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# The Method of Diesel Particulate Matter Operative Control

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## Abstract

The engine ecological indicators should be controlled during certain period of engine running. Maintaining intended level of the exhaust emissions from diesel engine during certain running, requires, first of all, high stability of the engine working process, and secondly, organization of suitable operative control of the engine over pre-defined le-vels of different ecological indicators. The measurement of concentration of harmful gaseous substances (HGS) within a stream of the exhaust gases does not present difficulty in connection with portable gas analyzers, but mea-surement of particulate matters (PM) under operating conditions is impossible.

In this work, a modeling method based on indirect measurable indicators to determine the concentration of engine particulate matters and their main composition is described. This method accounts the dependency of PM from en-gine on the heavy hydrocarbons as well as provides different sources of these heavy hydrocarbons. The results ob-tained from the current modeling method are presented and considered in this paper.

**Keywords:** Diesel engine; Particulate matters; Soot; Firm sulphates; Heavy hydrocarbons; Fuel; Oil

## Introduction

According to the procedures conducting the test for durability of emission control systems (Annex II Commission Directive 2005/78/EC of 14 November 2005 implementing Directive 2005/55/EC of the European Parliament and of the Council on the approximation of the laws of the Member States relating to the measures to be taken against the emission of gaseous and particulate pollutants from compression-ignition engines for use in vehicles…), stability of engine ecological indicators (for level of environmental standards of Euro-V) has to correspond the in-service vehicles equipped by diesel engines of the following categories:

- N1 and M2–100 thousand km (or 5 years of that will come earlier).
- N2, N3 (with a full weight no more than 16 t) and M3 (with a full weight no more than 7,5 t)–200 thousand km (or 6 years);
- N3 (with a full weight over 16 t) and M3 (with a full weight over 75 t)–500 thousand km (or 7 years).

Maintaining level of exhaust gaseous (EG) emissions of diesels during specified test demands, first of all, increase of stability of engine working process, and secondly, the organization of suitable operative control of engine running conditions over pre-defined levels of different ecological indicators. Even the measurement of concentration of HGS in an EG doesn't present difficulty in connection with availability of portable gas analyzers of nitric oxides $NO_x$, carbon oxide CO and hydrocarbons $C_nH_m$, the measurement of PM emissions for in-service vehicle under specific operating conditions is impossible. According to standard test methods, the measurement of PM can be attained by gravimetric measurements demanding expensive stationary equipment and consuming a lot of time.

According to the gravimetric technique of measurement, PM is defined by means of mixing of EG and clean air to have stream of temperature not over 52°C (325 K) then the mixture stream is passed over a filter. As a result of stream filtration, all non-gaseous substances contained in the EG are settled. The particulate matters including aerosols of liquids as well as solid compounds are collected behind the filter at the specified temperature. As the mixing stream is passed over a water absorbing substance to remove any moisture, the collected substances by filter not include water vapor.

Thus, if the majority of polluting substances is represented by simple chemical compounds, PM have a wide chemical composition and various physical characteristics [1]. The solid part of the PM includes elemental carbon (commonly called soot) C, minerals as firm sulfates $MSO_4$, fuel ashes, and wear products of engine moving elements, while the liquid part includes heavy (with carbon groups from and above $C_{18}$) and light (with carbon groups from $C_5$ to $C_{17}$) hydrocarbons and oil coke. The part of high-molecular (heavy) hydrocarbons is symbolized as $C_aH_b$ hydrocarbons, while the total hydrocarbons including in PM are symbolized as $C_nH_m$. Sources of existence of soot and heavy hydrocarbons in the EG include the incompletely burned fuel and lubricant oil. Thus, the formation of PM in EG can be owing to the imperfection of working process of the engine and the availability of oil leakage into combustion cylinder. While the firm sulfates is resulted from the interaction of the combustion products of sulfur content in fuel with metals of barium Ba and calcium Ca which are parts of washing additives of oils.

