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Organization of Six-Cylinder Tractor Diesel Working Process

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Abstract. The purpose of the work is to consider the organization of the working process of six-cylinder diesel engines with a power of 116 and 156 kW and exhaust gas recirculation. The following systems and components were used in the experimental configurations of the engine: Common Rail BOSCH accumulator fuel injection system with an injection pressure of 140 MPa, equipped with electro-hydraulic injectors with seven-hole nozzle and a 500 mm^3 hydraulic flow; direct fuel injection system with MOTORPAL fuel pump with a maximum injection pressure of 100 MPa, equipped with MOTORPAL and AZPI five-hole nozzle injectors; two combustion chambers with volumes of 55 and 56 cm^3 and bowl diameters of 55.0 and 67.5 mm, respectively; cylinder heads providing a 3.0–4.0 swirl ratio for Common Rail system, 3.5–4.5 for mechanical injection system. The recirculation rate was set by gas throttling before the turbine using a rotary valve of an original design. The tests have been conducted at characteristic points of the NRSC cycle: minimum idle speed 800 rpm, maximum torque speed 1600 rpm, rated power speed 2100 rpm. It has been established that it is possible to achieve the standards of emissions of harmful substances: on the 116 kW diesel engine using of direct-action fuel equipment and a semi-open combustion chamber; on the 156 kW diesel using Common Rail fuel supply system of the Low Cost type and an open combustion chamber.

Keywords: diesel, swirl ratio, combustion chamber, fuel supply system, fuel sprayer

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Организация рабочего процесса шестицилиндрового тракторного дизеля

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Реферат. Рассмотрена организация рабочего процесса шестицилиндровых дизелей мощностью 116 и 156 кВт с рециркуляцией отработавших газов. В экспериментальных комплектациях двигателя использовались следующие системы и узлы: аккумуляторная система подачи топлива Common Rail BOSCH с давлением впрыска 140 МПа, оснащенная электрогидравлическими форсунками с семисопловыми отверстиями и проливом 500 мм^3; система впрыска непосредственного действия с топливным насосом MOTORPAL с максимальным давлением впрыска 100 МПа, оснащенная форсунками MOTORPAL и АЗПИ с пятисопловыми отверстиями; камеры сгорания двух типов объемами 55 и 56 см^3 с диаметрами горловин 55,0 и 67,5 мм; головки блоков цилиндра, обеспечивающие вихревое отношение для системы впрыска Common Rail 3.0–4.0, для механической системы впрыска 3,5–4,5. Степень рециркуляции задавалась дросселированием отработавших газов перед турбиной с помощью заслонки оригинальной конструкции. Испытания проводились по характерным точкам цикла NRSC на трех частотах вращения коленчатого вала: минимальной холостого хода 800 мин$^{-1}$, максимальной крутящего момента 1600 мин$^{-1}$ и максимальной мощности 2100 мин$^{-1}$. Установлено, что достижение норм выбросов вредных веществ возможно: на дизелях

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мощностью 116 кВт с использованием топливной аппаратуры непосредственного действия и с полуоткрытой камерой сгорания; на дизелях мощностью 156 кВт с использованием системы топливоподачи Common Rail типа Low Cost и открытой камерой сгорания.

Ключевые слова: дизель, вихревое отношение, камера сгорания, система топливоподачи, распылитель топлива

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Introduction

The diesel engine building is one of the main areas of mechanical engineering developed recently in the Republic of Belarus. Minsk Motor Plant is the oldest enterprise in the republic, which produces multi-purpose diesel engines in a wide power range (Fig. 1) for 56 years. The enterprise development strategy, implemented within the framework of plant and state scientific and technical programs, is aimed at producing competitive products that meet modern technical requirements of international standards and quality [1].

The technical regulations of the Customs Union require newly manufactured or imported new tractors diesel engines to comply with Stage 3A environmental standards, which should increase the demand for diesel engines of this ecological class [2–9]. Two modifications of six-cylinder tractor diesel engines are currently in greatest demand: D-260.1S3A with a power of 116 kW and D-260.4S3A with a power of 156 kW.

