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DOI: doi.org/10.18372/38224
UDC: 621.436-634:502.17


## 2.7 NITROGEN OXIDE AND DISPERSE PARTICLES EMISSION REDUCTION IN DIESEL ENGINES


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Constant toughening of requirements for diesels has directed the development of the world engine manufacturing to improving ecological indeces. The major difficulty for diesel engine-building is nitrogen oxide (NOx) and particles mater (PM) emission reduction. Their level limit is determined by the requirements of technical guidelines. Concerning available at the moment technologies, the strategy of emission reduction (ER) is conditioned by the compromise between the degree of diesel design complexity and fume cleaning efficiency [1, 2, 3].

Among the factors considered above the following parameters are worth mentioning: the injection pressure, the fuel injection advance angle and the exhaust fume recycle rate for reasons of the major influence on fume emission and the fuel-economic indicator. At the same time the effective value range shift of varying parameters is determined by the basic diesel engine design parameters. The use of injection systems allows to control flexibly the injection pressure and the fuel injection advance angle without making the engine design too complex. Together with the use of the exhaust gas recirculation (EGR) system the injection systems allow to coordinate design parameters and engine-on mode specifications.

The improving potential of diesel engine operating cycle is currently not exhausted: it is the main means of attaining up-to-date regulated markers, which makes the research of the fume emission reduction potential by means of improving engine workflows relevant and requested.

The most difficult task for diesel engines is to meet the requirements of $NO_x$ and PM emission reduction [3].

The purpose of the research is to reduce the so called "unrefined" NOx and PM emission by means of choosing design and adjustment parameters of diesel engines workflows taking into account the priority of fuel economy.

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 $CO_2$ concentration in engine exhaust of the inlet gas.

The test facility meets all the international UNO requirements (Rules №№ 24, 49, 96).An investigating methodology has been developed. According to it, for the efficient use of time and labor costs reduction the sequence of parameter changes Pinj, Θ and ρegr 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 quadric 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.

Configuration parameters study has been carried out with account for ecological performance improvement and corrected car economy (ge) on the basis of a produced by Minsk Engine Plant 90 kilowatt turbocharged diesel (Д-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 (ECH), gas distribution phases and the way of exhaust gas recirculation (EGR) organization [4]. As a result, regulated EGR contoured by high pressure with the chill of circulated exhaust gas (EG) has been chosen. The developed elements of the configuration are in Fig. 2.

