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INVESTIGATION OF RELATIONSHIP BETWEEN COEFFICIENTS OF OPERATION EFFICIENCY OF DIESEL PARTICULATE MATTER FILTERS OF DIESEL ICE. PART 1: PARTICULATE MATTER EMISSION AND OPACITY

This article describes the results of analysis and numerical study of prof. I.V. Parsadanov conversion formula as the one of relevant issues of the metrological features of determination of PM mass hourly emission of piston ICE on the testing bench without dilution tunnel. Purpose of the study is detection of relationship between magnitudes of cleaning efficiency coefficients of particulate matter filter of diesel piston ICE for opacity and emission of particulate matters with using of conversion formula for whole diapason of changing of influencing factors. It was showed that the magnitudes of values of efficiency coefficients of operation of particulate matter filter of diesel internal combustion engine for indicators of opacity and concentration of unburned hydrocarbons in exhaust gas which was obtained by direct measurements during bench motor tests and also mass hourly emission of particulate matter in exhaust gas flow which was obtained with using of the conversion formula, is not equal to each other for every individual operational regime of diesel engine. Calculation assessment and graphical illustration of relationship between magnitudes of this coefficients for opacity and emission of particulate matter for whole diapason of changing of influencing factors was carried out.

Introduction

The process of accident-free exploitation of power plants, namely vehicles, with piston internal combustion engine (PICE), namely diesel, is characterized by certain indicators of its ecological safety level [1]. One of the main of legislative normalized indicators of that level is mass hourly emission of particulate matter (PM) in exhaust gas (EG) flow G_{PM} in kg/h [2]. The methodological basis of ensuring of necessary ecological safety level of the process is appropriate ecological safety management system (ESMS) that was developed and described in [1, 3]. The main manner for solving of the task is decreasing of magnitude of G_{PM} by the way of processing of EG flow (neutralization), namely purification of EG flow from PM (filtration), and also the main instrument for such solving is diesel particulate matter filters (DPF) of different constructions [1]. Efficiency of functioning of ESMS should be assessed complexly with using of different known criteria based mathematical apparatuses [4], which should takes into account the value of G_{PM} .

Problem statement

The value of G_{PM} in accordance to normative documents should be obtained by experimental way thru using of gravimetric method and such measuring instruments as full- of partial-flow dilution tunnels [4]. It should be noted that cost of such complexes of measuring instruments of foreign manufacturing are in range from two hundreds to two millions US dollars. But nowadays in Ukraine there are only two such complexes and only one of them are certificated. It means that the most of scientists who works within ICE field of knowledge such measuring instruments is not available.

In connection of worded above problem the widespread becomes the conversion formulas of different types that allows to converts the magnitudes of indicators of opacity (coefficient of weakening of light flux N_D in %) and toxicity (volume concentration of un-

burned hydrocarbons C_{CH} in ppm) of EG into the magnitudes of G_{PM} value. Thus we are talking about the usage of readings of other measuring instruments that are more affordable and less expensive, namely opacimeters (around 2 thousand US dollars) and multicomponent gas analyzers (around 3 thousand US dollars). There are several known conversion formulas – Parsadanov [2], Alkidas [5], Muntean [6], MIRA [7], but the most widespread in Ukraine is the first of them.

The degree of purification of PICE EG flow from legislative normalized pollutant, namely PM, with using of aggregate of vehicle EG neutralization system, namely DPF, is characterized by magnitude of appropriate cleaning efficiency coefficient K_{CE} [1]. In case when such device executes the purification of PICE EG flow from several pollutants simultaneously, albeit with different efficiency, than interest of scientific and technical kind is the task about relationship between magnitudes of values of cleaning efficiency coefficients for different types of pollutants.

In case when the one ecological safety indicators of studied process forms the others and connected with each other by appropriate conversion formulas then worded above task takes the nature of methodical and instrumental errors [1] what are the relevance of the study. Besides the additional relevance such to the study gives the results of intensive development of alternative energetic, namely solar energy technologies that based on photovoltaic converters which based on nanostructured semiconductor materials [8 – 10].