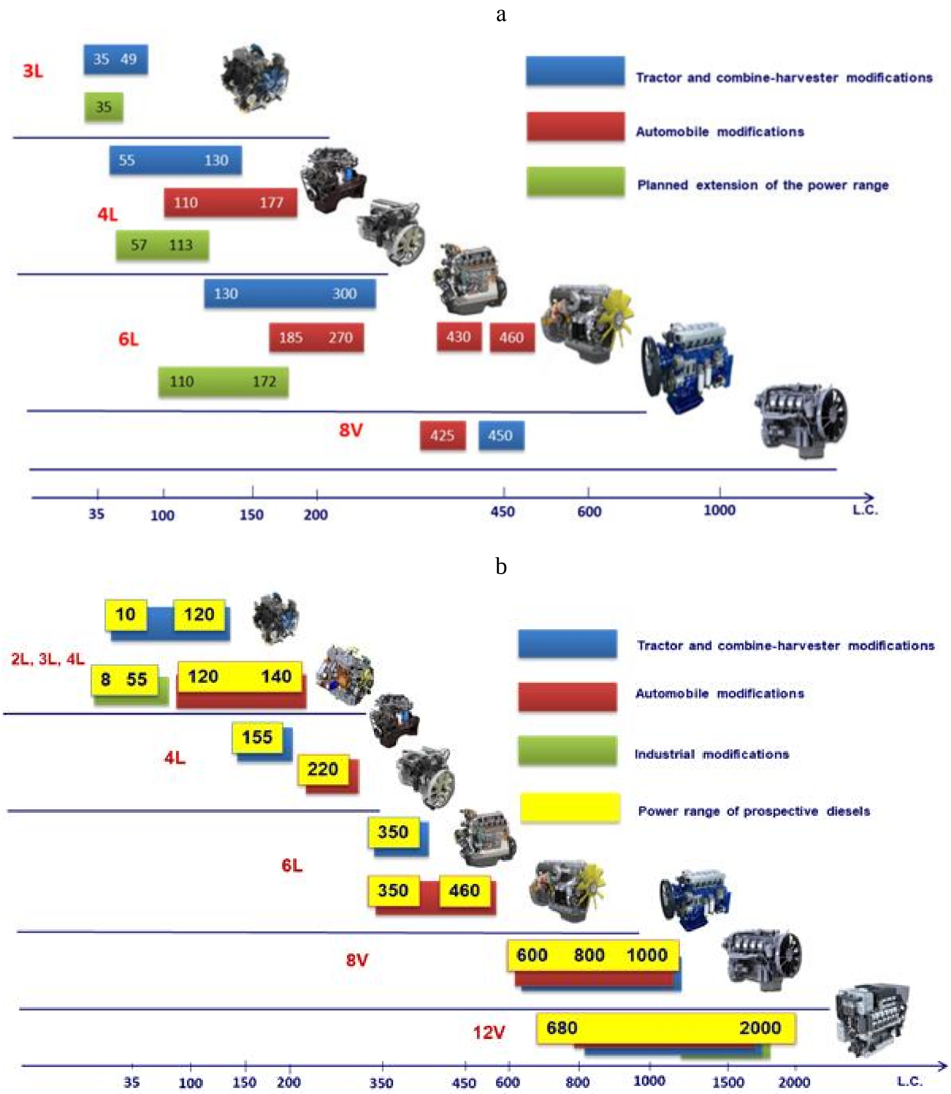

Fig. 1. Power range of the engines manufactured by Minsk Motor Plant: a – serial engines; b – promising

Main part

The environmental performance of the Stage 3A level is achieved mainly by coordinating the combustion chamber shape, the fuel supply equipment parameters, the intake ports swirl ratio, the valve timing and the use of exhaust gas recirculation (EGR) [1, 10–16].

D-260 engines use cylinder heads with two valves per cylinder, which should ensure the simplicity of the gas distribution mechanism design and maintenance. The somewhat increased resistance of the gas exchange channels is compensated to some extent by engine boost. The inlet channels are bifunctional – screw. When profiling the channels, the correctness of the adopted structural decisions is checked by 3D-modeling of the gas flow at given pressure drops (Fig. 2) with the determination of air flow and the average angular velocity of the air charge.

