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INCREASE OF HIGH-SPEED QUALITIES AND ECONOMIC EFFICIENCY OF USE SYSTEMS OF ECOLOGICAL DIAGNOSTICS DIESEL ENGINES - MICROTUNNELS

Purpose. Reducing the duration and cost of procedures for environmental diagnostics of diesel power plants by increasing the speed of measurements of normalized PM index – average operating emissions of particulate matters with exhaust gases of diesel engines. **Methods.** Analysis and synthesis of information, mathematical modeling, experimental studies, calculation experiment. **Results.** In accordance with the requirements of the international standard ISO 8178, a method of accelerated measurement (MAM) of the PM index is proposed, which is characterized by the maximum allowable sample filtration rate and the minimum allowable masses of particulate matter in the filters, the use of which can significantly improve the economic efficiency of applying microtunnels: with single- and multi-filter sampling methods - in 3,1 ... 4,1 times and in 5,3 ... 7,1 times, respectively. **Conclusions.** Compared to the most common methods of control of particulate matter emissions that are realized in mini and microtunnels of Perkins, AVL, Mitsubishi companies, they are characterized by higher speed and economic efficiency of use - indicators that are of great importance in testing high-power diesel engines – locomotive diesel, ships and others. It is substantiated that the use of MAM allows to shorten the duration and cost of environmental testing of mainline diesel engines - 2TE116 and shunting - TEM-2 locomotives: certification tests - by 9 ... 28%, which is 0.2 ... 0.7 h and 0, 8 ... 1,5 thousand UAH; research tests - 43 ... 53%, which is 1.7 ... 3.0 h and 4.0 ... 7.5 thousand UAH. With the reduction of the actual emission levels of particulate matter with the exhaust gases of the diesel engine, the efficiency of the use of MAM increases.

Keywords: diesel, exhaust gases, particulate matter, ecological compatibility, microtunnel, accelerated measurement, efficiency

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ПІДВИЩЕННЯ ШВИДКОСТІ ТА ЕКОНОМІЧНОЇ ЕФЕКТИВНОСТІ ВИКОРИСТАННЯ СИСТЕМ ЕКОЛОГІЧНОГО ДІАГНОСТУВАННЯ ДИЗЕЛІВ-МІКРОТУНЕЛІВ

Мета. Зменшення тривалості та вартості процедур екологічного діагностування дизельних силових установок різного призначення за рахунок підвищення швидкості вимірювань нормованого показника РМ – середньоексплуатаційного викиду твердих частинок з відпрацьованими газами дизеля. **Методи.** Аналіз та синтез інформації щодо нормативної бази, процедур випробувань, обладнання та рахункових методик для проведення екологічних випробувань дизелів; математичне моделювання та експериментальні дослідження параметрів ефективності процедури екологічного діагностування дизеля – тривалості, потрібної кількості палива, вартості; розрахунковий експеримент з оцінки доцільності підвищення швидкості виміру показника РМ. **Результати.** Відповідно до вимог міжнародного стандарту ISO 8178 запропоновано спосіб прискореного виміру (СПВ) показника РМ, який характеризується максимальною допустимою швидкістю фільтрації проби – 100 см/м та мінімально допустимими масами навішувань твердих частинок на фільтрі: 0,25 мг – при однофільтровому методі відбору проб твердих частинок та 0,17 мг – при багатофільтровому методі. Використання СПВ дозволяє суттєво покращити економічну ефективність застосування цих методів в мікротунелі – в 3,1 ... 4,1 рази та в 5,3 ... 7,1 разів, відповідно. **Висновки.** Порівняно з найбільш поширеними сьогодні способами контролю викидів твердих частинок, які реалізуються в міні- та мікротунелях фірм Perkins, AVL, Mitsubishi, СПВ характеризується більш високими швидкістю та економічною ефективністю використання – показниками, які мають високу значимість при випробуваннях дизелів великої потужності – тепловозних, суднових та ін. Обґрунтовано, що використання СПВ дозволяє скоротити тривалість та вартість екологічних випробувань дизелів магістрального – 2TE116