Purpose of the study

Detection of relationship between magnitudes of cleaning efficiency coefficients of DPF for opacity and PM emission with using of conversion formula. *Object of the study* is efficiency of operation of system of neutralization of legislative normalized pollutants in diesel PICE EG flow, namely DPF. *Subject of the study* is relationship between magnitudes of indicators that char-

acterized object of the study which connected with each other by conversion formula.

Analysis of publications

In studies [1, 3] was developed ESMS of exploitation process of vehicle with PICE; in study [2] was proposed the conversion formula that developed based on results of analysis of data from certification tests of autotractor diesel engine SMD-31 on motor testing bench of Ricardo firm that equipped with full-flow dilution tunnel of AVL firm; in study [4] was investigated the certain metrological features of the conversion formula with using of mathematical apparatus of Pierson curves family; in studies [5 – 7] was proposed the other conversion formulas; in studies [8 – 10] contains the features of obtaining and researching of properties of nanostructured semiconductor materials based on InP, GaP and GaAs; in studies [11, 12] showed the experimentally obtained data about operational characteristics of DPF of nontraditional construction that used in this study as initial data for calculations and detects the differences in magnitudes of cleaning efficiency coefficients of DPF for opacity, emission of PM and unburned hydrocarbons in diesel PICE EG flow.

Analysis and calculated investigation of prof. I.V. Parsadanov conversion formula

The said conversion formula that described in monograph [2] and was transformed in this study for greater clarity has the following form.

$$G_{PM} = (a \cdot N_D + b \cdot N_D^2 + c \cdot C_{CH} + d \cdot C_{CH}^2) \cdot k, \text{ kg/h}; \quad (1)$$

$$a = 2,3 \cdot 10^{-3} \text{ kg}/(\text{h}\cdot\%); \quad b = 5,0 \cdot 10^{-5} \text{ kg}/(\text{h}\cdot\%^2);$$

$$c = 0,45 \cdot f, \text{ kg}/(\text{h}\cdot\text{ppm}); \quad d = 0,33 \cdot f^2 \text{ kg}/(\text{h}\cdot\text{ppm}^2);$$

$$f = \frac{4,78 \cdot 10^{-3} \cdot (G_{air} + G_f)}{0,7734 \cdot G_{air} + 0,7239 \cdot G_f}; \quad (2)$$

$$k = 10^{-3} \cdot (0,7734 \cdot G_{air} + 0,7239 \cdot G_f), \text{ kg/h}. \quad (3)$$

where G_f and G_{air} – mass hourly fuel and air consumption of PICE, kg/h.

In accordance with results of motor bench tests of autotractor diesel engine 2Ch10.5/12 exhaust system of which equipped with DPF that given in studies [11, 12] we can conclude the following points:

- magnitude of the value N_D changes in the range from 10 % (regime of minimal idle – regime A) to 72 % (regime of maximal torque – regime B);
- magnitude of the value C_{CH} changes in the range from 35 ppm (regime B) to 250 ppm (regime A);
- magnitudes of the values $K_{CE}(G_{PM})$, $K_{CE}(N_D)$ and $K_{CE}(C_{CH})$ are not equal each other for the same steady PICE operational regimes (points of PICE operational regimes field);
- magnitudes of the values N_D and C_{CH} has nonlinear impact on magnitude of the value G_{PM} because in formula (1) these values are both in the first and in the second degree;
- magnitude of the value N_D in the range that observed on motor test bench has much more significant impact on the value G_{PM} than the magnitude of the value C_{CH} .

Equation (1) is illustrated on Fig. 1 in form of isolines family with constant magnitudes of influencing factors.