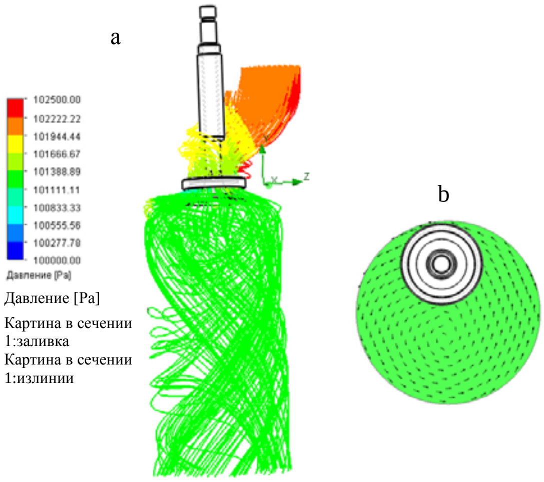

Fig. 2. Results of the inlet channel virtual purge:
a – pressure distribution; b – velocity field in the outlet section

The mathematical model of a viscous heat-conducting fluid flow is based on the Navier – Stokes equations system, combining the laws of mass, momentum and energy conservation of a fluid in an unsteady setting [17–21].

To control the parameters of the cast heads inlet channels, a non-motorized purge stand with a straightening grate is used [22]. Typically, the data of virtual and natural purges differ by no more than 5 %. For D-260 engines, the head designs have been developed that provide an air swirl generation at the inlet with a swirl ratio of 3.0–4.0 and 3.5–4.5.

Heads with a lower swirl ratio are used on engines equipped with accumulator fuel systems with high injection rates and open combustion chambers (Fig. 3a) [23, 24]. Large swirl ratios are used for engines with direct-acting fuel equipment and a semi-open combustion chamber (Fig. 3b) [25].

The commercially available satisfying Stage 3A environmental standards six-cylinder D-260 diesel engines are equipped with: BOSCH Common Rail fuel supply system with electronic control; pistons with an open combustion chamber; a cylinder head with a screw inlet channel providing a swirl ratio $H = 3.0–4.0$; unregulated turbo charging. Low pressure EGR is used to reduce NO_x emissions [26].

In order to increase the competitive attractiveness of six-cylinder engines, it was decided to use fuel supply systems of a lower price category – a fuel supply system with a direct-acting pump and a mechanical regulator manufactured by MOTORPAL. The fuel supply system layout with a direct-acting pump is shown in Fig. 4.

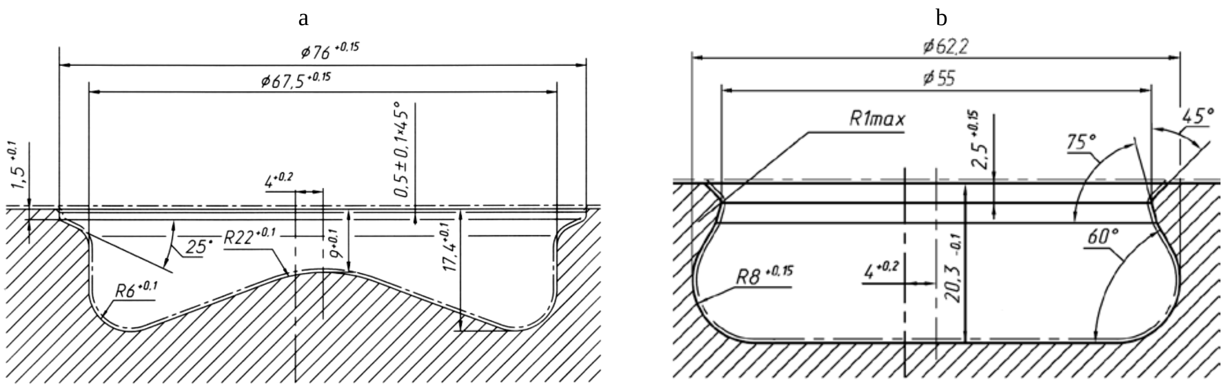

Fig. 3. Combustion chambers: a – open combustion chamber; b – semi-open combustion chamber

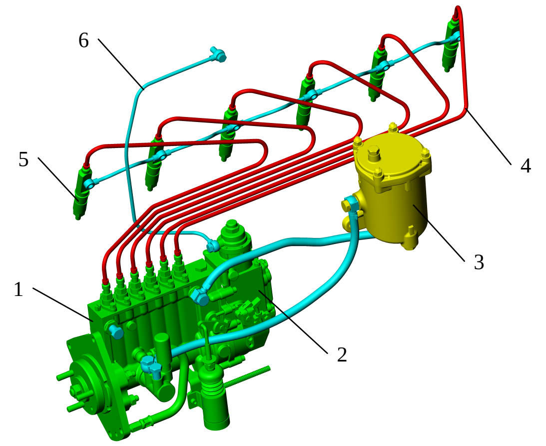

Fig. 4. Fuel supply system layout with a MOTORPAL pump:
1 – high pressure fuel pump; 2 – speed governor;
3 – fuel filter; 4 – high pressure fuel line; 5 – injector;
6 – tube to the corrector for charge air pressure

