.766\cdot10^{-5}$	–0.135	114.6
C_{CH_ICE}	ppm	$7.863\cdot10^{-5}$	–0.256	232.3	$2.912\cdot10^{-5}$	$-8.99\cdot10^{-2}$	74.7
C_{CH_DPF}	ppm	$7.400\cdot10^{-5}$	–0.242	218.4	$2.490\cdot10^{-5}$	$-7.789\cdot10^{-2}$	65.3
G_{PM_ICE}	kg/h	$-5.250\cdot10^{-8}$	$1.424\cdot10^{-4}$	$-7.1\cdot10^{-2}$	$-5.580\cdot10^{-8}$	$1.511\cdot10^{-4}$	$-7.6\cdot10^{-2}$
G_{PM_ICE}	kg/h	$7.140\cdot10^{-9}$	$1.709\cdot10^{-5}$	$-1.6\cdot10^{-2}$	$1.290\cdot10^{-8}$	$3.258\cdot10^{-5}$	$-2.4\cdot10^{-2}$
$K_{CE}(N_D)$	%	$-1.247\cdot10^{-4}$	0.328	–153.0	$-1.472\cdot10^{-4}$	0.387	–180.7
$K_{CE}(C_{CH})$	%	$-4.310\cdot10^{-6}$	1.499	–3.7	$1.174\cdot10^{-5}$	$2.049\cdot10^{-2}$	20.1
$K_{CE}(G_{PM})$	%	$-1.359\cdot10^{-4}$	0.356	–156.1	$-1.429\cdot10^{-4}$	0.373	–157.7

Table 2

Parameters of approximating polynomials

y	[y]	a	b	c	a	b	c
$x=t_{EG}$, $[x]=°C$		$[y]/[x]^2$	$[y]/[x]$	$[y]$	$[y]/[x]^2$	$[y]/[x]$	$[y]$
At values		n_{cs}=900 min^{-1}			n_{cs}=1000 min^{-1}		
N_{D_ICE}	kW	0	$-1.309\cdot10^{-2}$	65.7	0	$-9.037\cdot10^{-3}$	69.6
N_{D_DPF}	kW	0	$4.149\cdot10^{-2}$	21.9	0	$6.000\cdot10^{-2}$	12.5
C_{CH_ICE}	ppm	0	0.303	−47.3	0	0.258	−43.8
C_{CH_DPF}	ppm	0	0.304	−51.4	0	0.257	−45.2
G_{PM_ICE}	kg/h	0	$-4.447\cdot10^{-6}$	$2.1\cdot10^{-2}$	0	$-3.132\cdot10^{-6}$	$2.3\cdot10^{-2}$
G_{PM_ICE}	kg/h	0	$1.717\cdot10^{-5}$	$3.2\cdot10^{-3}$	0	$2.331\cdot10^{-5}$	$3.7\cdot10^{-5}$
$K_{CE}(N_D)$	%	$-6.078\cdot10^{-5}$	$-3.207\cdot10^{-2}$	59.8	$-1.172\cdot10^{-4}$	$-6.713\cdot10^{-5}$	65.4
$K_{CE}(C_{CH})$	%	$9.502\cdot10^{-5}$	−0.114	36.4	$7.371\cdot10^{-5}$	$-8.286\cdot10^{-2}$	24.7
$K_{CE}(G_{PM})$	%	$-9.772\cdot10^{-5}$	$-1.975\cdot10^{-2}$	73.0	$-1.690\cdot10^{-4}$	$3.025\cdot10^{-2}$	75.3
At values		n_{cs}=1200 min.$^{-1}$			n_{cs}=1400 min.$^{-1}$		
N_{D_ICE}	kW	0	$-9.063\cdot10^{-3}$	73.6	0	$-1.246\cdot10^{-2}$	72.0
N_{D_DPF}	kW	0	$8.356\cdot10^{-2}$	−3.5	0	$7.408\cdot10^{-2}$	0.828
C_{CH_ICE}	ppm	0	0.163	−26.3	0	0.142	−24.5
C_{CH_DPF}	ppm	0	0.163	−28.4	0	0.140	−25.3
G_{PM_ICE}	kg/h	0	$-3.976\cdot10^{-6}$	$2.6\cdot10^{-2}$	0	$-5.746\cdot10^{-6}$	$2.5\cdot10^{-2}$
G_{PM_ICE}	kg/h	0	$2.825\cdot10^{-5}$	$4.1\cdot10^{-3}$	0	$2.512\cdot10^{-5}$	$2.8\cdot10^{-3}$
$K_{CE}(N_D)$	%	$-1.525\cdot10^{-4}$	$2.363\cdot10^{-3}$	83.3	$-1.457\cdot10^{-4}$	$2.428\cdot10^{-2}$	79.2
$K_{CE}(C_{CH})$	%	$5.937\cdot10^{-6}$	$-3.240\cdot10^{-2}$	18.6	$1.834\cdot10^{-4}$	−0.190	52.1
$K_{CE}(G_{PM})$	%	$-2.363\cdot10^{-4}$	$7.457\cdot10^{-2}$	81.9	$-2.26\cdot10^{-4}$	$6.476\cdot10^{-2}$	80.7
At values		n_{cs}= 1600 min^{-1}			n_{cs}= 1800 min^{-1}		
N_{D_ICE}	kW	0	$-4.132\cdot10^{-3}$	56.6	0	$-5.179\cdot10^{-3}$	42.1
N_{D_DPF}	kW	0	$5.049\cdot10^{-2}$	10.7	0	$2.370\cdot10^{-2}$	18.0
C_{CH_ICE}	ppm	0	0.106	−16.1	0	0.117	−19.4
C_{CH_DPF}	ppm	0	0.109	−19.0	0	0.120	−21.6
G_{PM_ICE}	kg/h	0	$-1.281\cdot10^{-6}$	$1.7\cdot10^{-2}$	0	$-1.241\cdot10^{-6}$	$1.1\cdot10^{-2}$
G_{PM_ICE}	kg/h	0	$1.705\cdot10^{-5}$	$4.1\cdot10^{-4}$	0	$7.796\cdot10^{-6}$	$3.0\cdot10^{-3}$
$K_{CE}(N_D)$	%	$-1.157\cdot10^{-4}$	$4.846\cdot10^{-4}$	64.1	$-7.900\cdot10^{-5}$	$-2.197\cdot10^{-3}$	46.1
$K_{CE}(C_{CH})$	%	$-6.087\cdot10^{-5}$	$1.088\cdot10^{-2}$	15.4	$5.876\cdot10^{-5}$	$-9.200\cdot10^{-2}$	34.6
$K_{CE}(G_{PM})$	%	$-1.751\cdot10^{-4}$	$3.877\cdot10^{-2}$	71.5	$-1.088\cdot10^{-4}$	$7.347\cdot10^{-3}$	56.7

