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EFFECTIVENESS EVALUATION OF THE MEASURING SYSTEM WITH A MICROTUNNEL MKT-2 FOR ECOLOGICAL DIAGNOSIS OF DIESEL LOCOMOTIVES

The article is devoted to the solution of the urgent task of reducing the duration and cost of the procedure for measuring the average operating mass emission of particulate matter with exhaust gases of a diesel engine - the standardized environmental indicator PM. The paper describes the technical characteristics and operation principle of a universal measuring system with a microtunnel MKT-2 for controlling the mass emissions of particles with exhaust gases from various types of diesel engines. The method of complex evaluation of the effectiveness of this system was developed by the criteria: accuracy of measurements, duration of sampling of particles in standardized test modes, cost-effectiveness of using MKT-2. With the help of this technique and the results of ecological tests of diesel engine 3A-6D49 of diesel locomotive TGM6 on the cycle ISO 8178-F, the efficiency of MKT-2 was conducted, as a result of which it was established that the resulting measurement error of PM is 3.1%, which corresponds to the requirements of normative documents; the duration of sampling of particles is from 1.8-2.5 minutes - in the modes of the average and nominal power of the diesel engine to 7.5 minutes - at idle; MKT-2 is characterized by a high economic efficiency of use: additional fuel costs during the ISO 8178-F cycle associated with increased sampling time of particles are negligible and amount to 0.5%. Recommendations have been developed for the improvement of MKT-2, the implementation of which will reduce the duration of sampling by 3.8 times.

Introduction

With the entry into force of the Stage III regulations in the EU railway transport, the average operating emissions of particulate matter (PM, g/(kW·h)) with the exhaust gases (EG) was added to the number of standardized environmental indicators of locomotive diesels (LD) [1]. At the same time, this indicator was started to be measured in the course of environmental tests of the LD together with other normalized values – GAS_x indicators – the average operating mass emissions from the EG of gaseous pollutants: nitrogen oxides, carbon monoxide and hydrocarbons.

The measurement procedure for the PM index has a number of features that should be taken into account when carrying out environmental tests of the LD. These include:

- a) the need to use a special measuring system – a diluting tunnel in which the dilution of the EG from the diesel engine is carried out with clean atmospheric air;
- b) the impact on the duration of the PM measurement procedure of the sampling rate of PM in the tunnel and the regulated PM sample mass on the filter;
- c) the dependence of the duration and cost of the procedure for environmental diagnosis of the LD from the time spent on determining the PM index, which increase with a decrease in the actual emission levels of PM with the EG from diesel engine.

These features are taken into account in the development of the prototype of the measuring system – the microtunnel MKT-2 [2-4]. In the period 2015-2018, this system was improved, resulting in increased

its degree of automation, accuracy and versatility – the ability to use in the testing of various types of diesel and the implementation of various test procedures. The microtunnel MKT-2 passed successful tests during bench and full-scale tests of various diesel installations, including diesel locomotives [5, 6].

Formulation of the problem

The purpose of this work was to carry out a comprehensive assessment of the effectiveness of the MKT-2 microtunnel according to the following criteria: accuracy of PM mass emissions measurements, time spent on PM sampling at normalized diesel operation modes, economic efficiency of MKT-2 use in environmental testing of LD.

At the same time, the following tasks were solved: 1) development of a methodology for a comprehensive assessment of the effectiveness of the measuring system with MKT-2; 2) a study of the effectiveness of the microtunnel MKT-2 according to the specified criteria, taking into account the requirements of the international standard ISO 8178; 3) development of recommendations for the improvement of MKT-2, which make it possible to improve its efficiency.

Composition and principle of operation of the measuring system with MKT-2

The structure of this system includes two main elements (fig. 1): 1) microtunnel MKT-2, designed to select part of the exhaust gas, diluting them with atmospheric air and sampling PM; 2) a chamber for stabilizing and weighing the filters, designed to determine the mass of PM collected on the filters during the tests.