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та маневрового – ТЕМ-2 тепловозів: сертифікаційних випробувань - на 9 ... 28%, що становить 0,2 ... 0,7 год і 0,8 ... 1,5 тис. грн.; дослідницьких випробувань – на 43 ... 53%, що складає 1,7 ... 3,0 год і 4,0 ... 7,5 тис. грн. Зі зменшенням фактичних рівнів викидів твердих частинок з вихлопними газами дизеля, ефективність використання СПВ зростає.

Ключові слова: дизель, відпрацьовані гази, тверді частинки, екологічність, мікротунель, прискорений вимір, ефективність

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ПОВЫШЕНИЕ БЫСТРОДЕЙСТВИЯ И ЭКОНОМИЧЕСКОЙ ЭФФЕКТИВНОСТИ ИСПОЛЬЗОВАНИЯ СИСТЕМ ЭКОЛОГИЧЕСКОГО ДИАГНОСТИРОВАНИЯ ДИЗЕЛЕЙ - МИКРОТУННЕЛЕЙ

Цель. Уменьшение продолжительности и стоимости процедур экологического диагностирования дизельных силовых установок за счет повышения скорости измерений нормированного показателя РМ – среднеэксплуатационного выброса твердых частиц с отработавшими газами дизеля. **Методы.** Анализ и синтез информации, математическое моделирование, экспериментальные исследования, расчетный эксперимент. **Результаты.** Предложен способ ускоренного замера (СПВ) показателя РМ, который характеризуется максимально допустимой скоростью фильтрации пробы и минимально допустимыми массами навесок твердых частиц на фильтрах, использование которого позволяет существенно повысить экономическую эффективность использования микротуннелей. **Выводы.** Обосновано, что использование СПВ позволяет сократить продолжительность и стоимость сертификационных испытаний дизелей магистрального - 2ТЭ116 и маневрового - ТЭМ-2 тепловозов на 9 ... 28%, что составляет 0,2 ... 0,7 ч и 0,8 ... 1,5 тыс. грн.

Ключевые слова: дизель, отработанные газы, твердые частицы, экологичность, микротуннель, ускоренный замер, эффективность

Introduction

The process of ecologization of transport internal combustion engines is characterized by the phased introduction of the value of the average operational discharge of particulate matter (PM) with exhaust gases (EG) to the standardized indicators of the toxicity of diesel engines. So, since 1993, this indicator has been measured during ecological tests of automobile diesel engines, since 1997 - diesel engines of agricultural machines, and since 2007 - ship and locomotive diesel engines. In the long run, the PM index will become the normalized value for other types of diesel engines: domestic, industrial, engines of special equipment, etc.

Since the beginning of the normalization of mass emissions of the PM, there appeared a problem of increasing the duration and cost of environmental tests of diesel engines due to increased time expenditures for determining PM. The essence of this problem is as follows. The normative basis for environmental tests of diesel engines is the international standard ISO 8178 [1-3]. This document provides determining the value of PM together with other indicators of toxicity of diesel EG - the average operational emissions of gaseous pollutants: nitrogen oxides, carbon monoxide and hydrocarbons designated as GAS_x. The GAS_x and PM indices are determined during the test cycles, which consist

of normalized engine operating modes [3]. At each mode sampling of pollutants for analysis is carried out. The technology for controlling PM emissions involves preliminary dilution of the engine EG with atmospheric air and then passing it through the PM sampling filters. In this case, the duration of the sampling is determined by the rate of its filtration and the hanging-on mass of PM that is collected on the filters. During testing one of two methods of sampling PM is possible: single-filter (SF), which involves the use of one filter over the whole test cycle or multi-filter (MF), which involves the use of one filter at each test mode.