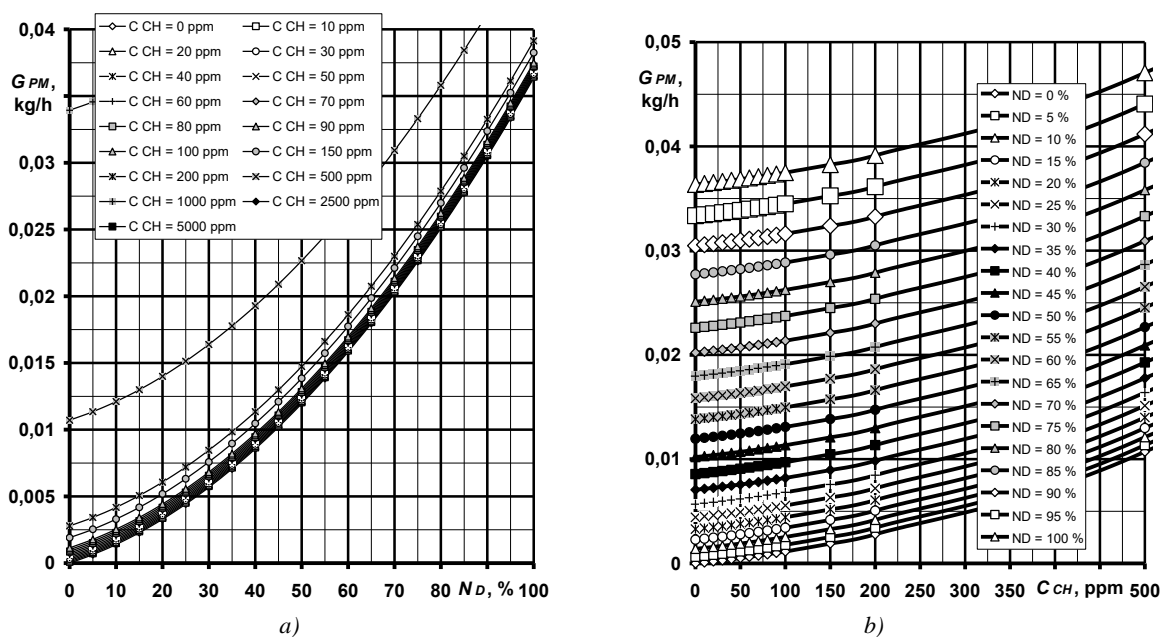


Fig. 1. Isolines of dependences of magnitude of mass hourly PM emission in PICE EG flow G_{PM} from the magnitudes of values coefficient of weakening of light flux N_D (a) and volume concentration of unburned hydrocarbons in EG flow C_{CH} (b)

Analysis of relationship between magnitudes of operation efficiency coefficients of DPF for opacity and PM emission

The data that experimentally obtained during bench motor tests of operational characteristics of DPF which was developed with the participation of the author of this study showed in studies [11, 12] and was used in the study as initial data.

Under the term “DPF operational efficiency coefficient for opacity, PM and unburned hydrocarbons emission” we understand the values that described by formulas (4) – (6).

$$K_{CE}(G_{PM}) = (G_{PM,ICE} - G_{PM,DPF}) / G_{PM,ICE} \cdot 100\% , (4)$$

$$K_{CE}(N_D) = (N_{D,ICE} - N_{D,DPF}) / N_{D,ICE} \cdot 100\% , (5)$$

$$K_{CE}(C_{CH}) = (C_{CH,ICE} - C_{CH,DPF}) / C_{CH,ICE} \cdot 100\% , (6)$$

where indexes *DPF* and *ICE* marks the values for the cases of PICE exhaust system of which equipped and not equipped with DPF respectively.

From the results of analysis of data from studies [11, 12] we can conclude the following points:

– studied DPF improves simultaneously indicators of EG opacity (N_D) and EG toxicity (C_{CH}), but together with declination of indicators of PICE fuel efficiency (from 5.2 % (regime A) to 3.7 % (regime B)) because it has the hydraulic resistance (from 5.2 kPa (regime A) to 11.4 kPa (regime B));

– magnitude of the value $K_{CE}(G_{PM})$ changes in the range from 75 % (regime B) to 32 % (regime A);

– magnitude of the value $K_{CE}(N_D)$ changes in the range from 62 % (regime B) to 28 % (regime A);

– magnitude of the value $K_{CE}(C_{CH})$ changes in the range from 9 % (regime B) to 14 % (regime A);

– magnitude of the value G_{PM} changes in the range from $22.7 \cdot 10^{-3}$ kg/h (regime B) to $2.7 \cdot 10^{-3}$ kg/h (regime A).