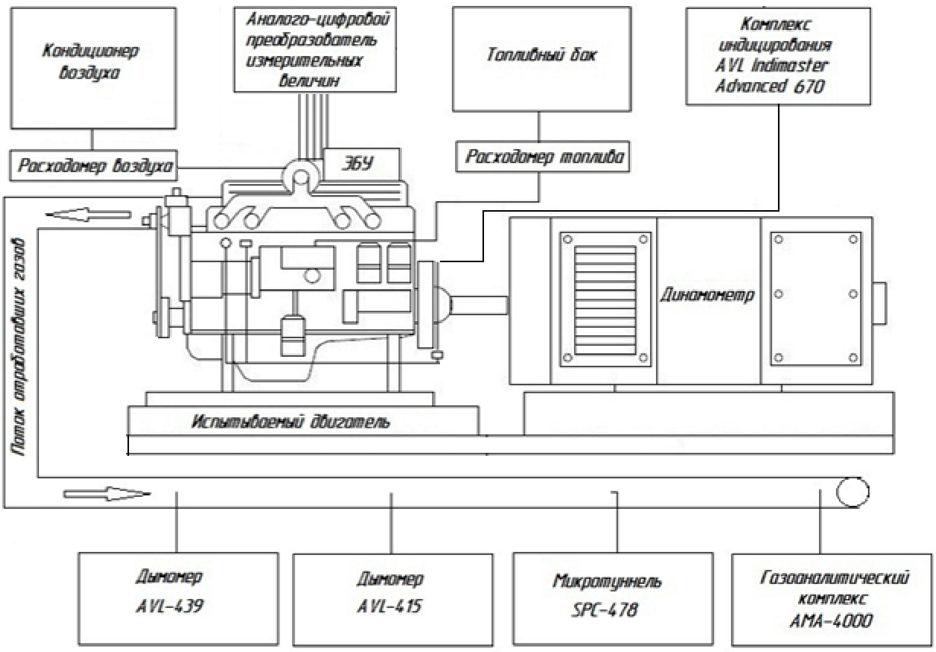


Fig. 1. Test facility lay-out

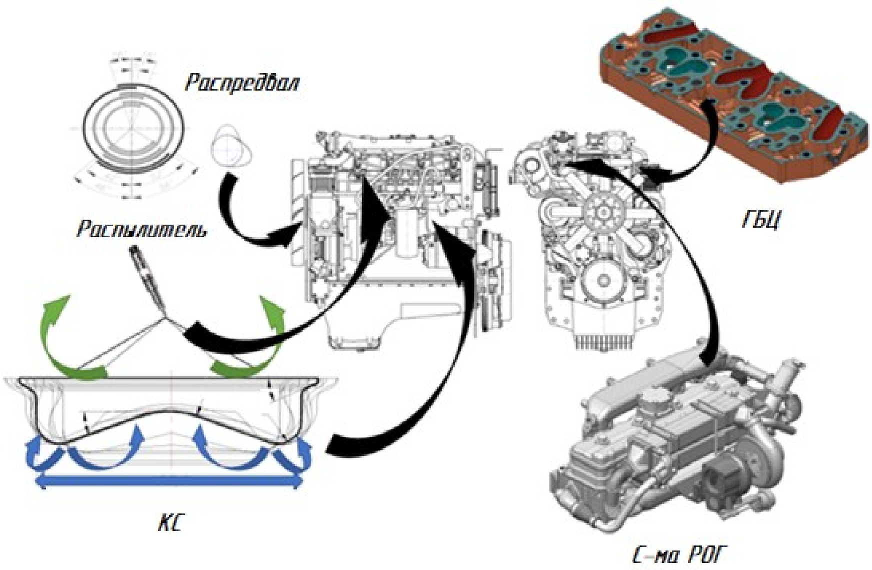


Fig. 2. Developed elements of the study object configuration

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

In order to conduct calculated analyses an integrated mathematical model of the diesel with ERG system working process has been created. It is based on the first law of thermodynamics and includes N. Razleitsev's analysis technique of the fuel combustion process with updated coefficients, deduced empirical dependence for calculations of disperse particles emission and the temperature of the exhaust gas after the turbocharger [4].

For mathematical model verification the calculation data for the nominal rating was compared with the experimental data.

Conformance checks of the indicator diagram (ID) design form by Fisher's criterion have been performed [5], which is the quotient obtained when the variance estimate of inadequacy $S_D$ is divided by the variance estimate of the single observation error $S_e$:

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

where $\varphi_n$ – number of degrees of freedom of random quantity numerator $F$; $\varphi_d$ – number of degrees of freedom of random quantity denominator $F$.

The observed value $F$ = 1,08 < $F$cr= 1,16 for statement performance probability $Pb$ = 0,95 provides support for the model adequacy.

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

The calculation algorithm was implemented in programming environment Delphi.

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

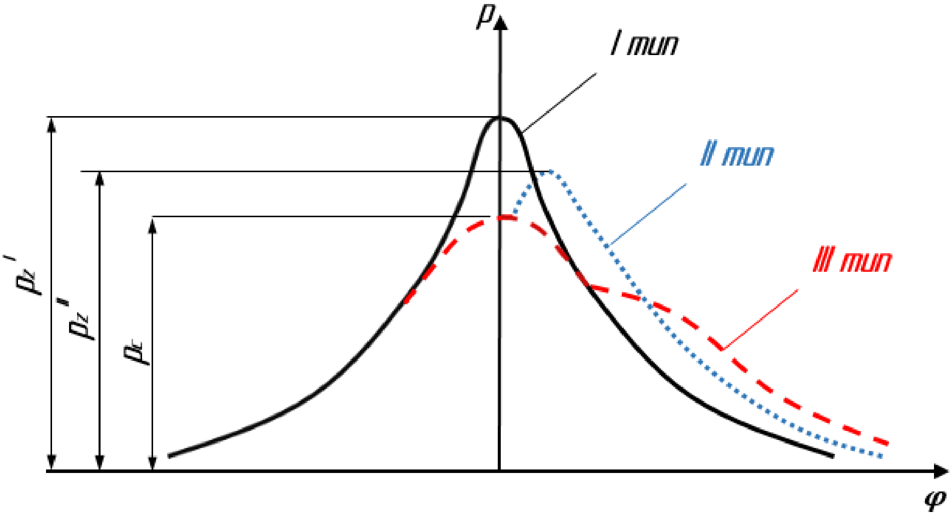

Fig. 3. Indicator diagrams

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

Calculated analyses of PM and NOx emission adjustment parameters according to the saturated plan of the experiment for each NRSC (Non-Road Transient Steady-state Cycle) ecological cycle mode have been conducted. 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 pinj and ρegr 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 (Tr') 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 ge 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 regressional 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 ($NO_{x\,min}$).