The most commonly used way of controlling PM emissions, realized in micro- and minitunnels of Perkins, AVL [4, 5], Mitsubishi [6], is characterized by increased time expenditure on sampling PM, which substantially exceeds the sampling time for gaseous pollutants - 5- 7 minutes at each test mode. As a result, the procedure for determining the PM index is more time-consuming and more expensive than the GAS_x indicator control procedure: at the SF method - 1.2 ... 1.5 times more; at the MF method - 1.9 ... 2.5 times. The indicated problem is of high relevance in testing high-power diesel engines, in particular – diesel locomotives, marine engines, etc.

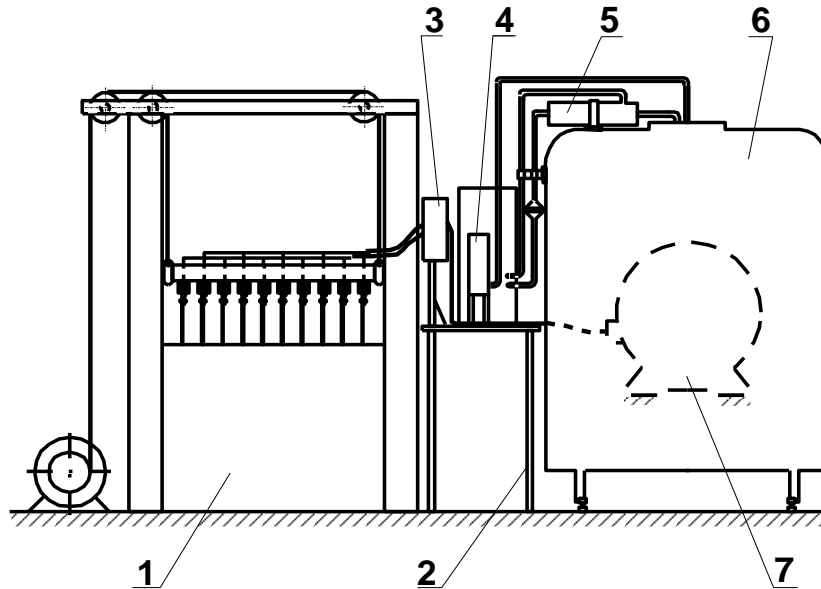
To solve this problem and increase the economic efficiency of environmental tests of

diesel engines, it is necessary to use more rapid methods of measurement of PM indicator.

Object and methods of research

Technical equipment, procedure for conducting environmental tests of diesel plants. According to the requirements of ISO 8178, environmental tests of diesels are carried out with the help of special equipment, which

includes: loading device, system of selection and analysis of samples of gaseous pollutants (GP) and system of sampling and analysis of PM - microtunnel (Fig. 1).



1 – loader (rheostat setup); 2 – a rack with devices; 3 – electric panel; 4 – system of selection and analysis of GP samples; 5 – PM emission control system (microtunnel); 6 – locomotive; 7 – diesel installation.

Fig. 1 – Equipment for ecological diagnostics of locomotive diesel engines

The loading device is used to control the diesel load in the entire range of operating modes of its operation. The system of selection and analysis of GP samples is intended for measurement of concentrations of gaseous substances contained in diesel EG. This system includes: devices for the selection and transportation of gas samples and gas analyzers.

Devices for the selection and transportation of gas samples are used to select the amount of EG samples necessary for the analysis and to bring it to gas analyzers. These devices must ensure the immutability of the sample when it is transported from the place of selection to the site of analysis. The control and registration of concentrations of GP in selected samples are carried out by means of gas analyzers. To measure the GAS_x normalized parameters, the system for the selection and analysis of GP samples must contain appropriate gas analyzers. In samples selected, the content of other substances, such as: carbon dioxide, oxygen, sulfur dioxide, etc. can also be

monitored. The PM sampling and analysis system (microtunnel) is used to measure the concentration of PM contained in diesel EG.