Dependences of magnitudes of the values $K_{CE}(G_{PM})$ and $K_{CE}(N_D)$ from magnitude of the value $N_{D,ICE}$ at invariant magnitude of the value $N_{D,DPF}$ for different diapasons of values of readings of opacimeter is presented on Fig. 2.

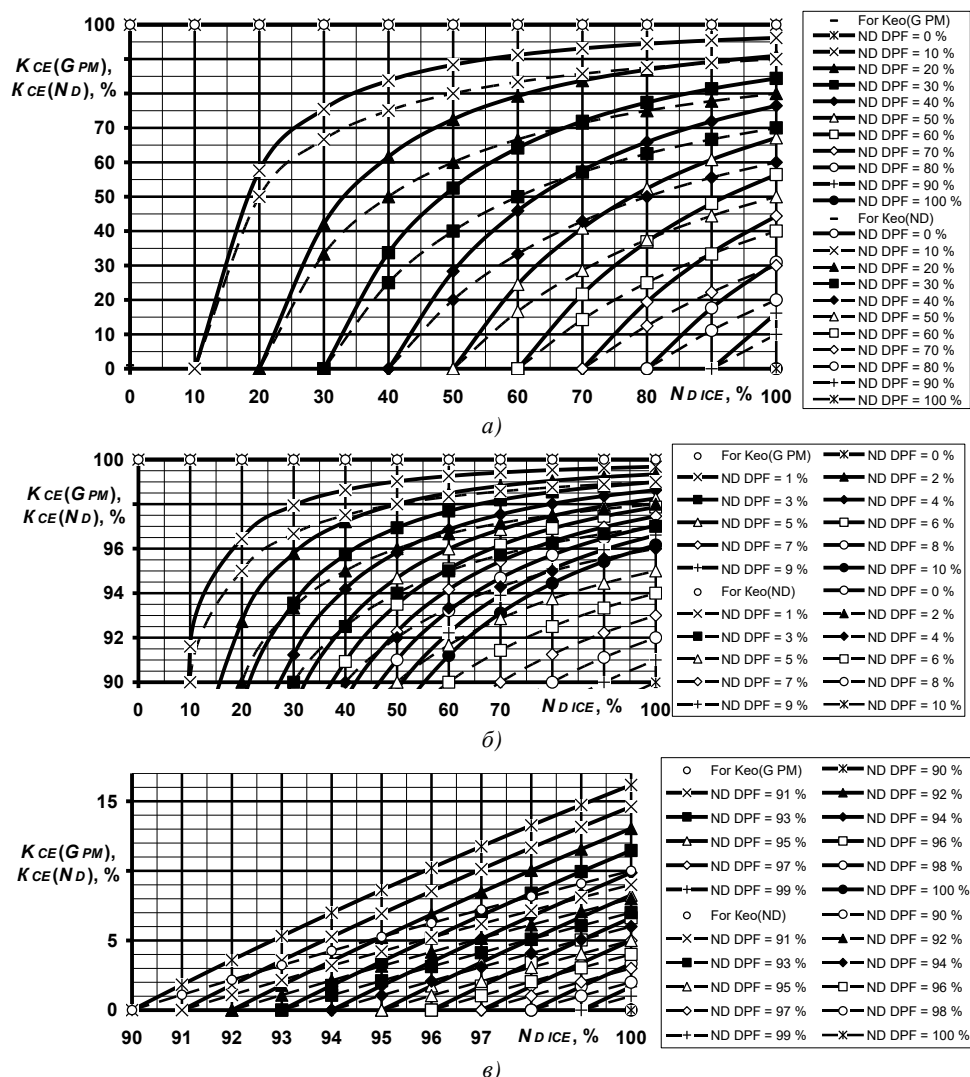


Fig. 2. Dependences of magnitudes of the values $K_{CE}(G_{PM})$ and $K_{CE}(N_D)$ from magnitude of the value $N_{D,ICE}$ at invariant magnitude of the value $N_{D,DPF}$ for different diapasons of values of readings of opacimeter

On the Fig. 2 it can be seen that magnitude of the values $K_{CE}(G_{PM})$ and $K_{CE}(N_D)$ in case of invariant values of readings of opacimeter and presence of DPF $N_{D,DPF}$ are depends from the values of readings of opacimeter and absence of DPF $N_{D,ICE}$ nonlinearly and also curvature of them decreases almost to zero due to decreasing of the value $N_{D,DPF}$ as well as difference between magnitudes of the values $K_{CE}(G_{PM})$ and $K_{CE}(N_D)$ that also increase due to increasing of value $N_{D,ICE}$.