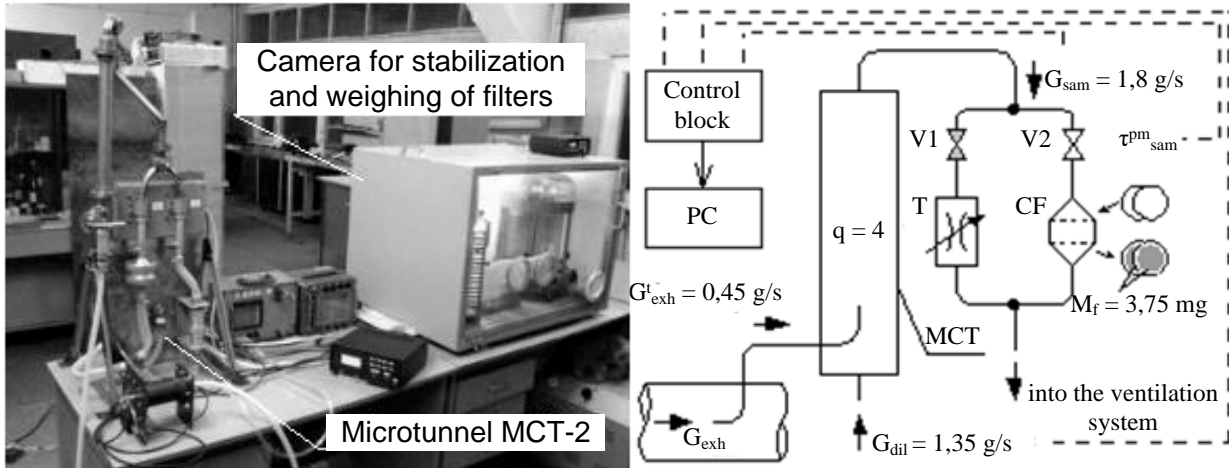


Fig. 1. General view and schematic diagram of measuring system with MKT-2: PC – personal computer; V1, V2 – ball valves; T – throttle; CF – cartridge filters for selecting PM; MKT – microtunnel

Measurement of the PM index using the presented measuring system is carried out as follows. Part of the EG taken from the exhaust system of the LD with mass flow rate G_{exh}^t enters the microtunnel, where they are diluted with a flow of air with a mass flow rate – G_{dil} , in order to simulate the natural process of dispersing the EG in the atmosphere. A flow of dilute EG with a mass flow rate of G_{sam} is passed through filters on which PMs are collected whose mass is M_f measured in the chamber for stabilizing and weighing the filters. Values of parameters G_{exh}^t , G_{dil} , G_{sam} and M_f provided by the MKT-2 automation system during the LD tests are shown in fig. 1.

To determine the mass ejection of PM in a separate operating mode of LD – PM_{mass} is used the dependence:

$$PM_{mass} = \frac{M_f}{M_{sam}} \cdot q \cdot G_{exh} = \frac{M_f}{\tau_{sam}^{pm}} \cdot \frac{G_{exh}}{G_{sam} - G_{dil}}, \text{ g/h}, \quad (1)$$

where M_f – mass of PM sample; $M_{sam} = G_{sam} \cdot \tau_{sam}^{pm}$ – mass of diluted EG, passed through filters for selection of PM, g; τ_{sam}^{pm} – duration of sampling PM, s; $q = G_{sam}/G_{exh} = G_{sam}/(G_{sam} - G_{dil})$ – coefficient of dilution of EG by air; G_{exh} – mass flow rate of EG in the diesel exhaust system, kg/h.