The procedure for ecological diagnostics of a diesel engine is a cycle, which consists of normalized modes of its operation in accordance with the requirements of ISO 8178 [3]. Taking into account the real conditions of operation of a diesel engine is carried out by using weight factors of the test modes WF, which are equal to the relative durations of diesel operation at these modes during its service (Table 1).

The control of pollutants emissions from diesel EG is carried out as follows. The test starts from the pre-warming stage of the diesel engine in an idling conditions. This stage is considered to be completed if the regulated values of temperatures and pressures of water and lubrication oil in the systems of cooling and lubrication of a diesel engine have been achieved.

Table 1

**Characteristics of the test cycle ISO 8178-F for ecological diagnostics
of diesel locomotives**

Cycle mode	Diesel power (in% of nominal value)	Weight factor WF
1	100	0,25
2	35	0,15
3	Idling conditions	0,60

After this the test cycle begins – the successive work of the diesel engine on each standardized test mode, which consists of two stages: temperature stabilization of the diesel engine and sampling pollutants. During the stage of temperature stabilization of the diesel, stabilization of water temperature, lubrication oil and EG, as well as water and oil pressure in the systems of cooling and lubrication of diesel, is achieved. During the sampling pollutants phase a parallel sampling is performed for the analysis of GP and PM contained in the diesel EG. In this case, the sampling of PM can be done by two methods: SF and MF. At the SF method, sampling PM is carried out by using one filter throughout the test cycle, and at the MF method – by using one filter at each test mode. SF method allows to determine only the indicator of average operational PM emissions and is used in the course of certification tests of diesel engines; the MF method allows to determine the mass PM emissions at the normalized operating modes of the engine and the index of average operational PM emissions and is used in conducting research tests of diesel engines.

During the sampling pollutants phase the requirements for limiting the sampling time must be fulfilled. According to ISO 8178 the minimum duration of the GP sampling procedure is 5 minutes, it requires at least 3 measurements of GP concentrations per a test mode with 1 min intervals. The minimum allowable duration of the PM sampling procedure is determined indirectly and depends on such parameters of the PM emission control system as the velocity of the filtration of the diluted EG sample and the mass of the PM accumulated on the filters. The minimum permissible duration of the sampling period for pollutants in each mode is defined as the highest of the minimum allowable lengths of sampling procedures for GP and PM.

After performing the test cycle, the results of the tests determine the GAS_x and RT.

Analysis of the possibility of increasing the rate of measurement of PM indicator. ISO 8178 has the following limitations of parameters

that affect the velocity of PM mass emissions: the filtration rate of a diluted EG-vf sample must be in the range of 35 ... 100 cm/s; The hanging-on mass of the PM collected in the filters must not be less than the minimum acceptable value: at the SF method, $M_{f(\min)} = 0.25$ mg, at the MF method, $M_{fi(\min)} = 0.14$ mg (using filters with 70 mm in diameters) [1].

The most common methods for controlling PM emissions are characterized by sample filtration velocities – $vf = 60 \dots 80$ cm/s and hanging-on masses of PM at the SF and MF methods of sampling – $M_f = M_{fi} = 1.3$ mg (Fig. 2).

As can be seen from Fig. 2, the normative requirements allow the implementation of the method of accelerated PM measurement (MAM), which is characterized by the maximum permissible rate of filtration of the sample – $v_{f(\max)} = 100$ cm/s and the minimum permissible hanging-on mass of PM – $M_{f(\min)} = 0.25$ mg and $M_{fi(\min)} = 0.14$ mg. Application of this method allows to reduce the time expenditure on PM sampling: at the SF method – 3,1 ... 4,1 times less; at the MF method – 5.3 ... 7.1 times and, consequently, reduce the cost of diesel environmental tests procedure.

