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INVESTIGATION OF THE INFLUENCE OF THE DISPERSE COMPOSITION OF DIESEL PARTICULATE MATTER ON THE EFFICIENCY OF THEIR RATIONING AND NEUTRALIZATION BY SOOT FILTERS

Purpose. Increase in the efficiency of control of diesel particulate matter in the study of the operation of diesel particulate filters by taking into account their particulate composition. **Methods.** Analysis and synthesis of information in the study of the structure and properties of diesel particulate matter, mathematical modeling in assessing the effectiveness of control and neutralization of particles with soot filters, statistical processing of experimental data, a computational experiment in conducting a comprehensive assessment of the efficiency of the diesel particulate filter. **Results.** The structure, toxicological properties, dispersed composition and quantitative characteristics of diesel particulate matter are analyzed. The principle of the action of the particulate filter is described. The functions of the distribution densities of countable, surface and mass concentrations of solid particles of various fractions: nuclei, accumulation, large particles are considered. A method for the complex evaluation of the efficiency of a diesel particulate filter on the basis of indices of countable, surface and mass concentrations of particles has been developed. A complex analysis of the efficiency of the diesel particulate filter was carried out. **Conclusions.** The necessity of taking into account the dispersed composition of diesel solid particles in the analysis of their properties, rationing and the evaluation of the efficiency of the diesel particulate filter is substantiated. It was found that with a high efficiency of reducing the total mass of solid particles in the particulate filter - 93.8%, the amount, surface area and mass of fine particles with dimensions of 20-40 nm significantly increase - 4.2, 1.9 and 2.55 times, respectively. The increase in the relative fraction of fine particles after passing through the particulate filter is 72%.

Keywords: diesel engine, brake tester, exhaust gases, particulate matter, concentration, mass emission, particulate filter, efficiency

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ДОСЛІДЖЕННЯ ВПЛИВУ ДИСПЕРСНОГО СКЛАДУ ДИЗЕЛЬНИХ ТВЕРДИХ ЧАСТИНОК НА ЕФЕКТИВНІСТЬ ЇХ НОРМУВАННЯ ТА НЕЙТРАЛІЗАЦІЇ САЖОВИМИ ФІЛЬТРАМИ

Мета. Підвищення ефективності контролю дизельних твердих частинок при дослідженні роботи сажових фільтрів за рахунок врахування їх дисперсного складу. **Методи.** Аналіз і синтез інформації, математичне моделювання, статистична обробка даних, розрахунковий експеримент. **Результати.** Проаналізовано: структуру, дисперсний склад і кількісні характеристики твердих частинок. Розроблено методику комплексної оцінки ефективності роботи сажового фільтру за показниками лічильної, поверхневої та масової концентрації частинок. Проведено комплексний аналіз ефективності роботи сажового фільтру вантажного автомобіля. **Висновки.** Обгрунтовано необхідність врахування дисперсного складу дизельних твердих частинок при аналізі їх властивостей, нормуванні та оцінюванні ефективності нейтралізації сажовими фільтрами. Встановлено, що при високій ефективності зниження сумарної маси твердих частинок в сажовому фільтрі кількість, площа поверхні і маса дрібнодисперсних частинок з розмірами 20 ... 40 нм суттєво зростають.

Ключові слова: дизельний двигун, гальмівний стенд, вихлопні гази, тверді частинки, концентрація, масовий викид, сажовий фільтр, ефективність

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ИССЛЕДОВАНИЕ ВЛИЯНИЯ ДИСПЕРСНОГО СОСТАВА ДИЗЕЛЬНЫХ ТВЕРДЫХ ЧАСТИЦ НА ЭФФЕКТИВНОСТЬ ИХ НОРМИРОВАНИЯ И НЕЙТРАЛИЗАЦИИ САЖЕВЫМИ ФИЛЬТРАМИ

Цель. Повышение эффективности контроля дизельных твердых частиц при исследовании работы сажевых фильтров за счет учета их дисперсного состава. **Методы.** Анализ и синтез информации, математическое моделирование, статистическая обработка данных, расчетный эксперимент. **Результаты.** Проанализированы: структура, дисперсный состав и количественные характеристики твердых частиц. Разработана методика комплексной оценки эффективности работы сажевого фильтра по показателям счетной, поверхностной и массовой концентраций частиц. Проведен комплексный анализ эффективности работы сажевого фильтра грузового автомобиля. **Выводы.** Обоснована необходимость учета дисперсно-

го состава дизельных твердых частиц при анализе их свойств, нормировании и оценке эффективности нейтрализации сажевыми фильтрами. Установлено, что при высокой эффективности снижения суммарной массы твердых частиц в сажевом фильтре количество, площадь поверхности и масса мелкодисперсных частиц с размерами 20…40 нм существенно возрастают.

