

<https://doi.org/10.21122/2227-1031-2020-19-4-305-310>

UDC 621.436.068.4

Ensuring Requirements for Emissions of Harmful Substances of Diesel Engines

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Abstract. The purpose of this work is to consider the requirements for emissions of harmful substances of diesel engines by selecting design and adjustment parameters that determine the organization of the workflow, and the exhaust gas cleaning system, taking into account the reduction of fuel consumption. Design elements and geometric characteristics of structures for a turbocharged diesel engine of Д-245 series produced by JSC HMC Minsk Motor Plant (4ЧН11/12.5) with a capacity of 90 kW equipped with an electronically controlled battery fuel injection have been developed: exhaust gas recirculation along the high pressure circuit, shape and dimensions of the combustion chamber, the number and angular arrangement of the nozzle openings in a nozzle atomizer, and inlet channels of the cylinder head. Methods for organizing a workflow are proposed that take into account the shape of the indicator diagrams and affect the emissions of nitrogen oxides and dispersed particles differently. Their implementation allows us to determine the boundary ranges of changes in the control parameters of the fuel supply and exhaust gas recirculation systems when determining the area of minimizing the specific effective fuel consumption and the range of studies for the environmental performance of a diesel engine. The paper presents results of the study on the ways to meet the requirements for emissions of harmful substances, obtained by considering options for the organization of working processes, taking into account the reduction in specific effective fuel consumption, changes in the average temperature of the exhaust gases and diesel equipment. To evaluate these methods, the following indicators have been identified: changes in specific fuel consumption and average temperature of the toxicity cycle relative to the base cycle, the necessary degree of conversion of the purification system for dispersed particles and NO_x. Recommendations are given on choosing a diesel engine to meet Stage 4 emission standards for nitrogen oxides and dispersed particles.

Keywords: requirements, emissions, harmful substances, installation, model, research, design parameters, ecology, toxicity cycle, process, fuel efficiency

For citation: Kuharonak G. M., Kapsky D. V., Berezun V. I. (2020) Ensuring Requirements for Emissions of Harmful Substances of Diesel Engines. *Science and Technique*. 19 (4), 305–310. <https://doi.org/10.21122/2227-1031-2020-19-4-305-310>

Обеспечение требований к выбросам вредных веществ дизелей

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Реферат. Рассмотрены требования к выбросам вредных веществ дизелей путем выбора конструктивных и регулировочных параметров, определяющих организацию рабочего процесса, и системы очистки отработавших газов с учетом снижения расхода топлива. Разработаны элементы и геометрические характеристики конструкций для дизеля с турбонаддувом серии Д-245 производства ОАО «УКХ «Минский моторный завод» (4ЧН11/12,5) мощностью 90 кВт, оснащенного аккумуляторной системой впрыска топлива с электронным управлением (система рециркуляции отработавших газов по контуру высокого давления, форма и размеры камеры сгорания, количество и угловое расположение сопловых отверстий распылителя форсунки и впускные каналы головки блока цилиндров). Предложены способы организации рабочего процесса, учитывающие форму индикаторной диаграммы, по-разному влияющие на выбросы оксидов азота и дисперсных частиц. Их реализация позволяет определить граничные диапазоны изменения регулировочных параметров систем топливоподачи и рециркуляции отработавших газов при определении области минимизации удельного эффективного расхода топлива и диапазона изучения экологических показателей дизеля. Приведены результаты исследования способов обеспечения требований к выбросам вредных веществ, полученные путем рассмотрения вариантов организации рабочих процессов с учетом снижения удельного эффективного расхода

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топлива, изменения средней температуры отработавших газов и комплектации дизеля. Для оценки этих способов выделены показатели: изменение удельного расхода топлива и средней температуры цикла токсичности по отношению к базовому циклу, необходимая степень конверсии системы очистки по дисперсным частицам и NO_x. Даны рекомендации по выбору комплектации дизеля для обеспечения норм Stage 4 по выбросам оксидов азота и дисперсных частиц.

Ключевые слова: требования, выбросы, вредные вещества, установка, модель, исследования, конструктивные параметры, экология, цикл токсичности, процесс, топливная экономичность

Для цитирования: Кухарёнок, Г. М. Обеспечение требований к выбросам вредных веществ дизелей / Г. М. Кухарёнок, Д. В. Капский, В. И. Березун // *Наука и техника*. 2020. Т. 19, № 4. С. 305–310. <https://doi.org/10.21122/2227-1031-2020-19-4-305-310>

Introduction

Constant tightening of the requirements for diesel engines, directed the vector of development of the world engine-building towards improving environmental performance [1–8]. For a diesel engine, the greatest difficulty is the reduction of emissions of nitrogen oxides (NO_x) and particulate matter (PM), the maximum level of which is determined by the requirements of the technical regulations of the Customs Union. The reduction of emissions of harmful substances (BBB) is due to the finding of a compromise between the degree of complication of the diesel engine design and the efficiency of exhaust gas cleaning (OG) [1–3].