On the Fig. 3 there are curves of dependences of relationship between magnitudes of values $K_{CE}(G_{PM})$ and $K_{CE}(N_D)$ from magnitudes of values $N_{D,ICE}$ (readings of opacimeter) at constant magnitude of value C_{CH} (readings of gas analyzer) that averaged on the step $\Delta N_D = 10\%$ for whole diapasons of change of magnitude of influencing factors $N_{D,ICE} = 0 - 100\%$ and $C_{CH} = 0 - 5000$ ppm. Also on Fig. 3 showed the dependence of value $\Delta N_D/N_D$ from value $N_{D,ICE}$.

On the Fig. 4 there are curves of dependences of

relationship between magnitudes of values $K_{CE}(G_{PM})$ and $K_{CE}(N_D)$ from magnitudes of values $N_{D,ICE}$ at constant magnitude of value $C_{CH} = 0$ ppm and constant magnitude of value $N_{D,DPF}$ and $N_D = 0 - 100\%$.

Thus, the Fig. 2 shows, that magnitudes of value $K_{CE}(N_D)$ always less than magnitudes of value $K_{CE}(G_{PM})$. It means that in the case of assessment of DPF operational efficiency with using of the magnitudes of value $K_{CE}(N_D)$ such efficiency will always be undervalued in comparison with the case of using of magnitudes of value $K_{CE}(G_{PM})$. The magnitude of such effect depends from magnitudes of value $N_{D,ICE}$ (there is direct correlation) as well as from magnitudes of value $N_{D,DPF}$ (there is reverse correlation).

The qualitative aspects of that effect which was determined on the Fig. 2 can be assessed quantitatively based on data showed on the Fig. 3. It can be seen that the magnitude of such effect depends from magnitudes of value C_{CH} and reaches of its maximum 168% at $C_{CH} = 0$ ppm, $N_{D,ICE} = 100\%$ and $K_{CE}(N_D) = \Delta N_D = 10\%$.