The average operating mass emission of PM – the PM index is measured during the execution of the test cycle consisting of normalized operating modes of the LD. The international cycle ISO 8178-F consists of 3 operating modes of the LD [7]: 1) nominal power – P_{nom} ; 2) average power – 35% of P_{nom} ; 3) locomotive diesel idling – P_{idle} . The native analog of this procedure is the 5-step cycle of DSTU32.001 94, consisting of such regimes [8]: 1) P_{nom} ; 2) 75% of P_{nom} ; 3) 50% of P_{nom} ; 4) 25% of P_{nom} ; 5) P_{idle} . To calculate PM is used the dependence:

$$PM = \frac{\sum_{i=1}^n PM_{mass_i} \cdot WF_i}{\sum_{i=1}^n P_i \cdot WF_i}, \text{ g/(kW} \cdot \text{h)}, \quad (2)$$

where n – the number of test modes; PM_{mass_i} and P_i – the mass emission of PM and the effective power of the LD measured at the i th mode; WF_i – the weight factor of the i th test mode.

The method of complex evaluation of the effectiveness of the microtunnel MKT-2

In accordance with this methodology, the effectiveness of MKT-2 is assessed using the following criteria:

1) the resulting errors in the measurement of PM mass emissions in certain operating modes of LD – δPM_{mass} and the average operating emission of PM – δPM ;

2) the duration of sampling of PM in separate test modes – τ_{sam}^{pm} ;

3) the relative cost of the PM index measurement procedure – \overline{C}_{test}^{PM} :

$$\overline{C}_{test}^{PM} = \frac{C_{test}^{PM}}{C_{test}^{GAS_x}} \cong \frac{M_{fuel}^{PM}}{M_{fuel}^{GAS_x}}, \quad (3)$$

where C_{test}^{PM} and $C_{test}^{GAS_x}$ – cost of measurement procedures for PM and GAS_x indicators; M_{fuel}^{PM} and $M_{fuel}^{GAS_x}$ – mass of fuel, which are expended during measurements of PM and GAS_x .

To determine these criteria, the following calculation formulas are used, resulting from the analysis of normalized procedures for measuring the values of PM_{mass} and PM:

$$\delta PM_{mass} = \sqrt{\sum_{i=1}^n \left(\frac{\partial PM_{mass}}{\partial x_i} \cdot \frac{\delta x_i \cdot x_i}{PM_{mass}} \right)^2}, \quad (3)$$

$$\delta PM = \sqrt{\sum_{j=1}^n \left(\frac{\partial PM}{\partial x_j} \cdot \frac{\delta x_j \cdot x_j}{PM} \right)^2}, \quad (4)$$

where x_i, x_j – the parameters by which the values PM_{mass} and PM are calculated (see formulas (1) and (2)); $\delta x_i, \delta x_j$ – relative errors in measuring the parameters x_i and x_j ;

Formulas (3, 4) are expressions for determining errors in quantities measured indirectly:

$$\tau_{sam}^{PM} = \frac{M_f}{G_{exh}^t \cdot c_{pm}}, \text{ s}, \quad (5)$$

where M_f – mass of PM collected on a filter, mg; G_{exh}^t – mass flow rate of EG entering the tunnel, g/s; c_{pm} – mass concentration of PM in EG, g/kg;

$$\frac{PM}{C_{test}^{PM}} = \frac{\sum_{i=1}^n (\tau_{temp} + \max\{\tau_{sam}^{GASx}, \tau_{sam_i}^{PM}\}) \cdot G_{fuel_i}}{\sum_{i=1}^n (\tau_{temp} + \tau_{sam}^{GASx}) \cdot G_{fuel_i}}, \quad (6)$$

where n – number of test modes; $\tau_{temp} \approx 20$ min – duration of the period of temperature stabilization of the diesel; $\tau_{sam}^{GASx} \approx 3$ min and τ_{sam}^{PM} – duration of sampling procedures for gaseous pollutants and PM; G_{fuel} – mass flow rate of fuel entering the engine at the i th mode, kg/h.