The fuel pump 6M4330ZT (MOTORPAL, Czech Republic) with a diameter of 10 mm and a stroke of 14 mm of the plunger is equipped with a mechanical governor and a fuel feed corrector by the charge air pressure. The maximum fuel injection pressure is 100 MPa. When developing the working process on a 116 kW diesel engine, three sets of hydromechanical injectors were used:

– injectors VA70P360 with nozzles DOP147P528 (μf = 0.22 mm^2) (MOTORPAL, Czech Republic) (Fig. 5a) (for an open combustion chamber);

– injectors VA70P360 with sac-less nozzles DOP140P528 (μf = 0.18–0.20 mm^2) (MOTORPAL, Czech Republic) (Fig. 5b);

– injectors AZPI 172.1112010-11.01 with nozzles AZPI 172.1112110-12.01 (μf = 0.23–0.25 mm^2).

Matching of the combustion chamber shape and the fuel flames location was carried out using 3D-models [24, 27]. The places where the fuel jets axes meet the combustion chamber walls are shown in Fig. 6.

The comparative tests (Tab. 1) for the NRSC cycle showed the possibility of achieving emission standards for Stage 3A. The use of sac-less nozzles led to a decrease in fuel leakage and, as a consequence, to a decrease in nozzles coking, soot and CH_x hydrocarbons emissions [12, 28]. Tests of the D-260.4S3A diesel engine with direct-acting fuel equipment showed a high exhaust smoke level while ensuring the target NO_x emissions (Tab. 1) using the EGR. As a result, achieving the Stage 3A level for particulate emissions on a D-260.4 engine with a direct-acting fuel system with semi-open and open combustion chambers is not possible at this stage. Therefore, the proposed use of the type Low Cost Common Rail accumulator system.

The schematic diagram of the type Low Cost Common Rail system is shown in Fig. 7. It includes:

– the fuel pump CB 28;

– injectors CRIN2 with seven-hole nozzles A433 205 533 (jet cone angle δ = 147.6° and a hydraulic flow of 500 cm^3/30 s/100 bar);

– the pressure accumulator LWRN18 with a maximum injection pressure of 1400 bar;

– the control unit EDC17CV54 with software version P_1142.3.0.0 for the Low Cost system.

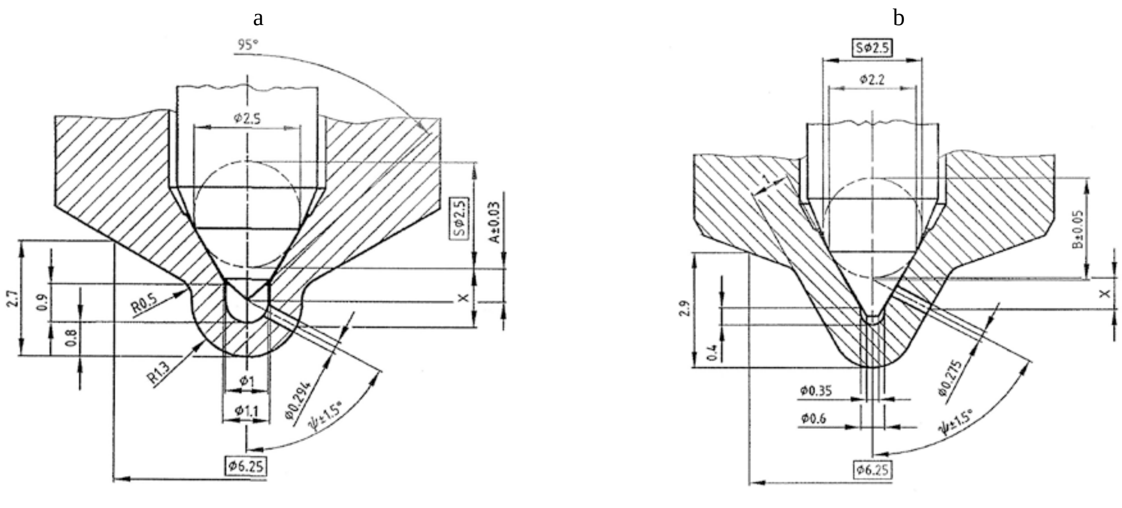

Fig. 5. Nozzle cone shapes: a – with a blind-hole (with a dead volume);
b – with the exit of nozzle holes to the surface of the locking cone (sac-less nozzle)