It should be noted that the reduction of the hanging-on mass of PM to the minimum allowable value leads to a certain decrease in the accuracy of measurements of PM index. However, as shown by studies presented in papers [7–9], the resulting error of measurements of the PM index while implementing MAM does not exceed the permissible value – $\pm 8.5\%$ [2], and, therefore, this method can be applied in practice.

The method of evaluating the expediency of using the method of accelerated PM measurement involves a comparative analysis of the effectiveness of two ways of measuring the PM index (see Figure 2) one of the fastest contemporary methods – method 1 and MAM – method 2. As the criteria of efficiency of these methods, the following is used:

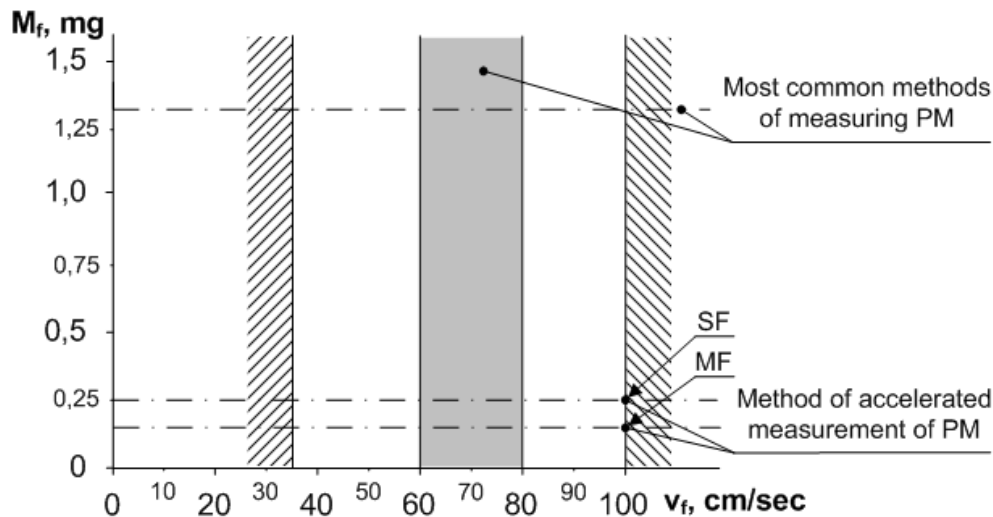


Fig. 2 – Values of factors that determine the rate of measurements of the PM indicator

A) absolute values: duration of tests – τ^{test} , fuel consumption while testing – $M_{\text{fuel}}^{\text{test}}$ and cost of tests – C^{test} , which are determined by the expressions:

$$\tau^{\text{test}} = \tau^{\text{heat}} + \sum_{i=1}^n \left(\tau_i^{\text{st}} + \max \left\{ \tau_i^{\text{sam}(\text{GAS}_x)}; \tau_i^{\text{sam}(\text{PM})} \right\} \right), \quad (1)$$

where τ^{heat} – duration of pre-warming stage of a diesel engine, h;

n – number of test cycle modes (for the ISO 8178-F series cycle $n = 3$);

τ_i^{st} – time expenditure for temperature stabilization of diesel, h;

$\tau_i^{\text{sam}(\text{GAS}_x)}$ and $\tau_i^{\text{sam}(\text{PM})}$ – duration of gaseous pollutants and PM sampling, respectively, year;

$$M_{\text{fuel}}^{\text{test}} = G_{\text{fuel}}^{\text{heat}} \tau^{\text{heat}} + \sum_{i=1}^n \left(G_{\text{fuel}i} \times \left(\tau_i^{\text{st}} + \max \left\{ \tau_i^{\text{sam}(\text{GAS}_x)}; \tau_i^{\text{sam}(\text{PM})} \right\} \right) \right) \quad (2)$$

where $G_{\text{fuel}}^{\text{heat}}$ – fuel consumption at the stage of pre-heating of the diesel engine, kg / h;