Ключевые слова: дизельный двигатель, тормозной стенд, выхлопные газы, твердые частицы, концентрация, массовый выброс, сажевый фильтр, эффективность

Introduction

Diesel particulate filters are the most common means of diesel particulate matter (PM) neutralization - the second largest (after the NO_x) pollutant in the exhaust of a diesel engine [1]. To evaluate the effectiveness of the filter the criterion of the relative decline of the mass concentration - C_m (or emission) of PM as a result of the filtering process is traditionally used. This approach to the evaluation of the effectiveness of diesel particulate filters is not perfect because it does not consider changes in the number concentration - C_n (the amount of PM per unit volume) and surface - concentration C_s (the total area of the surface of PM per unit volume) of PM. At the same time the value of C_n and C_s are important toxicological indicators of the extent of the negative impact of diesel particles on the human health and the environment.

A number of of experimental researches [2-7] show diesel particulate filters with high efficiency, determined by the criterion C_m, miss a significant amount of fine particles, including the most dangerous - nanoparticles (diameter less than 50 nm [8,9]) with a high penetration ability to the human respiratory system. The article offers a comprehensive approach to the evaluation of the effectiveness of particulate filters using 3 criteria - values C_m, C_n and C_s.

Methods of research

The aim of this study is to provide a comprehensive evaluation of the efficiency of diesel particulate filters in terms of counting, surface and mass concentrations of PM in accordance with their disperse composition. To achieve this goal the following tasks are performed:

1) the study of the structure and toxicological properties of the diesel particle;

2) analysis of the experimental data on the number, surface area and mass of diesel particulate of various sizes;

3) development of a method of complex estimation of efficiency of the diesel particulate filter; 4) study of the efficiency of the filter using the developed technique.

The structure and toxicological characteristics of the diesel particles.

PM is multicomponent formation composed of the following elements: diesel soot (product of fuel pyrolysis), soluble organic fraction - SOF (fuel and oil hydrocarbons - not burned, condensed and adsorbed on the soot particles surface), sulfates (salts of sulfuric acid) and other inclusions (depreciation products, ash from additives, etc.). The relative proportion of these elements in the PM depends on the mode of diesel and vary in wide ranges [10] (Fig. 1).

Negative impact of PM on the environment and humans is caused in three directions:

- particles when inhaled irritate respiratory tract and in case of a chronic exposure cause pulmonary diseases; PM generally have dimensions of 0.1 ... 0.54 mm in diameter and can reach the alveoli of the lungs or can be delayed in the nasal sinuses, trachea or bronchi;

- particles can carry carcinogenic substances that are adsorbed on their surface (1 g of carbon (soot) has a surface area of about 75 m^2);

- the presence of suspended particles in the air impairs visibility on roads (automobile exhaust become visible when the concentrations of particles in exhaust gas are 130 mg/m^3 and more); particle size of 0.15 microns may be suspended in the air for about 8 days.

In the 90s of the twentieth century extensive research conducted on toxicology of diesel EG in general and toxicology of diesel particles in particular. World Health Organization (WHO), the International Agency for Re-
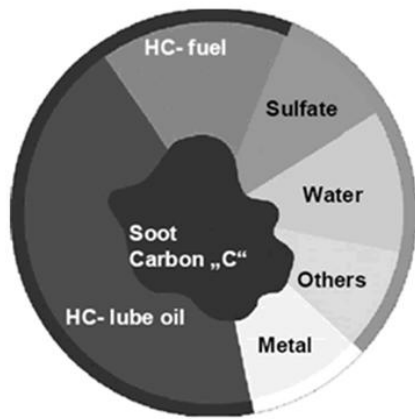
Fig. 1 – The components included in the PM, and their relative share

search on Cancer (IARC) [11], USA Health Effect Institute (HEI) [12], USA Environmental Protection Agency (EPA) [13, 14] made a conclusion that diesel EG including the PM is the cause of increase of the general morbidity and mortality. Especially dangerous diesel PM are for people working in close proximity to sources of diesel particles emissions, for persons with chronic respiratory diseases, diseases of the cardiovascular system, immune system disorders, for children.