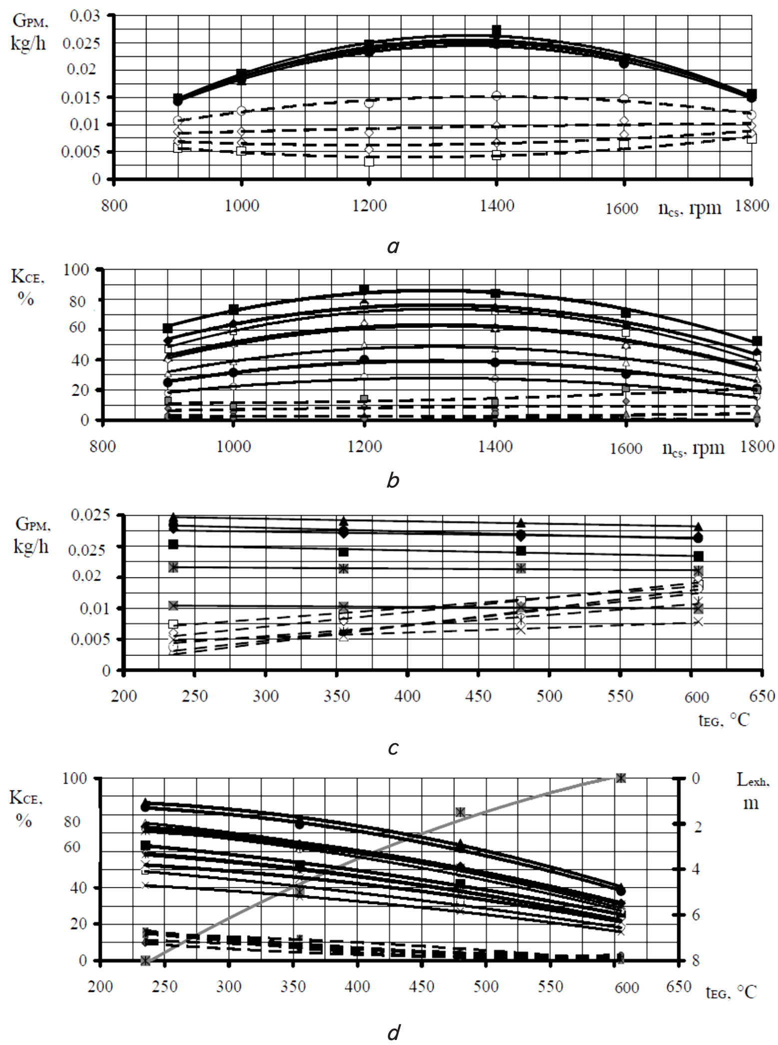


Fig. 2. Dependence of mass exhaust of PM from EG of the diesel engine 2Ch10.5/12 and operational efficiency of DPF by different components of PM on rotation frequency of the cranckshaft and temperature of EG at the inlet to the housing of DPF (places where DPF is installed along the exhaust tract of the diesel engine): *a* – dependence of mass exhaust of PM with EG flow on rotation frequency of the cranckshaft of the diesel engine; *b* – dependence of coefficient of cleaning of EG flow on rotation frequency of the cranckshaft of the diesel engine; *c* – dependence of mass exhaust of PM with EG flow on temperature of dispersed medium of aerosol "Diesel EG-PM"; *d* – dependence of coefficient of efficiency of cleaning the EG flow on temperature of dispersed medium of aerosol "Diesel EG-PM". For *a, b*: ■, □ – t_{EG}=235 °C (L_{exh}=8.0 m); ◆, ◊ – t_{EG}=355 °C (L_{exh}=5.0 m); ▲, Δ – t_{EG}=480 °C (L_{exh}=1.5 m); ●, ○ – t_{EG}=605 °C (L_{exh}=0.0 m); for *a, c*: ■, ◆, ▲, ● – without DPF; □, ◊, Δ, ○ – with DPF; for *b, d*: ■, ◆, ▲, ●, ∗, × – $K_{CE}(G_{PM})$; □, ◊, Δ, ○, ∗, × – $K_{CE}(N_D)$; □, ◊, Δ, ○, ∗, × – $K_{CE}(C_{CH})$; ∗ – L_{exh}; for *c, d*: ■, □, □ – n_{cs}=900 min^{-1}; ◆, ◊, ◊ – n_{cs}= 1000 min^{-1}; ▲, Δ, Δ – n_{cs}=1200 min^{-1}; ●, ○, ○ – n_{cs}= 1400 min^{-1}; ∗, ∗, ∗ – n_{cs}=1600 min^{-1}; ×, ×, × – n_{cs}=1800 min^{-1}

6. Discussion of results of research into a lay-out coefficient

Fig. 1, *a* shows that dependence N_D on L_{exh} is insignificantly small, which is caused by the measurement of smoke density of EG and coagulation of PM. Such dependence for N_{D_DPF} is of essential character and both quantitatively and qualitatively changes the form with maximum for the form with minimum, and the extremum is shifted from value n_{cs} 1200 to 1400 min^{-1}. This is due to the peculiarities of operational process of the diesel PICE with DPF.