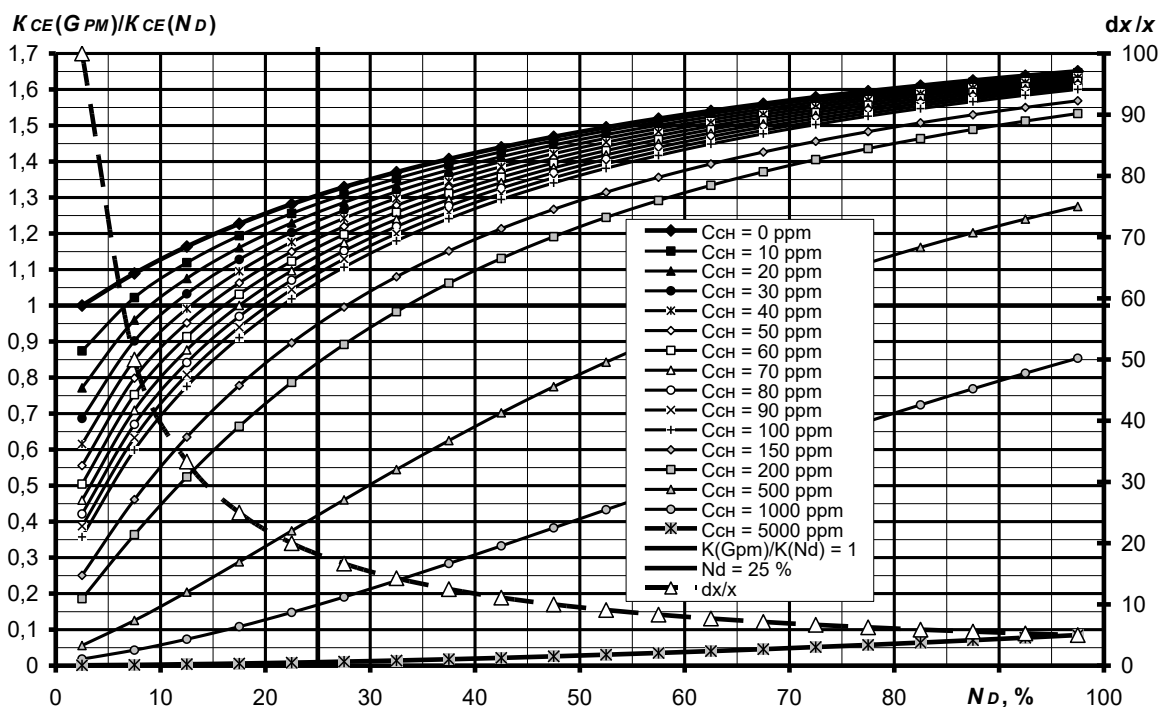


Fig. 3. Curves of dependences of ratio between magnitudes of values $K_{CE}(G_{PM})$ and $K_{CE}(N_D)$ from magnitudes of values $N_{D,ICE}$ at constant magnitude of value C_{CH} that averaged on the step $\Delta N_D = 10\%$ for whole diapasons of change of magnitude of influencing factors $N_{D,ICE} = 0 - 100\%$ and $C_{CH} = 0 - 5000$ ppm

On the Fig. 3 can be seen that magnitude of ratio of coefficients $K_{CE}(G_{PM})/K_{CE}(N_D)$ on every selected step $\Delta N_D = N_{D,ICE} - N_{D,DPF} = 10\%$ has nonlinear dependence from magnitudes of the value of $N_{D,ICE}$ and increase with it at any magnitudes of the value C_{CH} . The border curve at $C_{CH} = 0$ ppm is not contain the points with magnitudes less than 1.0 and maximum value 1.68 the observed ratio reaches at $N_{D,ICE} = 100\%$. Curvature of isolines decreases with increasing of magnitude of the value C_{CH} and at $C_{CH} = 500$ ppm comes to naught. Influence of magnitudes of the value

C_{CH} on magnitudes of the value observed ratio until $C_{CH} = 500$ ppm with increasing of magnitudes of the value $N_{D,ICE}$ are declining and at $C_{CH} > 500$ ppm on the contrary – rises. When $C_{CH} > 0$ ppm the observed ratio can take on values that less than 1.0 at with well-defined magnitudes of the value $N_{D,ICE}$. The coordinates of the points of equality of magnitudes of the values $K_{CE}(G_{PM})$ and $K_{CE}(N_D)$, that is $N_{D,ICE}$ and C_{CH} , has direct correlation together. From certain magnitude of the value C_{CH} (about 900 ppm) the value of observed ratio always has magnitudes less than 1.0.

The curve dx/x on the Fig. 3 is the ratio $\Delta N_D/N_{D,ICE}$ and reflexes the relative value of contribution of selected step of decreasing of absolute value of opacity of EG flow with using of DPF that detected as the difference in readings of opacimeter on the background of the current level of indicators of PICE EG opacity.

At worded above diapasons of values $N_{D,ICE}$ and C_{CH} the ratio $K_{CE}(G_{PM})/K_{CE}(N_D)$ mostly has magnitudes more than 1.0.

On the Fig. 4 can be seen, that ratio of the values $K_{CE}(G_{PM})$ and $K_{CE}(N_D)$ at constant values of readings of opacimeter and presence of DPF in PICE exhaust system $N_{D,DPF}$ are depends from values of readings of opacimeter and absence of DPF in PICE exhaust system $N_{D,ICE}$ nonlinearly for the case of when $N_{D,ICE} > N_{D,DPF}$ and $C_{CH} = 0$ ppm and always greater than 1.0 (that is belongs to the range 1.0 – 1.68) and increases with rising of value $N_{D,DPF}$ and declining of value $N_{D,ICE}$.