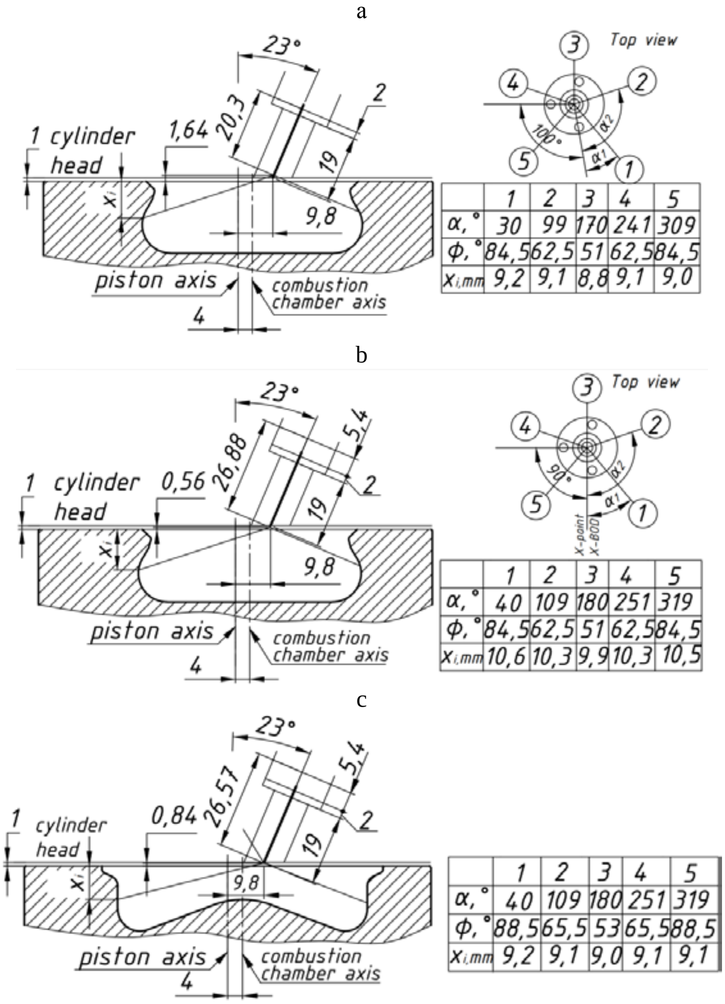

Fig. 6. Determination of the points of intersection of the fuel flames axes with the combustion chambers walls:
a – AZPI 172.1112110-12.01 nozzle; b – MOTORPAL DOP140P528; c – MOTORPAL DOP147P528

Table 1

Results of D-260.1 and D-260.4 diesel engines comparative tests with various nozzles and combustion chambers according to the NRSC cycle

Diesel	Options	g_{CH}, g/(kW·h)	g_{NOx}, g/(kW·h)	g_{SC}, g/(kW·h)	g_{eRP}, g/(kW·h)	$g_{eT\max}$, g/(kW·h)	N_{RP}, %HSU	$N_{T\max}$, %HSU
D-260.1S3A	Nozzles AZPI 172.1112110-12.01	0.48	3.43	0.240	228.4	204.9	7.9	9.1
	Nozzles DOP140P528	0.21	3.84	0.164	229.9	204.5	6.6	4.3
	UNECE Regulation No 96 (02)	4.0 (NO_x + CH)		0.300	–			
D-260.4S3A	Nozzles DOP140P528	–	3.42	0.360	229.3	215.6	16.5	17.8
	Nozzles DOP147P528, open combustion chamber	–	3.46	0.338	229.2	216.0	12.8	17.6
	UNECE Regulation No 96 (02)	4.0 (NO_x + CH)		0.200	–			

To increase the recirculation and turbocharging units reliability, a transition to the high-pressure EGR system, the diagram of which is shown in Fig. 8 [26, 29, 30]. In the high-pressure EGR system, the recirculated exhaust gases do not pass through the turbocharging units, which should have a positive effect on the operating conditions of the charge air cooler and compressor. However, in order to obtain the required gas cooling depth, the size of the standard built into the catchment pipe cooler is not enough. Therefore, an additional EGR cooler (similar to the serial one with four-cylinder engines) is included in the experimental setup.