Results of studies on the effectiveness of MKT-2 and recommendations for its improvement

Based on the analysis of the technical characteristics of MKT-2 and the chamber for stabilization and weighing of filters, the results of ecological tests of diesel engine 3A-6D49 of locomotive TGM6 according to the cycle ISO 8178-F [9] (table 1) and the application of dependences (3) – (6) calculations of the efficiency criteria of the measuring system with MKT-2 were carried out, which showed the following:

Table 1. The results of measurements of mass emissions of PM with the EG of the diesel engine 3A-6D49 on the cycle modes of ISO 8178-F

№mode.	WF	P, kW	G _{fuel} , kg/h	c _{pm} , g/kg	PM _{mass} , g/h
1	0,25	821,3	205,7	0,092	626,4
2	0,15	244,5	55,1	0,067	167,0
2	0,60	9,4	8,4	0,023	30,7

a) the errors δPM_{mass} and δPM , provided by the micro-tunnel MKT-2, are 5.1% and 3.1%, respectively, which does not exceed the values allowed by the regulatory documents (table 2);

Table 2. Characteristics of the accuracy of the measuring system with MKT-2

Parameter	Relative error of parameter measurement		
	Provides MKT-2	The requirements of ISO 8178 [10]	
		Measurements on the stand	Measurements on the object
M_f	2,7% ($M_f = 0,40$ mg)	2,7% ($M_f = 0,14$ mg)	
τ_{sam}^{pt}	0,25%	---	
G_{exh}	1,7%	4%	5%
G_{sam}	0,8%	2%	
G_{dil}	0,8%	2%	
P	2% of P_{nom}	2% of P_{nom}	5% of P_{nom}
PM_{mass}	5,1%	6,0%	8,5%
PM	3,1%	3,6%	5,1%

b) the duration of sampling of PM at different modes of the cycle ISO 8178-F is: on the first mode – 7,5 min, on the second – 2,5 min, on the third – 1,8 min; thus the value of τ_{sam}^{PM} exceeds the sampling time of gaseous pollutants only at idling speed;

c) the relative cost of the PM measurement procedure is 1,005, which is an insignificant – 0,5% increase in the cost of the PM measurement procedure relative to the cost of the GAS_x measurement procedure.

The results of the calculations indicate satisfactory measurement accuracy, short PM sampling times and cost-effectiveness of using the MKT-2 measuring system. In order to further improve the performance of

this equipment, the following recommendations were made:

1) increase in the capacity of the sampling pump that generates mass flow in the tunnel – G_{sam} , from 1,8 g/s or 90 l/min to the maximum allowable value of 2,4 g/s or 120 l/min, which will shorten the sampling time of PM in 1,3 times;

2) the replacement of analytical weights with an accuracy of $\pm 0,02$ mg by more accurate – with an error of $\pm 0,002$ mg, which will reduce the mass of the sample of PM M_f to a minimum allowable value of 0,14 mg and 2,9 times reduce the sampling time of PM – τ_{sam}^{PM} ; while this value will not exceed τ_{sam}^{GASx} even

at small – up to 0,01 mg/l PM concentrations in the EG of the diesel engine.

Conclusions

1. Investigations of the efficiency of the measuring system with the microtunnel MKT-2 showed the following:

a) MKT-2 makes it possible to measure mass emissions of PM in certain operating modes of the locomotive diesel engine with an error of 5,1%, and the average operating mass emission of PM with an error of 3,1%, which meets the requirements of regulatory documents;

b) the duration of sampling of PM in MKT-2 ranges from 1,8-2,5 min – in the modes of average and nominal power of diesel up to 7,5 min – at idling speed, which does not significantly exceed the sampling time of gaseous pollutants, which is 3 minutes;

c) MKT-2 is characterized by high economic efficiency of use: the additional fuel costs during the ISO 8178-F cycle, associated with the increased duration of PM sampling, are only 0,5%.