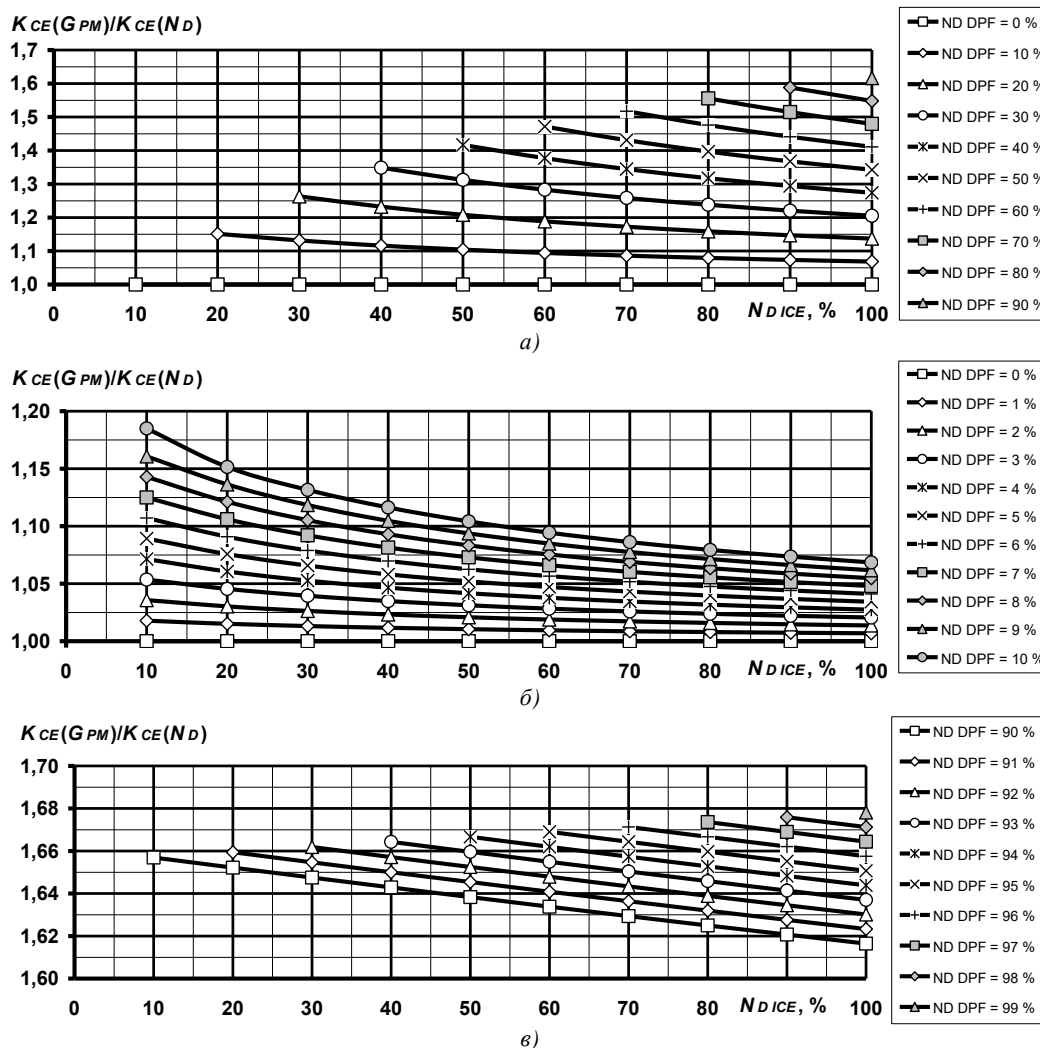


Fig. 4. Curves of dependences of relationship between magnitudes of values $K_{CE}(G_{PM})$ and $K_{CE}(N_D)$ from magnitudes of values $N_{D,ICE}$ at constant magnitude of value $C_{CH} = 0$ ppm and constant magnitude of value $N_{D,DPF}$ and $N_D = 0 - 100\%$

Conclusions

Thus, in this study were analyzed and numerical investigated the conversion formula of prof. I.V. Parsadanov about the influence of indicators of PICE EG opacity and toxicity on magnitude of value of PM mass hourly emission in diesel engine EG flow.