Parameter selection has been conducted with the help of an imbedded program module «finding solutions» from the Microsoft Excel Table, where a principle of non-linear optimization is laid down.

For the first direction the following parameters have been chosen: $p_{inj}$ = 160 mPas, θ = 10 degrees и $\rho_{egr}$ = 0,12 if emitted $NO_x$= 6,07 g/kWh, PM = 0,04 g/kWh and $g_e$ = 214,2 g/kWh.

While calculating the whole body of data the results of the search for NOx 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.

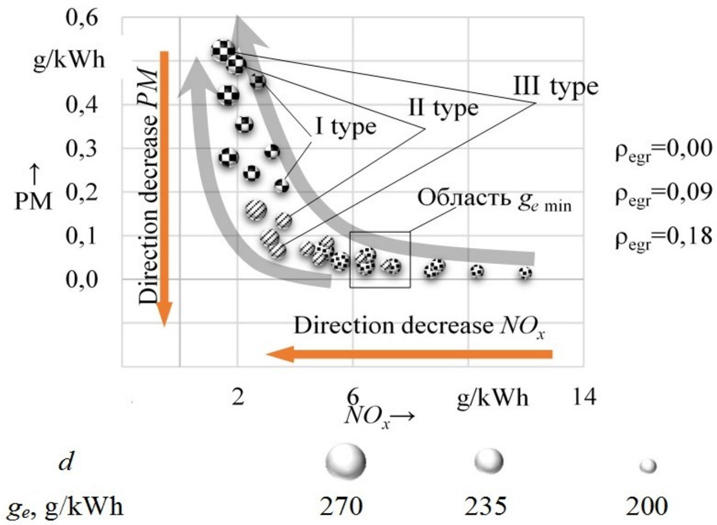


Fig. 4. PM-NOx diagram for nominal conditions

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 ($g_{e\ min}$). 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. As percentage in figure 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 Pinj 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 ρegr is in the value range of 0,16, but in the latter case it approximates 0.

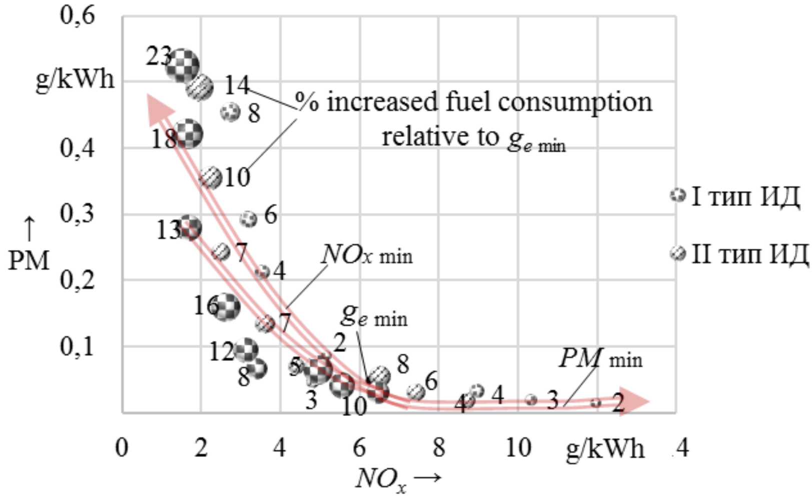


Fig. 5. Dimensions of ecological indices improvement for nominal operation conditions

In the range of obtained values the study of diesel emission reduction strategies has been carried out. For their estimation the following characteristics have been singled out:

$\Delta g_e$ – fuel consumption change in regard of the basic cycle, defined by workflow management adjustment parameters which provide ge minimization at all toxicity level;

$\Delta T_{avr}$ – average toxicity level temperature change in regard of the basic cycle;

$C_{PM}$, $C_{NOx}$ – desired degree of PM and $NO_x$ clean-up system conversion in order to meet Stage 4 regulations. The degree is defined as difference quotient between the values of «raw» and normable diesel emission reduction to the value of «raw» emission.

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 (Table 1).