$G_{\text{fuel}i}$ – fuel consumption at i -mode test, kg / h;

$$C^{\text{test}} = M_{\text{fuel}}^{\text{test}} \times c_{\text{fuel}} + k_{\text{oil}} \times M_{\text{fuel}}^{\text{test}} \times c_{\text{oil}} + \tau^{\text{test}} \times c_{\text{test}} \quad (3)$$

where c_{fuel} , c_{oil} – specific values of the cost of fuel and lubrication oil, respectively, in UAH / kg;

c_{test} – cost of one hour of personnel work, UAH / h;

k_{oil} – coefficient equal to the ratio of the mass of the lubrication oil to the mass of fuel consumed during the tests;

B) the relative values: the duration of the tests – $\overline{\tau^{\text{test}}}$, the fuel consumption for their carrying out $\overline{M_{\text{fuel}}^{\text{test}}}$, and the cost of the tests – $\overline{C^{\text{test}}}$, which are defined as the ratio of τ^{test} , $M_{\text{fuel}i}^{\text{test}}$ C^{test} corresponding to the procedure for determining PM index to the corresponding quantities conform to the procedure of determining GAS_x indicators.

Results and discussion

Investigations of the expediency of using MAM were conducted on the basis of the results of environmental tests of the mainline - 2TE116 and shunting – TEM-2 diesel locomotives equipped with diesel engines 1A-5D49 and PD1M, respectively [10, 11]. As a sampler device, a universal system for ecological diagnostics of diesels was considered – the microtunnel MKT-2 [12, 13] with the compensatory sampling EG method [14] and the temperature control of the sample

preparation for analysis [15]. In the course of the research there has been estimated the influence of the gradual reduction of the emission norms of PM emissions from diesel EG on the efficiency of the MAM factor as a result of environmental standards improvement. This factor was taken into account by using a relative magnitude equal to the ratio of current and future levels of PM emissions.

The results of the research prove the cost-effectiveness of using MAM at railway

transport, as well as in other industries where diesel plants which are characterized by significant fuel consumptions are used (Figures 3, 4).

Thus, during the environmental tests of locomotive diesel engines, the duration, fuel

consumption and cost of tests are reduced: at the SF method – by 9 ... 28%, which is per a test 0,2 ... 0,7 hours, 25 ... 45 kg and 0,8 ... 1,5 thousand UAH; at the MF method – by 43 ...