Symptoms of effects caused by short-term exposure of low levels of diesels EG are determined by medical research of occupational groups that regularly exposed to EG, such as miners, workers of bus depot, shipyards, locomotive depot. The list of emerging deviations include: inflammation of the mucous membranes of the eyes, headache, dizziness, nausea, weakness, tinnitus, oppression of the lung activity, coughing, shortness of breath, etc. After leaving the area of diesel facility operation these symptoms mostly disappear quickly without any significant deviations.

PM and their extracts are found to be mutagenic for bacteria and cell cultures, such as human lymphocytes, reproductive cells [12-15]. Currently carcinogenic activity of PM becomes more evident. Diesel particles are classified by the International Agency for Cancer Research (IARC) to group of (probably) carcinogenic to humans [16] and the US Environmental Protection Agency determined as substances that may be carcinogenic with high probability [11]. As the result in more than 30 research papers carried out by the USA Health Effect Institute in different regions for different professional groups, smokers and nonsmokers, it was established that long-time professional

impact of diesel EG on human leads to 40 % increase of the relative risk of lung cancer [17]. Largely, due to particles diesel EG have such characteristics. It is associated with the PM properties, particularly their high dispersion and chemical composition.

Comparison of particles sedimentation in different parts of the respiratory system with dispersed composition of diesel aerosol proves that PM is potentially dangerous pollutant of lungs because of their small size. Moreover, the health risk of particles with a diameter 0,1 ... 1 mm, the mass concentration up to 80%, and the rate of sedimentation in the lungs - 40%, are on a par with the particles with a diameter less than 0.1 microns, whose number concentration can reach several tens of millions of units per 1 m^3 with a coefficient of sedimentation in the lungs 70%.

In general, in lungs of adult while breathing at rest from 12 to 20% by weight of diesel particles contained in inhaled air is deposited. In childhood, the proportion of PM that are deposited in the lungs is higher than in adults, and the peak of this relationship is at age of five. [18]. Thus, we can assume that children are the second group of risk after people working in the immediate proximity of PM emission sources.

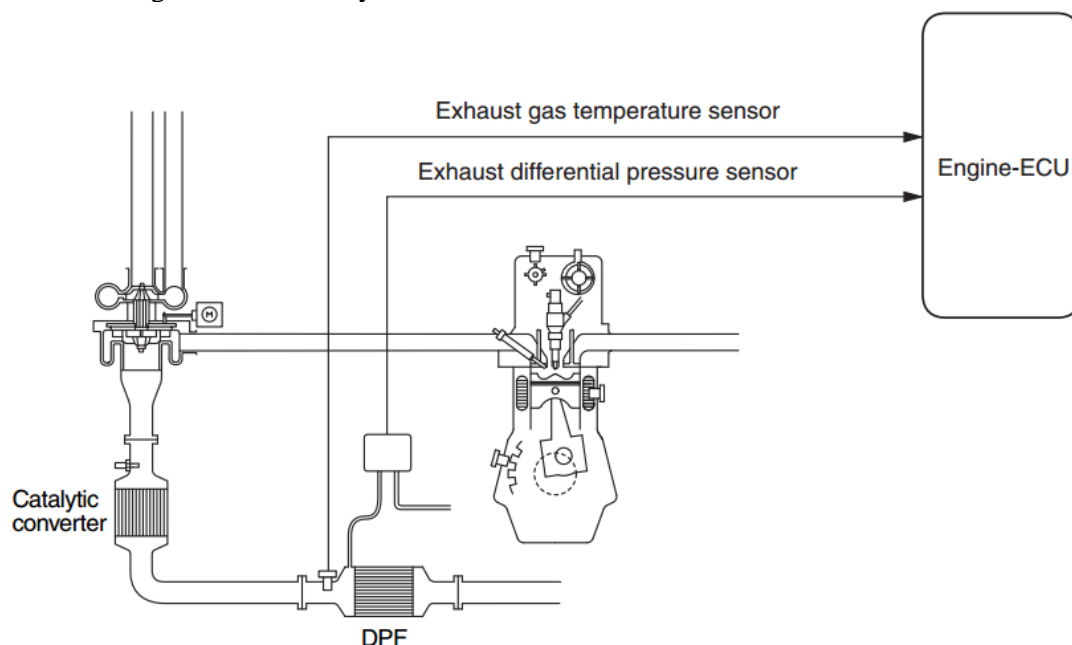**Action principle of the diesel particulate filter.**