Fig. 1, *b* shows that dependence C_{CH_ICE} on L_{exh} bears significant character and is approaching a horizontal straight line; it is conditioned by the process of condensation C_nH_m on PM. Dependence C_{CH_DPF} on L_{exh} almost repeats the one given above, which means low efficiency of cleaning of EG flow from gaseous C_nH_m with the help of the examined DPF.

Fig. 2, *a* shows that dependence G_{PM} on L_{exh} bears the character, similar to dependence N_D on L_{exh}, due to the peculiarities of formula of recalculation of magnitudes N_D and C_{CH} in G_{PM}, described in [17, 46].

The same applies to dependences $K_{CE}(N_D)$, $K_{CE}(C_{CH})$ and $K_{CE}(G_{PM})$ on L_{exh} in Fig. 2, *b*, which is the total effect of the above.

On the whole, Fig. 1, *c, d* and Fig. 2, *c* show that dependences of magnitudes N_D, C_{CH} and G_{PM} on magnitude t_{DPFint} are linear in nature, and such dependence for magnitude $K_{CE}(G_{PM})$ is not linear in character, which differs little from the linear (Fig. 2, *d*).

The two latter dependences may be described by the following formulas.

$$G_{PM\_ICE} = = -3,304\cdot10^{-6}\cdot t_{DPFint} + 2,038\cdot10^{-2}\ \text{kg/h}; \quad (5)$$

$$G_{PM\_DPF} = = 1,978\cdot10^{-5}\cdot t_{DPFint} + 2,235\cdot10^{-3}\ \text{kg/h}; \quad (6)$$

$$K_{CE}(G_{PM}) = -1,683\cdot10^{-4}\cdot t^2_{DPFint} + +3,266\cdot10^{-2}\cdot t_{DPFint} + 73,2\ \%. \quad (7)$$

Influence of magnitudes $t_{DPFint\,max}$ and n_{cs} on magnitude k_L is illustrated in Fig. 3.