For evaluating the emissions of PM, it is necessary to consider time for filter selection and installation before measurements, time for preliminary tests of air consumption during all modes of the engine test-driving cycle (TDC), time for carrying out the TDC, time for weighing of filters before and after tests. Thus, data collected for measuring of PM emission in EG according to standardized TDC requires hours, so it is impossible to give conclusion quickly. Moreover after this lengthy

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time processing, the received results are represented in only one Figure about specific emission (PM in the EG) without possibility to analyze factors determining PM emission.

## Purpose of Research

This study aims to develop a mathematical model to determine the concentration of the particulate matter.

## Main Results and Discussion

There are adjustable modeling techniques suggested by other authors cited in the literature to determine the concentration of PM in the EG depending on the measurement of indirect data. These efforts can be divided into two major groups; one includes only the measurement of smoke level in the EG (group I of models [2-11]) while the other includes the measurements of smoke level in the EG and the concentration of hydrocarbons in the EG (group II of models [3,5,9,10]). The level of engine smoke and emitted hydrocarbons define mainly which group the engine is belonged to.

The engine having high level of smoke in the EG (not less than 50% on Hartridge scale) is considered to emit mainly soot (carbonaceous compounds). While that have smaller values of smoke in the EG, the influence of heavy hydrocarbon emissions becomes significant. However, when values of both indicators are small, there is noticeable influence of firm sulfates (i.e. availability of sulfur in fuel) which, usually does not allocate from the general emission of firm particles. Models of group I are applied for engines where PM emissions are completely considered to be only soot and models of group II are used for other two cases. The main error in models of group II is caused due to the consideration of constant contents of heavy hydrocarbons no matter engine power setting; according to different models, their contents fluctuate from 25 to 55% in the PM. However, the other tests showed that, this ratio isn't constant, and depends on the engine operating mode as it defines the ratio between fuel and air, and affects the development of many processes within engine cylinder; including fuel injection, evaporation, ignition and combustion [2,12] (Figure 1).

Based on the analysis available in the literature [2-11] and results obtained by the author for evaluating the extent of total hydrocarbons disintegration on separate groups [12], author developed a mathematical model to determine PM concentration in the EG under the following assumptions:

- PM consist of three main components: soot (C), firm sulfates ($MSO_4$) and heavy hydrocarbons ($C_aH_b$);
- Soot content (C) is proportional to the smoke level (N) in the EG.
- Formation of firm sulfates ($MSO_4$) is proportional to fuel consumption ($G_f$) and the sulfur content (S) in the fuel considering 100% transformation of sulfur combustion products into firm sulfates.
- The share of heavy hydrocarbons $C_aH_b$ in a total $C_nH_m$ depends on the engine operating mode which is identified here by the temperature of the EG ($t_r$).
- There are different sources of heavy hydrocarbons $C_aH_b$ (including fuel $CH_{fuel}$ and lubricating oil $CH_{oil}$ defined by level of oil consumption $G_{oil}$).
- The uncertainty of the developed model is caused by ash and coke contents in the EG and fuel, wear products of engine moving elements (which can be included in soot fraction).