Diesel particulate filtering was first considered in the 1970s due to concerns regarding the impacts of inhaled particulates. Particulate filters have been in use on non-road machines since 1980, and in automobiles since 1985. Historically medium and heavy duty diesel engine emissions were not regulated until 1987 when the first California Heavy Truck rule was

introduced capping particulate emissions at 0.60 g/BHP Hour. Since then, progressively tighter standards have been introduced for light- and heavy-duty roadgoing diesel-powered vehicles and for off-road diesel engines. Similar regulations have also been adopted by the European Union and some individual European countries, most Asian countries, and the rest of North and South America.

While no jurisdiction has explicitly made filters mandatory, the increasingly stringent emissions regulations that engine manufactures must meet mean that eventually all on-road diesel engines will be fitted with them. In the European Union, filters are expected to be necessary to meet the Euro VI heavy truck engine emissions regulations currently under discussion and planned for the 2012-2013 time frame. In 2000, in anticipation of the future Euro 5 regulations PSA Peugeot Citroën became the first company to make filters standard on passenger cars.

Wall-flow diesel particulate filters usually remove 85% or more of the soot, and under certain conditions can attain soot removal efficiencies approaching 100%. Some filters are single-use, intended for disposal and replacement once full of accumulated ash. Others are designed to burn off the accumulated particulate either passively through the use of a catalyst or by active means such as a fuel burner which heats the filter to soot combustion temperatures (Fig. 2).

Fig. 2 – The scheme of installation of the diesel particulate filter in the exhaust system of a diesel engine

Diesel engines produce a variety of particles during combustion of the fuel/air mix due to incomplete combustion. The composition of the particles varies widely dependent upon engine type, age, and the emissions specification that the engine was designed to meet. Two-stroke diesel engines produce more particulate per unit of power than do four-stroke diesel engines, as they burn the fuel-air mix less completely.

Diesel particulate matter resulting from the incomplete combustion of diesel fuel produces soot (black carbon) particles. These particles include tiny nanoparticles—smaller than a thousandth of a millimeter (one micron).

Soot and other particles from diesel engines worsen the particulate matter pollution in the air and are harmful to health. New particulate filters can capture from 30% to greater than 95% of the harmful soot. With an optimal diesel particulate filter (DPF), soot emissions may be decreased to 0.001 g / km or less.

The quality of the fuel also influences the formation of these particles. For example, a high sulfur content diesel produces more particles. Lower sulfur fuel produces fewer particles, and allows use of particulate filters. The injection pressure of diesel also influences the formation of fine particles.

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Filters require more maintenance than catalytic converters. Ash, a byproduct of oil consumption from normal engine operation, builds up in the filter as it cannot be converted into a gas and pass through the walls of the filter. This increases the pressure before the filter. Regular filter maintenance is a necessity.

Experimental data on the C_m, C_n and C_s value.

The results of experimental studies on the particle size influence at the number, sur-

face and mass concentration, generalized for different types of diesel engines, are shown in Fig. 3 [19].