The decisive influence on emissions of harmful substances and fuel-economic indicators of a diesel engine is provided by the adjustment parameters: fuel injection pressure P_{in} , injection advance angle θ and exhaust gas recirculation rate ρ [9–11]. However, the range shift of the effective values of the variable parameters is determined by the basic design parameters of the engine. The use of battery injection

systems allows flexible control of the injection pressure and the injection advance angle without complicating the design, and together with the HORG system, they allow the design parameters of the engine to be coordinated for different operating modes.

The purpose of this work is to ensure the requirements for emissions of harmful substances of diesel engines by selecting design and adjustment parameters that determine the organization of the workflow, and the exhaust gas cleaning system, taking into account the reduction of fuel consumption.

Main part

A test facility for complex research of diesels workflows and NO_x and PM emission estimation has been worked out (Fig. 1). Its peculiar features are the following: automation of measurement and data smoothing processes, on-line monitoring of the eye diagram changes, the beginning of injection and injection duration, recycle rate control of CO₂ concentration in engine exhaust of the inlet gas [12–16].

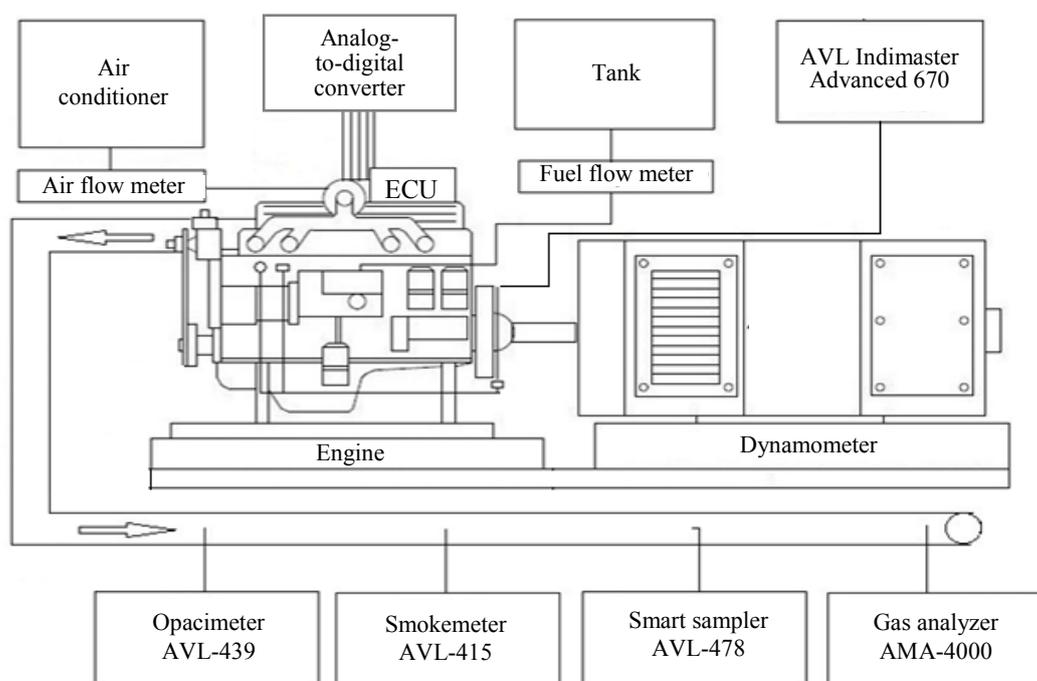


Fig. 1. Test facility lay-out

The test facility meets all the international UNO requirements (Rules No 24, 49, 96).

An investigating methodology has been developed. According to it, for the efficient use of time and labor cost reduction the sequence of parameter changes P_{in} , θ and ρ in providing an operating mode speed and torque = const was defined by the saturated plan of the experiment, which allows to express the acquired results in terms of quadratic regression equations. The required engine power was compensated for changing the quantity of the injection rate. For engine trend monitoring in order to reject misleading tests data while carrying out experimental research the verification of fuel-economic and ecological figures was provided on the chosen in advance control point with the equal fuel-injection equipment alignments and the degree of EGR.