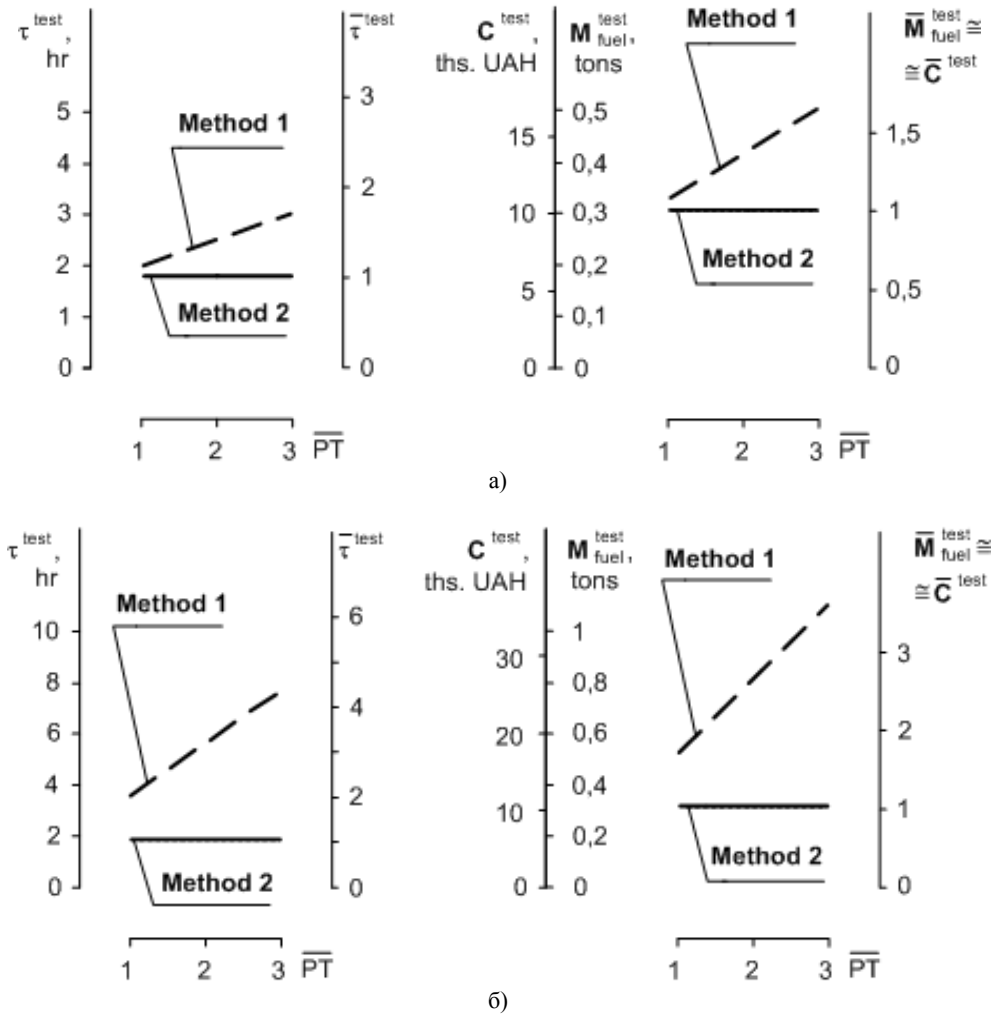


Fig. 3 – Results of the comparative analysis of the efficiency of methods 1 and 2 while testing the main locomotive 2TE116 using SF (a) and MF (b) PM selecting methods

53%, which is per a test 1,7 ... 3,0 hours, 120 ... 225 kg and 4,0 ... 7,5 thousand UAH. With the decrease of PM emission levels, the efficiency of the MAM increases: with PM increase for each unit, the values τ^{test} , $M_{\text{fuel}}^{\text{test}}$ and C^{test}

decrease further: at the SF method - by 0,3 ... 0,7 h, 45 ... 55 kg and 1,5 ... 1,8 thousand UAH; at the MF method – by 1,7 ... 3,0 years, 115 ... 235 kg and 3,8 ... 7,8 thousand UAH.

Conclusions

1. With the beginning of the normalization of the average specific emission of particulates (PM) with exhaust gases (EG) of diesel plants due to the lack of high speed of PM index measurement, the duration and cost of the procedure of ecological tests of diesel engines significantly increase: with the use of a

single-filter (SF) PM sampling method – in 1,2 ... 1,5 times, multiphase (MF) method – in 1,9 ... 2,5 times.

2. In accordance with the requirements of the international standard ISO 8178 a method of accelerated PM index measurement - MAM is proposed. It is characterized by the maximum