When considering the dispersed composition of PM three particle size ranges can be distinguished: fraction of nuclei - 3 ... 30 nm; fraction of accumulation - 30 ... 500 nm and the fraction of large particles - diameter greater than 1000 nm (1 micron). Presented in Fig. 3 diagrams of density distribution functions for
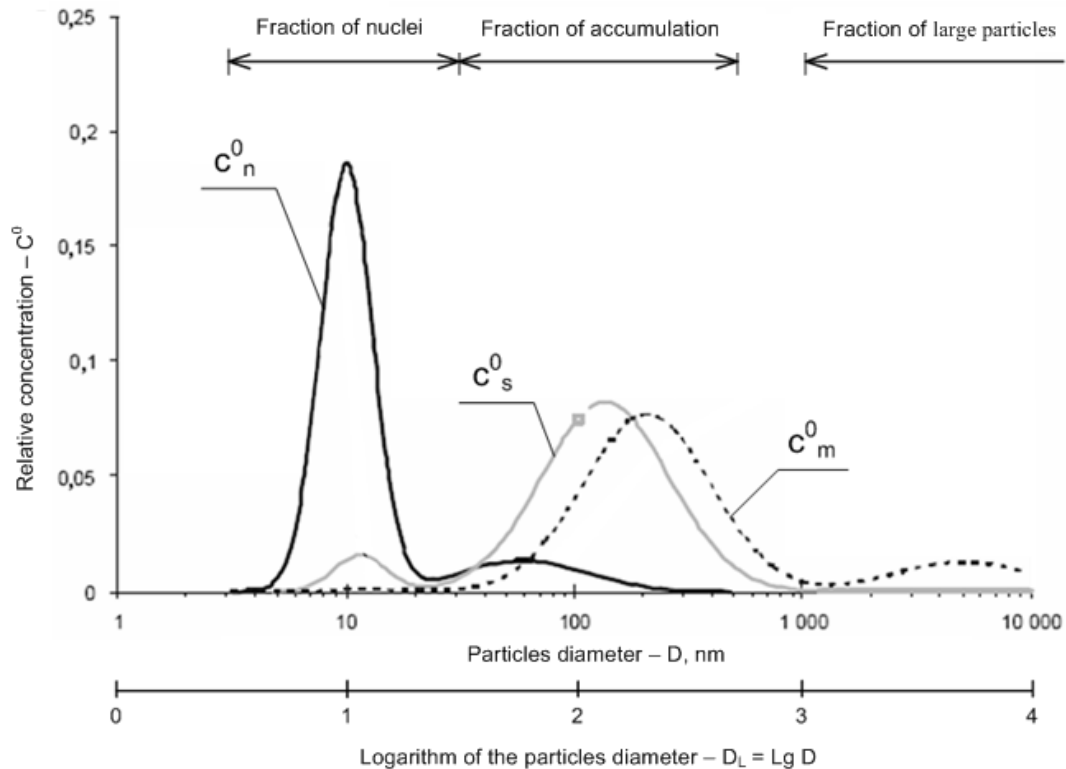
Fig. 3 – The function of the density distribution of the relative number, surface and mass concentrations of PM

the relative number, surface and mass concentrations of PM - c^0_n, c^0_s and c^0_m reflect the following properties of diesel particles:

- a fraction of nuclei constitute the greater number of the PM - 90% of the total, 20% of the total surface area and 5% of the total mass; 80% of particles and 15% of the total surface area accounts for a range of 10 ± 5 nm, wherein curves c^0_n and c^0_s have maximum;

- relative proportion of particles of accumulation fractions constitute 20% of the total, 80% of the total surface area and 85% of the total mass; in the fraction the highest number of particles (12%) is in the range of 30 ... 100 nm, curves c^0_s and c^0_m take the maximum values within the ranges 100 ... 200 nm and 150 … 300 nm respectively;

- a fraction of large particles is characterized by the lowest values of number - 2%, the total surface area - 1% and mass - 4%.

The data presented in Fig. 3, in addition to information about values of c^0_n, c^0_s and c^0_m functions reflect their relationship and make it possible to change one function to evaluate changes in the other two. This property was used in developing the methodology presented below.

Methods of integrated assessing of the efficiency of diesel particulate filter

The efficiency of the filter usage is proposed to assess along the 3 indicators of relative decline of number, surface and mass concentrations, defined by the following generalized formula:

$$\Im_{p} = \frac{(C_{p})_{n/f} - (C_{p})_{f}}{(C_{p})_{n/f}} \cdot 100\%, \qquad (1)$$

where: $\Im_{p}$ - the efficiency of the filter as measured by p, which is defined as following: number - n, surface - s or mass - m of PM; $(C_{p})_{n/f}$ and $(C_{p})_{f}$ - total relative concentrations of particles within the size range under consideration, both in the absence of diesel particulate filter and while its using.

The values of C_{p} are determined by the formula:

$$C_{p} = \int_{D_{L_{1}}}^{D_{L_{2}}} c_{p}(D_{L}) \cdot dD_{L}, \qquad (2)$$

where: D_{L1}, D_{L2} – initial and final value of the size range (diameters) of PM on a scale of base-10 logarithm; $c_{p}(D_{L})$ – the probability density function of indicator p.

$c_{p}(D_{L})$ function is determined on the basis of generalized distribution functions c^{0}_{n}, c^{0}_{s} and c^{0}_{m}, , shown in Fig. 3, as well as the well-known experimental distribution function of one of the indicators (denoted p^{*}) - $c^{r}_{p*}(D_{L})$:

$$c_{p}(D_{L}) = K_{r}(D_{L}) \cdot K_{p}(D_{L}) \cdot c^{r}_{p*}(D_{L}), \quad (3)$$

where: $K_{r}(D_{L})$ - correction function of experimental data; $K_{p}(D_{L})$ - a function of the transition from indicator p * to indicator p.