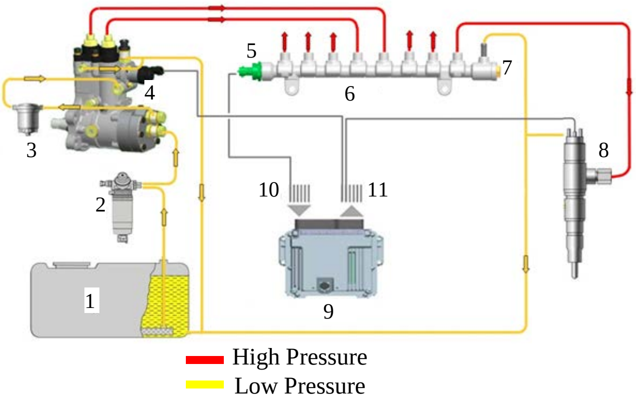

Fig. 7. Diagram of the Common Rail fuel system:
1 – fuel tank; 2 – coarse filter; 3 – fine filter; 4 – fuel pump;
5 – fuel pressure sensor; 6 – fuel rail; 7 – pressure-relief valve;
8 – injector; 9 – electronic control unit;
10 – signals from sensors; 11 – signals to actuators

Tests of six-cylinder diesel engines with the high-pressure EGR system showed the problem of organization the EGR gas flow in the right direction. In some operating modes, the charge air pressure is higher than the exhaust pressure upstream the turbine. To create the necessary pressure difference, an additional rotary valve was introduced into the recirculation system, which prevents the free passage of exhaust to the turbine. As a result of testing a diesel engine with a Low Cost type Common Rail system and the rotary EGR valve, the rotary valve positions were determined and turbocharging units were selected to achieve Stage 3A level for exhaust emissions. The test results of the engine D-260.4S3A are presented in Tab. 2.

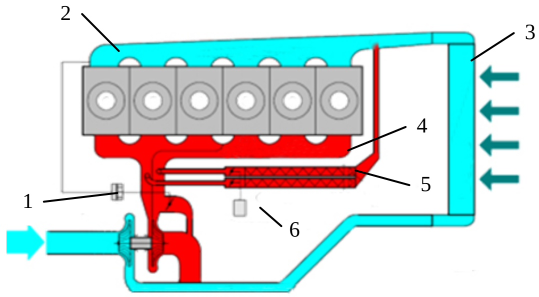

Fig. 8. Schematic diagram of the high-pressure EGR system: 1 – bypass valve; 2 – inlet manifold; 3 – charge air cooler; 4 – exhaust manifold; 5 – EGR cooler; 6 – rotary EGR valve

Table 2

Results of D-260.4S3A diesel tests with a Common Rail fuel system on the NRSC cycle

Parameters		Cycle Point								Per Cycle
		1	2	3	4	5	6	7	8	
n, rpm		2100	2100	2100	2100	1600	1600	1600	800	–
M_k, N·m		706	530	353	71	899	690	460	0	–
$\alpha_{EGRvalve}$, % op.		35	80	80	100	65	85	82	100	–
g_e, g/(kW·h)		220.5	227.1	243.4	472.6	221.7	219.7	227.9	–	–
N, %HSU		5.7	5.7	3.9	0.8	7.2	6.8	7.2	0.6	–
g_{NOx}, g/(kW·h)		4.61	2.57	2.00	3.25	4.39	2.47	1.69	–	3.30
g_{SC}, g/(kW·h)		0.136	0.146	0.111	0.031	0.148	0.141	0.168	–	0.138
UNECE Regulation No 96(02)	g_{NOx+CH}, g/(kW·h)	–								4.0
	g_{SC}, g/(kW·h)	–								0.2

CONCLUSION

Measures have been developed to organize the six-cylinder tractor diesel engines working process of the ecological level Stage 3A with high-pressure exhaust gas recirculation. It has been established that the achievement of emission standards on diesel engines with a power of 116 kW is possible using direct-acting fuel equipment and a semi-open combustion chamber. To comply with Stage 3A on 156 kW diesel engines, the use of a Low Cost type Common Rail fuel system with an open combustion chamber is required.

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