At the first stage to compose the basic toxicity level for each mode the workflow settings have been chosen which provide ge minimization. The summary $NO_x$ and PM emission indicators have been 8,1 g/kWh and 0,031 g/kWh respectively. At the same time the exhaust gas temperature according to the toxicity level constitutes 647 K.

At the 2$^{nd}$ and 3$^{rd}$ 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/kWh and 0,014 g/kWh has been obtained respectively. It allows to meet PM Stage 4 regulations without the use of the EGR system. Herewith, $\Delta g_e$ is 2,4 %, but the $\Delta T_{avr}$ increase is 4o. For the engine configuration without the EGR system $NO_x$ and PM emission constitutes 5,1 g/kWh and 0,089 g/kWh respectively, $\Delta g_e$ is 10,9 % and the $\Delta T_{avr}$ increase is 54o.

*Table* 1

NOx and PM emission reduction strategies data

| Calculation stage | $NO_x$, g/kWh | PM, g/kWh | $\Delta g_e$, % | $\Delta T_{avr}$, $^o$ | $C_{PM}$ | $C_{NOx}$ | 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 4th calculation stage the strategy of meeting PM reduction within the framework of Stage 4 regulations was considered with the opportunity to reduce NOx by using the EGR system. The PM value of 0,025 g/kWh within a cycle has been successful with the NOx emission of 7,7 g/kWh and with the ΔTavr increase of 4o together with the Δge increase of 2,4 %.

At the 5th calculation stage a NOx reduction strategy has been fulfilled. The cycle obtained provided NOx and PM with 2,5 g/kWh and 0,265 g/kWh respectively, $\Delta g_e$ has increased by 12 % and $\Delta T_{avr}$ – by 81o.

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).

## РЕФЕРАТ

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**ЗНИЖЕННЯ ВИКИДІВ ОКСИДІВ АЗОТУ ТА ДИСПЕРСНИХ ЧАСТИНОК ДИЗЕЛЯ**

Виконано оцінку напрямів зниження викидів $NO_x$ і PM через розгляд варіантів організації робочого процесу з урахуванням пріоритету паливної економічності при зростанні навантаження, вагових факторів циклу токсичності, комплектації двигуна, а також необхідної для досягнення цільового ступеню екологічної безпеки ступеня конверсії системи очищення ОГ і зміни середньої температури ОГ циклу токсичності.

Визначено параметри подачі палива і ступеня РОГ, що дозволили реалізувати в електронному блоці дизеля алгоритм управління, що забезпечує протікання робочого процесу в межах виконання норм Stage 4 по РМ без застосування сажевих фільтрів.

**Ключові слова:** дизель, параметри подачі палива, рециркуляція відпрацьованих газів, оксиди азоту, дисперсні частинки.

## РЕФЕРАТ

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### СНИЖЕНИЕ ВЫБРОСОВ ОКСИДОВ АЗОТА И ДИСПЕРСНЫХ ЧАСТИЦ ДИЗЕЛЯ

Проведена оценка направлений снижения выбросов $NO_x$ и РМ путем рассмотрения вариантов организации рабочего процесса с учетом приоритета топливной экономичности при росте нагрузки, весовых факторов цикла токсичности, комплектации двигателя, а также необходимой для достижения целевой ступени экологической безопасности степени конверсии системы очистки ОГ и изменения средней температуры ОГ цикла токсичности.

Определены параметры топливоподачи и степени РОГ, позволившие реализовать в электронном блоке дизеля алгоритм управления, обеспечивающий протекание рабочего процесса в границах выполнения норм Stage 4 по РМ без применения сажевых фильтров.

**Ключевые слова:** дизель, параметры топливоподачи, рециркуляция отработавших газов, оксиды азота, дисперсные частицы.

## ABSTRACT

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### NITROGEN OXIDE AND DISPERSE PARTICLES EMISSION REDUCTION IN DIESEL ENGINES

The paper focuses on the directions of the strategy to reduce emissions of NOx and PM. They were assessed by considering options for organizing the workflow taking into account the priority of fuel economy with increasing load, toxic cycle weight factors, engine configuration, as well as the degree of conversion of the exhaust gas cleaning system and average temperature required to achieve the target environmental safety level Exhaust cycle toxicity.

The fuel supply parameters and the degree of EGR are determined, which allowed to implement a control algorithm in the electronic block of a diesel engine that ensures the flow of the working process within the limits of the fulfillment of Stage 4 standards according to the RM without the use of particulate filters.

**Key words**: diesel, fuel supply parameters, exhaust gas recirculation, nitrogen oxides, particles mater.

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