The reproducibility of measurements was provided by systematic equipment calibration and check-out. Studies were conducted on the choice of design parameters with regard to improving environmental performance and reduce specific fuel consumption g_e . The following were configuration parameters study has been carried out with account for ecological performance improvement and corrected car economy (g_e) on the basis of a produced by Minsk Motor Plant 90 kWt turbocharged diesel (D-245 production number) which is equipped with the electronic fuel injection system. The following characteristics have been investigated: the shape of the combustion chamber, angular placement of the spray sparger, its configuration and the quantity of its nozzle holes, swirl ratio of inlet ports of the engine cylinder head, gas distribution

phases and the way of exhaust gas recirculation organization [17–24]. As a result, regulated EGR contoured by high pressure with the chill of circulated exhaust gas has been chosen. The developed elements of the configuration are in Fig. 2.

It has been revealed that the adjustment parameters P , θ and ρ which are changing in the engine's working process, play a crucial role in the working process organization that provides upholding ecological safety standards.

To carry out computational studies, a combined mathematical model of the diesel engine working process with the EGR system has been developed, based on the first law of thermodynamics, including the method of calculating the combustion process N. F. Razleitseva with refined coefficients, and the resulting empirical dependencies for calculating emissions of dispersed particles and exhaust gas temperature after the turbocharger [25–28]. To check the adequacy of the mathematical model, the calculation results for the nominal mode were compared with experimental data.

The compliance of the calculated form of the indicator diagram (ID) according to Fisher's criterion [5], which is the quotient of dividing the estimate of the variance of the S_D inadequacy by the estimate of the error of the single observation S_e , was performed

$$F = \frac{S_D / \varphi_n}{S_e / \varphi_d},$$

where φ_n – number of degrees of freedom of numerator; φ_d – number of degrees of freedom of denominator.

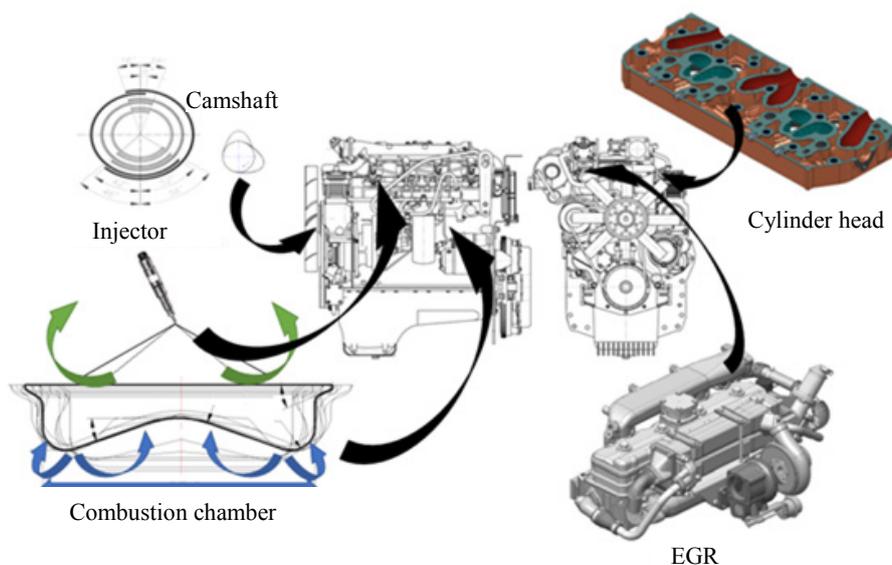


Fig. 2. Developed elements of the study object configuration

The observed value $F = 1.08 < F_{cr} = 1.16$ for statement performance probability $P_b = 0.95$ provides support for the model adequacy.

Dispersion numbers of the effective marker in examining the calculation sufficiency NO_x , PM and T'_r do not drop lower than 94 %. It testifies to the high statistical significance of characteristic curve for its calculation.

As a result, three means of the workflow organization have been singled out which influence NO_x and RM emission in different ways [29]. These means are determined by the type of ID that are shown in Fig. 3.