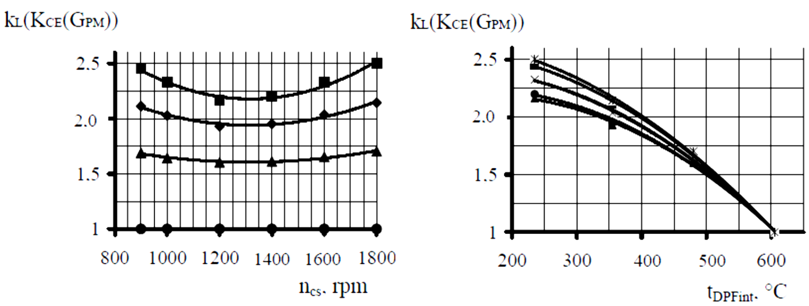
It shows that such influence in both cases is non-linear in nature and may be described by the following formula.

$$k_L = -5,579\cdot10^{-6}\cdot t^2_{DPFint\,max} + +1,167\cdot10^{-3}\cdot t_{DPFint\,max} + 2,3; R^2 = 0,99848. \quad (8)$$

It should be noted that for magnitude $K_{CE}(G_{PM})$, coefficient k_L is, in fact, similar to the complex of coefficients of the mathematical model of hydraulic resistance of DPF: of temperature coefficient k_t and of lay-out coefficient k_L. The fundamental difference between them in this case cannot be detected by the available experimental data. This is due to the lack of data on the physical simulation of the process of cleaning of EG flow from PM with the help of developed FE [45].

Lay-out coefficient for present mathematical model k_L by definition (which is the physical essence) is equal to ratio of values of $K_{CE}(G_{PM})$ at different fixed values $L_{exh}\neq0$ (or $t_{DPFint\,max}\neq \neq t_{DPFint\,max}(M_{Tmax})$, that is, by partial velocity characteristic) to values $K_{CE}(G_{PM})$ at $L_{exh}=0$ (or $t_{DPFint\ max}=t_{DPFint\ max}(M_{Tmax})$, that is, at EVC), at constant values of n_{cs}

The mathematical model of operational efficiency of DPF itself (formula (1)) describes results of experimental research. This is executed by taking EVC as a basis, when placing DPF directly behind the exhaust collector along the exhaust tract of the diesel engine at $L_{exh}=0$ (basic EVC – formulas (2) and (3)). The impact of global change in maximum temperature of EG flow at the inlet to the housing of DPF $t_{DPFint\ max}$, caused by a change in the place of location along exhaust tract at $L_{exh}\neq 0$ (formula (4)) and local changes in temperature t_{DPFint} at EVC itself, is taken into account by multiplying values $K_{CE}(G_{PM})$ at basic EVC n_{cs}=const on lay-out coefficient k_L (formula (8)).



a *b*

Fig. 3. Dependence of lay-out coefficient k_L on magnitudes n_{cs} (*a*) and $t_{DPFint\ max}$ (*b*): for *a*: ■ – L_{exh}=8 m; ◆ – L_{exh}=5 m; ▲ – L_{exh}=1.5 m; ● – L_{exh}=0.0 m; for *b*: ■ – n_{cs}=1400 min^{-1}; ◆ – n_{cs}=1200 min^{-1}; ▲ – n_{cs}=1000 min^{-1}; ● – n_{cs}=900 min^{-1}; ✱ – n_{cs}=1800 min^{-1}; × – n_{cs}=1600 min^{-1}; *a* – dependence of lay-out coefficient k_L on magnitudes n_{cs}; *b* – dependence of lay-out coefficient k_L on magnitudes $t_{DPFint\ max}$

7. Conclusions

1. It was established that the rational location of DPF along the length of the exhaust tract of the diesel engine is around the value L_{exh}=5.0 m. In this case, dependence for N_{D_DPF} on L_{exh} is essential in nature, because quantitatively and qualitatively, it changes the form with maximum to the form with minimum, and extremum is shifted from value of n_{cs} of 1200 to 1400 min^{-1}. This is due to peculiarities of operational process of the diesel engine PICE and DPF.

2. We established an influence of the global change in maximum temperature of EG flow at the inlet to the housing of DPF $t_{DPFint\ max}$ and local change in temperature t_{DPFint} by EVC. In this case, in the course of research, we considered by multiplying the values of $K_{CE}(G_{PM})$ by the basic EVC at n_{cs}=const on the value of a lay-out coefficient.

3. The mathematical model of operational efficiency of the PM filter for diesel plants was improved by considering a lay-out coefficient. This allows us subsequently to predict operational characteristics of DPF of any structure with regard to the place of its location in the exhaust tract of the diesel engine along the flow.

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