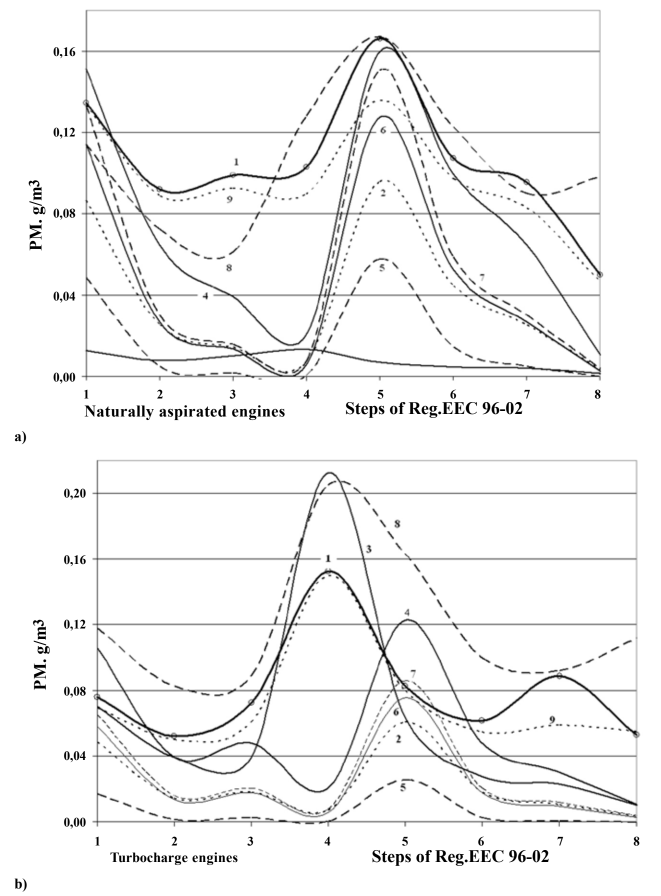


**Figure 1:** Settlement and experimental definition of particulate matter emission with the diesels exhaust gases: a) for the naturally aspirated engine; b) for the turbocharged engine.

*Designations*: 1-the experimental data, 2-[6], 3-[10], 4-[7], 5-[11], 6-[5], 7-[9], 8-[3] , 9-the developed model.

The general relation to determine the PM concentration in the EG from measuring of smoke level, sulfur mass content in the fuel, concentration of total hydrocarbons and other engine mechanical parameters (including fuel and oil consumptions and the exhaust gas temperature) can be expressed as follow:

$$PM = f_1(N) + f_2(S, G_f) + f_3(C_nH_m, t_r, G_{oil})$$

Calculations of the soot content and firm sulfates in the EG are performed considering the following relations:

a) soot content, g/m$^3$ [9]

$C = 10^{-6} N^3 - 2\cdot10^{-5} N^2 + 2,4\cdot10^{-3} N + 0,0041$ *or*

$C = 2,1\cdot10^{-3} FSN^3 + 2,3\cdot10^{-2} FSN^2 + 1,45\cdot10^{-2} FSN + 0,0016$,

where N and FSN - respectively, the smoke measured on an optical method (to % on Hartridge scale) and the smoke measured by a filtration method (smoke units on Bosch scale).

b) firm sulfates, g [4]

1. $S + O_2 \rightarrow SO_2$ *(the temperature of the EG $t_r$ above 1400°C)*

2. $SO_2 + O_2 + M \rightarrow \kappa_1 SO_3$ $\quad (540°C < t_r < 1400°C)$

3. $SO_3 + H_2O \rightarrow H_2SO_4 \cdot \kappa_2 H_2O$ $\quad (140°C < t_r < 540°C)$

4. $H_2SO_4 \cdot \kappa_2 H_2O + Me \rightarrow \kappa_3 MSO_4$ $\quad (t_r < 140°C)$

where S–is the sulfur content in the fuel, % on weight; $\kappa_i$ – the conversion coefficient;

M-third substance; Me–metal (Ba or Ca).

c) Calculation of concentration of unburned fuel hydrocarbons $CH_{fuel}$ and oil hydrocarbons $CH_{oil}$ in the EG, is made taking into account nature of their changes from diesel power (i.e. EG temperatures) [13,14]. For the first the minimum of value lies in a zone of average loadings, and values of the second are (as a first approximation) invariable in all range of loadings. Concentration of total hydrocarbons $C_nH_m$ in EG, naturally, is a sum $CH_{fuel}$ and $CH_{oil}$ (Figure 2).

The main differences of the current proposed approach from similar models include:

- The accounting of dependency of heavy hydrocarbons $C_aH_b$ content in the total $C_nH_m$ according to power setting;
- Specifying the different sources of heavy hydrocarbons formation.

The required measurements to carry out this model include, besides the EG temperature and sulfur content (received from fuel properties given by fuel producer), the concentration of total hydrocarbons and smoke level in the EG. The main time is consumed to define the lubricating oil consumption, which is necessary only for honing the engine researches. Moreover, the oil consumption in modern diesel engines due to leakage into combustion cylinder doesn't exceed 0.3% of the overall fuel consumption. Thus, it is possible to ignore the part of heavy hydrocarbons caused by lubricating oil and to consider only the measured unburned hydrocarbons in the EG.