Functions K_{r} и K_{p} is obtained by using the following expressions:

$$K_{r}(D_{L}) = \frac{c^{r}_{p*}(D_{L})}{c^{0}_{p}(D_{L})}; \qquad (4)$$

$$K_{p}(D_{L}) = \frac{c^{0}_{p}(D_{L})}{c^{0}_{p*}(D_{L})}; \qquad (5)$$

where: $c^{0}_{p}(D_{L})$ - generalized value of function of the density distribution (probability density function) for the indicator p; $c^{0}_{p*}(D_{L})$ - generalized value of probability density function for the indicator p *.

For example, if the experimental dependence $c^{r}_{n}(D_{L})$ is known, than a density distribution function of mass concentration determined by the expression (3) is as follows:

$$c_{m}(D_{L}) = K_{r}(D_{L}) \cdot K_{m}(D_{L}) \cdot c^{r}_{n}(D_{L}) =$$
$$= \frac{c^{r}_{n}(D_{L})}{c^{0}_{n}(D_{L})} \cdot \frac{c^{0}_{m}(D_{L})}{c^{0}_{n}(D_{L})} \cdot c^{r}_{n}(D_{L}) \qquad (6)$$

Results and discussion

Comprehensive evaluation of the freight car diesel particulate filter with known correlation between number concentration and particle size carried out using proposed method [3] (Fig. 4).

Two areas are identified in the researched range of particle sizes - 20 ... 600 nm: 1st - 20 ... 40 nm - an area where the number concentration increased after the filter application, 2nd - - 40 ... 600 nm - an area where the number concentration decreased.
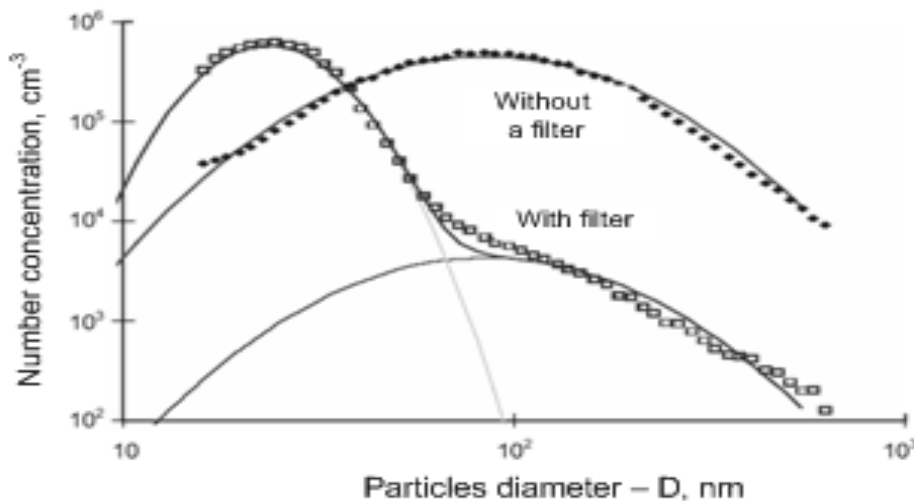