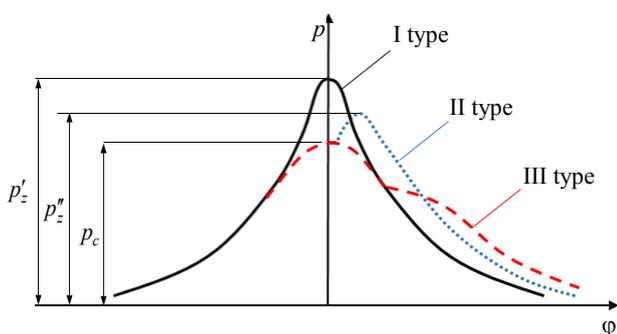


Fig. 3. Indicator diagrams

The first type (I type) is a one-humped ID depicting the ratio of peak combustion pressure to compressive pressure $p_z/p_c > 1$; II type is a double-humped ID depicting $p_z/p_c > 1$ and III type is a double-humped ID depicting $p_z/p_c \leq 1$ (with an indistinct peak p_z).

Calculated analyses of PM and NO_x emission adjustment parameters according to the saturated plan of the experiment for each NRSC ecological cycle mode have been conducted [12]. The margin limits of the variation range have been chosen according to the working processes in the area of the ID (three types). The variation range of P and ρ has been limited by the fuel consumption rate of the initial related type stage along with the correlated ecological parameters. As an additional restricting parameter the exhaust gas temperature after the turbocharger T'_r has been taken, which has been restricted with account of the study subject technical specifications. The margin limits of the adjustment parameters allow to define the minimization area g_e as well.

In order to choose the fuel supply parameters and the exhaust fume recycle rate the simulation data has been analyzed as well as the obtained regression dependence with regard of the ID type. Taking into consideration generally accepted

emission reduction strategies for each peak of NRSC cycle target-oriented approaches to solving the problems have been searched for. For the peak of the ecological cycle H-100 substantiation of combustion process parameters data is in Fig. 4. The data analysis has been performed in the following three directions:

- 1) minimization g_e (g_{emin});
- 2) PM minimization (PM_{min});
- 3) NO_x minimization (NO_{xmin}).

For the first direction the following parameters have been chosen: $P_{in} = 160$ MPa, $\theta = 10$ degrees and $\rho = 0.12$ if emitted $NO_x = 6.07$ g/(kW·h), $PM = 0.04$ g/(kW·h) and $g_e = 214.2$ g/(kW·h).

While calculating the whole body of data the results of the search for NO_x and PM minimization determine nonrational parameters from the point of view of fuel-economic figures. It shows itself in the choice of extreme settings of the working process in the range under consideration.

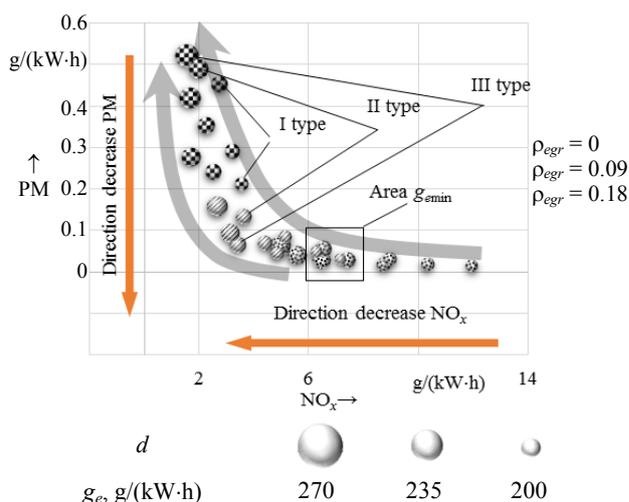


Fig. 4. PM- NO_x diagram for nominal conditions

Consequently, for the 2nd and 3rd directions the solutions have been searched for in limiting fuel consumption in relation to the data of the 1st direction (g_{emin}). To minimize PM the search for solutions was made in the following two ways: NO_x increasing and NO_x decreasing by means of imposing an additional boundary condition. The simulated result of the three directions of the emission reduction strategy for the cycle H-100 is depicted in the paper. As percentage in Fig. 5 fuel consumption variation is expressed.

In the proposed variant of decision making organization the parameters of fuel consumption degradation tend to organize the working process with

the initial stage of the indicator diagram and a transition from type I to type III. This is reflected in the fact of θ decrease while P_m is maintained at the upper variation limit. The difference in NO_x and PM minimization consists only in the fact that in the former case ρ is in the value range of 0.16, but in the latter case it approximates 0.