It was showed that the magnitudes of values of efficiency coefficients of operation of DPF of diesel ICE for indicators of opacity and concentration of unburned hydrocarbons in EG which was obtained by

direct measurements during bench motor tests and also mass hourly emission of PM in EG flow which was obtained with using of the conversion formula, is not equal to each other for every individual operational regime of diesel engine.

Calculation assessment and graphical illustration of relationship between magnitudes of this coefficients for opacity and emission of PM for whole diapason of changing of influencing factors was carried out.

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scientific work of young scientists, which is carried out at the expense of the general fund of the state budget of Ukraine of Berdyansk State Pedagogical University «Development of technology for assessing the quality and safety of nanotechnologies products during their life cycle» (State Registration № 0117U003860, 2017 – 2018) and also science and research work of Applied Mechanic Department of National University of Civil Protection of Ukraine «Methodological support for criteria-based assessment of ecological system management system of power plants of emergency rescue vehicles functioning process efficiency» (State Registration № 0117U003860, 2017 – 2018).

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ДОСЛІДЖЕННЯ СПІВВІДНОШЕННЯ КОЕФІЦІЄНТІВ ЕФЕКТИВНОСТІ РОБОТИ ФІЛЬТРА ТВЕРДИХ ЧАСТИНОК ДИЗЕЛЬНОГО ДВЗ. ЧАСТИНА 1: ВИКИД ТВЕРДИХ ЧАСТИНОК І ДИМНІСТЬ

О. М. Кондратенко

Проаналізовано і розрахунково досліджено формулу перерахунку проф. І.В. Парсаданова як одного з актуальних питань метрологічних особливостей процесу отримання значень масового годинного викиду твердих частинок поршневого ДВЗ на моторному випробувальному стенду, не обладнаному тунелем розведення. Метою дослідження є виявлення співвідношення значень коефіцієнтів ефективності роботи фільтра твердих частинок дизельного поршневого ДВЗ за викидами твердих частинок та димністю відпрацьованих газів із застосуванням формули перерахунку для всього діапазону зміни значень впливаючих факторів. Показано, що значення коефіцієнтів ефективності роботи фільтра твердих частинок дизельного двигача внутрішнього згорання за показниками димності й концентрації незгорілих вуглеводнів у відпрацьованих газах, отримані прямими вимірюваннями у ході стендових моторних випробувань, а також масового годинного викиду твердих частинок з потоком відпрацьованих газів, отримані за вказаною формулою перерахунку, не збігаються для кожного стаціонарного режиму його роботи. Розрахунково оцінено та проілюстровано графічно співвідношення значень цих коефіцієнтів за димністю і викидом твердих частинок для всього діапазону зміни впливаючих факторів.

ИССЛЕДОВАНИЕ СООТНОШЕНИЯ КОЭФФИЦИЕНТОВ ЭФФЕКТИВНОСТИ РОБОТЫ ФИЛЬТРА ТВЕРДЫХ ЧАСТИЦ ДИЗЕЛЬНОГО ДВС. ЧАСТЬ 1: ВЫБРОС ТВЕРДЫХ ЧАСТИЦ И ДЫМНОСТЬ

А. Н. Кондратенко

Проанализирована и расчетно исследована формула пересчета проф. И.В. Парсаданова, как один из актуальных вопросов метрологических особенностей процесса получения значений массового часового выброса твердых частиц поршневым ДВС на моторном испытательном стенде, не оборудованном тунелем разбавления. Целью исследования является выявление соотношения значений коэффициентов эффективности работы фильтра твердых частиц дизельного поршневого ДВС по выбросу твердых частиц и дымностью отработавших газов с применением формулы пересчета для всего диапазона изменения значений влияющих факторов. Показано, что значения коэффициентов эффективности работы фильтра твердых частиц дизельного двигателя внутреннего сгорания по показателям дымности и концентрации несгоревших углеводородов в отработавших газах, полученные прямыми измерениями при стендовых моторных исследованиях, а также массового часового выброса твердых частиц с потоком отработавших газов, полученные по упомянутой формуле пересчета, не совпадают для каждого стационарного режима работы двигателя. Расчетно оценено и проиллюстрировано графически соотношение значения этих коэффициентов по дымности и выбросу твердых частиц для всего диапазона влияющих факторов.