The suggested model allows the determination of PM emission in the diesel EG depending on simple indirect data without necessity to have sophisticated instruments. It is important to notice that, this model is applicable for large-size engines: stationary, ship and train.

Data on operational development of the serial diesel with a turbo charging below are provided as an example by gross power (on ISO 15550) 36,0 kW (Figure 3). Tests were carried out on a 8-step TDC of Regulation EEC No. 96-02. Applying the suggested model allows the determination of PM concentration in the EG of PM emission (Figure 4). The proposed model provides a decrease in specific emission of PM in the EG more than half that obtained in (Figure 3). Thus effect of engine operating mode on the determined PM and their composition using the current model has been significantly shown from comparison of (Figures 3 and 4).

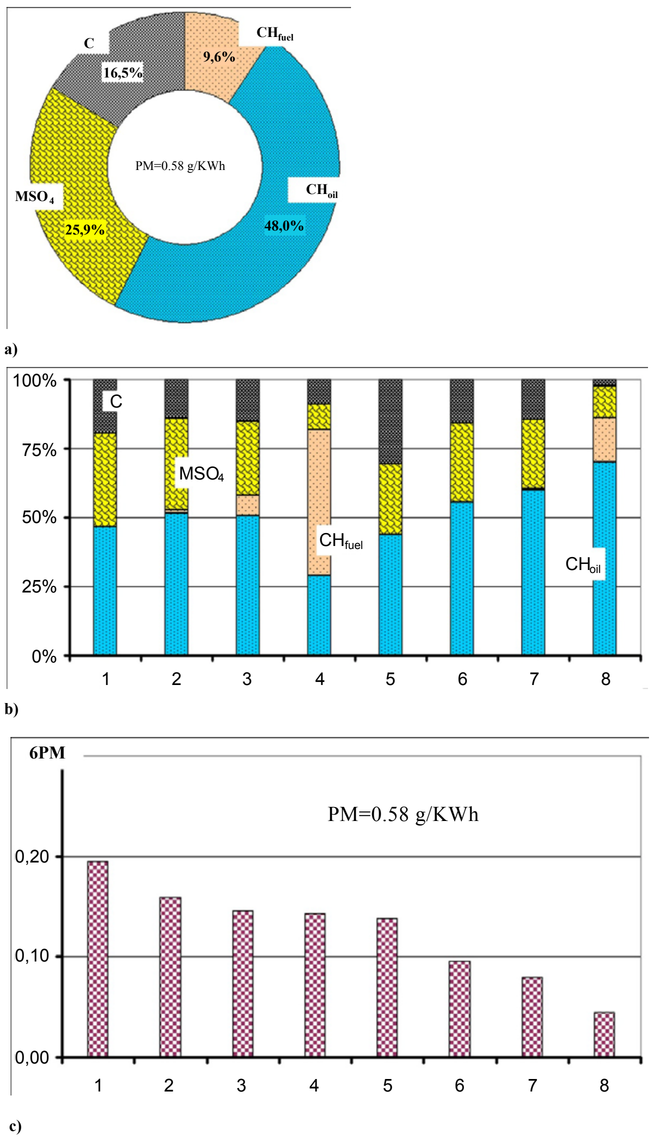


**Figure 3:** Assessment of the influence of different components of PM (a and b) and engine power mode (c) on PM concentration based on a 8-step driving cycle of Regulation ECE No. 96-02.