2. Have been developed the recommendations for improving the microtunnel MKT-2 and improving its efficiency:

a) an increase in the productivity of the sampling pump from 90 l/min to 120 l/min will reduce the duration of sampling of PM by 1,3 times;

b) the substitution of analytical weights with a measurement error of $\pm 0,02$ mg by more accurate weights with a measurement error of $\pm 0,002$ mg will allow to measure PM emissions at small concentrations up to 0,01 mg / l of PM in exhaust gases with a duration not exceeding 3 min.

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ОЦІНКА ЕФЕКТИВНОСТІ ВИМІРЮВАЛЬНОЇ СИСТЕМИ З МІКРОТУННЕЛЕМ МКТ-2 ДЛЯ ЕКОЛОГІЧНОГО ДІАГНОСТУВАННЯ ТЕПЛОВОЗНИХ ДИЗЕЛІВ

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Стаття присвячена вирішенню актуального завдання скорочення тривалості та вартості процедури вимірювання середньоексплуатаційного масового викиду твердих частинок з відпрацьованими газами тепловозного дизеля - нормованого екологічного показника РМ. В роботі наведено опис технічних характеристик і принципу дії універсальної вимірювальної системи з мікротунелем МКТ-2 для контролю масових викидів твердих частинок з відпрацьованими газами дизелів різних типів. Розроблено методику комплексної оцінки ефективності даної системи за критеріями: точність вимірювань, тривалість відбору проб твердих частинок на нормованих режимах випробувань, економічна ефективність використання МКТ-2. За допомогою даної методики і результатів екологічних випробувань дизеля 3А-6Д49 тепловоза ТГМ6 за циклом ISO 8178-F проведені дослідження ефективності МКТ-2, в результаті яких встановлено: результуюча похибка вимірювань показника РМ становить 3,1%, що відповідає вимогам нормативних документів; тривалості відбору проб твердих частинок на режимах випробувань складають 1,8 - 7,5 хв; відносне збільшення тривалості і вартості процедури екологічних випробувань дизеля є незначним і становить 0,5%. Розроблено рекомендації щодо вдосконалення МКТ-2, виконання яких дозволить скоротити тривалість відбору проб твердих частинок в 3,8 рази.

ОЦЕНКА ЭФФЕКТИВНОСТИ ИЗМЕРИТЕЛЬНОЙ СИСТЕМЫ С МИКРОТУННЕЛЕМ МКТ-2 ДЛЯ ЭКОЛОГИЧЕСКОГО ДИАГНОСТИРОВАНИЯ ТЕПЛОВОЗНЫХ ДИЗЕЛЕЙ

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Статья посвящена решению актуальной задачи сокращения продолжительности и стоимости процедуры измерения среднеексплуатационного массового выброса твердых частиц с отработавшими газами тепловозного дизеля – нормируемого экологического показателя РМ. В работе приведено описание технических характеристик и принципа действия универсальной измерительной системы с микротуннелем МКТ-2 для контроля массовых выбросов твердых частиц с отработавшими газами дизелей разных типов. Разработана методика комплексной оценки эффективности данной системы по критериям: точность измерений, продолжительность отбора проб твердых частиц на нормируемых режимах испытаний, экономическая эффективность использования МКТ-2. С помощью данной методики и результатов экологических испытаний дизеля 3А-6Д49 тепловоза ТГМ6 по циклу ISO 8178-F проведены исследования эффективности МКТ-2, в результате которых установлено: результирующая погрешность измерений показателя РМ составляет 3,1%, что соответствует требованиям нормативных документов; продолжительности отбора проб твердых частиц на режимах испытаний составляют 1,8 – 7,5 мин; относительное увеличение продолжительности и стоимости процедуры экологических испытаний дизеля незначительно и составляет 0,5%. Разработаны рекомендации по усовершенствованию МКТ-2, выполнение которых позволит сократить продолжительность отбора проб твердых частиц в 3,8 раза.