Fig. 4 – The results of experimental research of PM number concentration

Fig. 5 and 6 present the results of determining the c_s and c_m functions, obtained using the expression (3), and indicators of the filter efficiency calculated using the expression (1). Method of trapezoids was used for integrals calculations (2) [20].
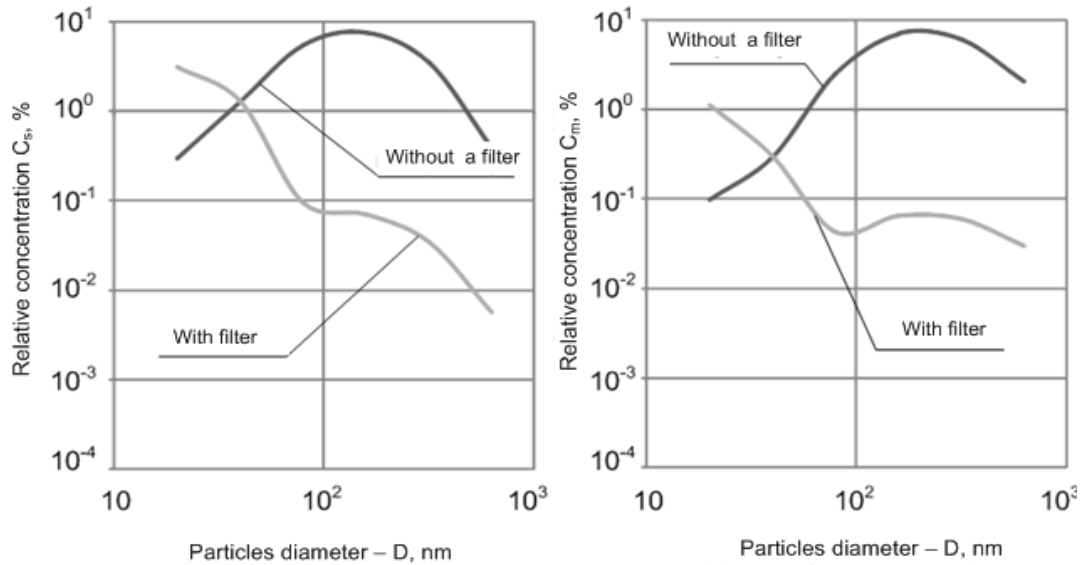
Fig. 5 – The values of the function of the density distribution c_s and c_m for the studied filter
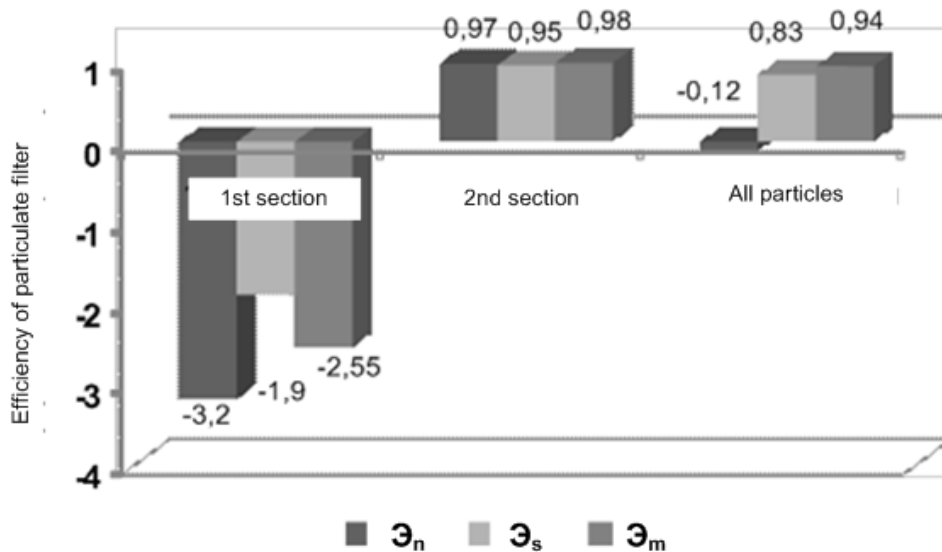
Fig. 6 – Efficiency indicators of studied diesel particulate filter

The research results show:

- The amount of PM: at the 1st section increased 4.2 times, at the 2nd section reduced by 30.5 times, over the whole range increased by 12%;

- the surface area of the particles at the 1st section increases 2.9 times, at the 2nd section reduced by 18.2 times, over the whole range decreased by 5.9 times;

- the mass of PM: at the 1st section - increases 3.55 times, at the 2nd section - reduced by 49.1 times, over the whole range reduced by 16.1 times.

Thus, with a substantial reduction of the total surface and mass of all particles their total number increases through the increase of the number of fine particles measuring 20 ... 40 nm. The relative proportion of these particles passing through the filter increases from 26% to 98%.

Conclusions

1. Fractional composition of captured particles is necessary to take into consideration while evaluating the efficiency of the particulate filter.

2. Developed a method of a complex estimation of efficiency of the diesel particulate filter according to three criteria: the counting, the surface and the mass concentration of particulate matter in view of the particulate composition.

3. Comprehensive assessment of the efficiency of the studied filter showed the significant decrease of the mass concentration of the total PM flow – by 93.8%, while there was a significant increase of number – 4.2 times, surface area – 1.9 times and mass – 2.55 times of the fine particles measuring 20 ... 40 nm.

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