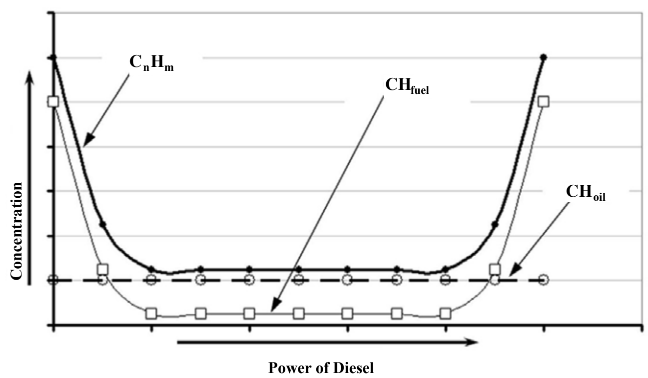


**Figure 2:** The simplified dependence of concentration of fuel hydrocarbons $CH_{fuel}$, oil hydrocarbons $CH_{oi}$ and total hydrocarbons $C_nH_m$ in the exhaust gases from diesel loading.

## Conclusions

A mathematical mode to determine particulate matter emission is developed depending on indirect indicators. The proposed model differs from similar techniques by specifying the contribution of different sources of heavy hydrocarbons including fuel and lubricant oil taking into account the effect of power setting on the formation of heavy hydrocarbons. According to the suggested model, the particulate matters are divided into four main components; soot, sulfate, fuel hydrocarbons and oil hydrocarbons. Moreover, this model can be

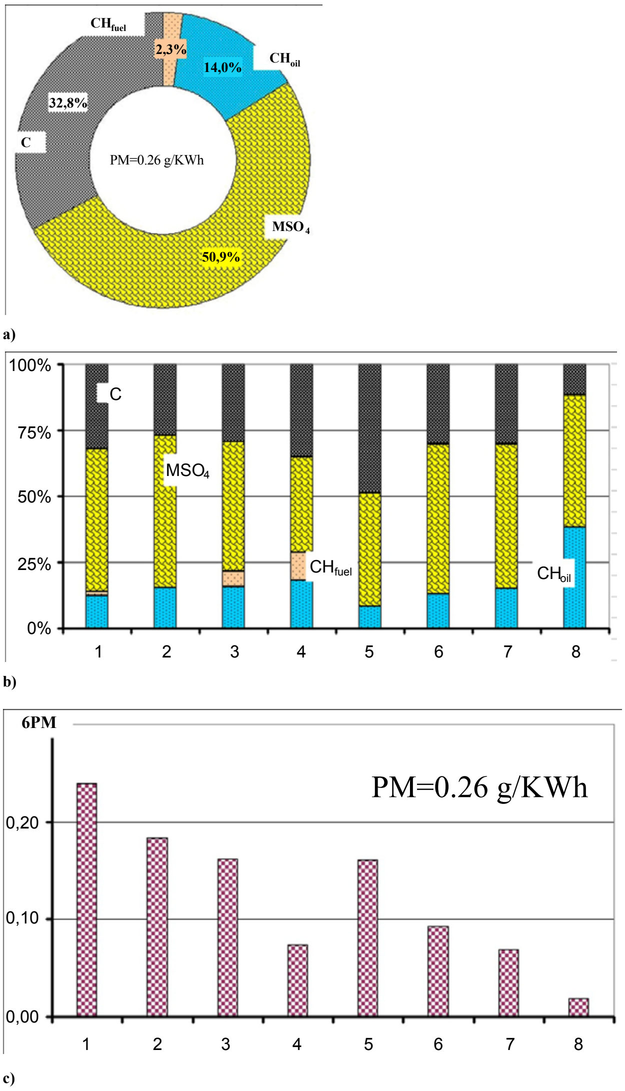


**Figure 4:** Result of operational development of the diesel.

*Designations*: according to Figure3.

applied no matter the engine operating mode or the mode of the driving test cycle of the vehicles, and it is more suited to large-size engines (stationary, ship and train).

The carried-out calculations on the basis of the current model reveal that:

- the content of heavy hydrocarbons $C_aH_b$ in the total $C_nH_m$ is dependence on an operating mode of the diesel and varies from 10 to 50%;
- the relative contents in particulate matter of heavy hydrocarbons, soot and firm sulfates for the engines which are carried out corresponding to emission norms ECE No. 96-02 for off-road cars diesels vary as follows: $C_aH_b$–20 … 80%, soot–10 … 50%, $MSO_4$–5 … 30%.

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