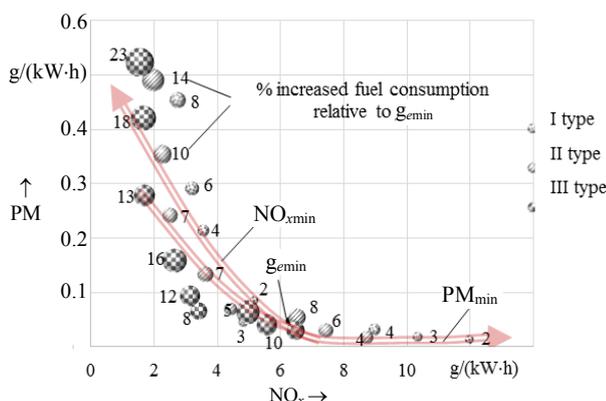


Fig. 5. Dimensions of ecological indices improvement for nominal operation conditions

In the areas of the obtained values, a study was conducted on ways to reduce diesel emissions, for the evaluation of which the following indicators were highlighted:

Δg_e – is the change in fuel consumption in relation to the base cycle;

ΔT_{avr} – is the change in the average temperature of the toxicity cycle relative to the base cycle;

C_{PM} , C_{NO_x} – is the required degree of conversion of the purification system for PM and NO_x to achieve the standards of Stage 4, defined as the ratio of the difference between the values of “raw” and normalized emissions to the value of “raw” emissions.

Five stages of workflows calculation have been identified with account for fuel consumption with load increase, toxicity level factor weight and the presence of the EGR system (Tab. 1).

Table 1

NO_x and PM emission reduction strategies data

Calculation stage	NO_x , g/(kW·h)	PM, g/(kW·h)	Δg_e , %	ΔT_{avr} , K	C_{PM}	C_{NO_x}	EGR
1	8.1	0.031	–	–	0.20	0.95	+
2	5.1	0.089	10.9	54	0.70	0.92	+
3	13.1	0.014	2.4	4	–	0.97	–
4	7.7	0.025	2.4	4	–	0.95	+
5	2.5	0.265	12.0	81	0.91	0.83	+

At the first stage to compose the basic toxicity level for each mode the workflow settings

have been chosen which provide g_e minimization. The summary NO_x and PM emission indicators have been 8.100 g/(kW·h) and 0.031 g/(kW·h) respectively. At the same time the exhaust gas temperature according to the toxicity level constitutes 647 K.

At the 2nd and 3rd stages a PM reduction strategy has been fulfilled involving the use of EGR system and its excluding. As a result, for the engine configuration without the EGR system the cycle with NO_x and PM of 13.1 g/(kW·h) and 0.014 g/(kW·h) has been obtained respectively. It allows to meet PM Stage 4 regulations without the use of the EGR system. Herewith, Δg_e is 2.4 %, but the ΔT_{avr} increase is 4 K. For the engine configuration without the EGR system NO_x and PM emission constitutes 5.100 g/(kW·h) and 0.089 g/(kW·h) respectively, Δg_e is 10.9 % and the ΔT_{avr} increase is 54 K.

At the 4th calculation stage the strategy of meeting PM reduction within the framework of Stage 4 regulations was considered with the opportunity to reduce NO_x by using the EGR system. The PM value of 0.025 g/(kW·h) within a cycle has been successful with the NO_x emission of 7.7 g/(kW·h) and with the ΔT_{avr} increase of 4 K together with the Δg_e increase of 2.4 %.

At the 5th calculation stage a NO_x reduction strategy has been fulfilled. The cycle obtained provided NO_x and PM with 2.500 g/(kW·h) and 0.265 g/(kW·h) respectively, Δg_e has increased by 12 % and ΔT_{avr} – by 81 K.

The choice of the emission reduction strategies was made with regard of fuel consumption and the reduction of engine configuration elements. Especially appealing are the strategies within the framework of PM Stage 4 regulations (variants 3 and 4).

CONCLUSIONS

1. The design parameters of the combustion chamber, cylinder head, nozzle and exhaust gas recirculation system of diesel engine are defined, allowing to organize the flow of the working process, taking into account the improvement of environmental and fuel-economic indicators.

2. Methods of workflow organization are proposed that differ in the shape of the indicator diagram, allowing to determine the range of changes in the parameters of fuel supply control and exhaust gas recirculation during each toxicity cycle mode.

3. Methods to meet the requirements for emissions of harmful substances from a diesel engine, differing in the priority of fuel efficiency with increasing load, the weighting factors of the toxic cycle, the exhaust gas temperature after the turbocharger and the degree of conversion of the exhaust gas cleaning system are investigated.

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Received: 09.07.2019

Accepted: 15.10.2019

Published online: 30.07.2020