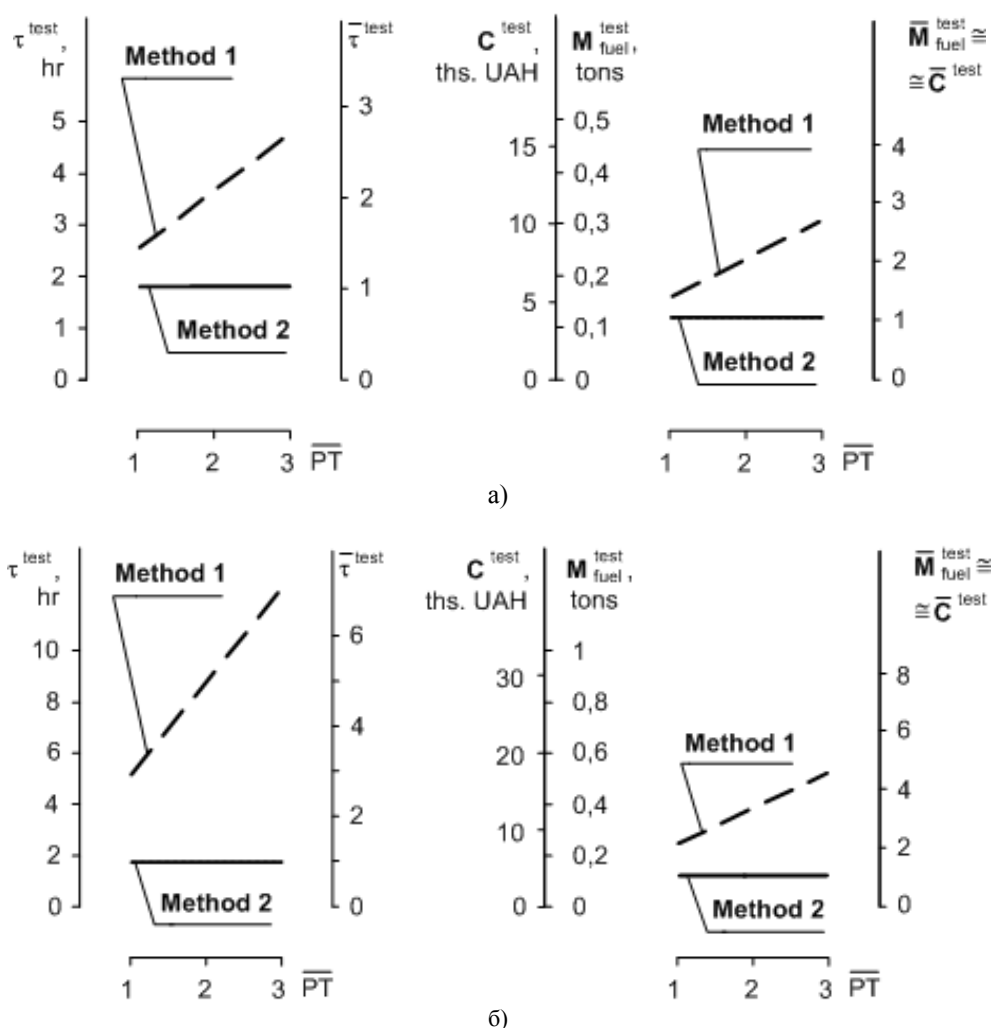


Fig. 4 – Results of the comparative analysis of the efficiency of methods 1 and 2 while testing the shunting diesel locomotive TEM-2 using SF (a) and MF (b) PM selecting methods

permissible rate of filtering of the PM sample – 100 cm / s and the minimum allowable hanging-on masses of PM collected on the filters – 0,25 mg and 0.14 mg by using SF and MF methods for PM selection, respectively. The use of MAM can significantly increase the speed of measuring PM index: at the SF method – in 3.1 ... 4.1 times, at the MF method - in 5.3 ... 7.1 times.

3. Compared with the most widespread methods of monitoring PM emissions, which are realized in mini-microtunnels of Perkins, AVL, Mitsubishi, MAM is characterized by higher speed and economic efficiency of use -

indicators that are of high importance in testing diesel engines of high power - locomotive diesel, ship and etc. The use of MAM can reduce the duration, fuel consumption and cost of testing locomotive diesel engines: at the SF method – by 9 ... 28%, which is per a test 0,2 ... 0,7 hours, 25 ... 45 kg and 0,8 ... 1,5 thousand UAH; at the MF method – by 43 ... 53%, which is per a test 1,7 ... 3,0 hours, 120 ... 225 kg and 4,0 ... 7,5 thousand UAH. With the reduction of the actual levels of PM emissions from the diesel EG, the effectiveness of the use of MAM increases.

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