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STAGE 3A ENVIRONMENTAL COMPLIANCE OF THE 6-CYLINDER TRACTOR ENGINE

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Abstract. Problem. *The development strategy of the Minsk Motor Plant, 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. The mandatory requirement for the successful promotion of diesel engines on the off-road vehicle market is to ensure the required environmental performance, with low fuel consumption and low engine cost. The well-known technical solutions aimed to achieve environmental indicators of the Stage 3A level significantly increase the cost of diesel engines, therefore, the achievement of the required environmental standards without a significant increase in the cost of engines can be considered an urgent task.* ***Purpose.*** *Stage3A Environmental Compliance for 6 Cylinder Tractor Diesel.* ***Methodology.*** *Experimental studies were carried out for diesel engines equipped with: a Common Rail BOSCH accumulator fuel supply system with an injection pressure of 140 MPa, injectors with 7 nozzle holes; a direct-action fuel supply system with a MOTORPAL fuel pump providing a maximum injection pressure of 100 MPa, MOTORPAL injectors and AZPI with five nozzle holes; combustion chambers of two types with bowl diameters of 55 and 67.5 mm; cylinder heads providing swirl ratios 3–4 and 3.5–4.5; high pressure exhaust gas recirculation system. The tests were carried out at characteristic points of the NRSC cycle at three crankshaft speeds: minimum idle speed 800 min^{-1}, maximum torque 1600 min^{-1}, and maximum power 2100 min^{-1}.* ***Results.*** *It turned out that it is possible to achieve Stage3A emissions standards on 116 kW diesel engines using direct fuel equipment and a semi-open combustion chamber, on 156 kW diesel engines using a Low Cost Common Rail fuel supply system and an open combustion chamber.* ***Originality.*** *The results of the combustion chamber shape choice, the parameters of the fuel-injection equipment, the swirl ratio of the inlet channels, valve timings and parameters of the exhaust gas recirculation system made it possible to organize diesel engine workflow of the Stage 3A ecological level.* ***Practical significance****. Construction elements of the six-cylinder diesel engines have been developed and introduced at the Minsk Motor Plant.*

Key words: *diesel, swirl ratio, combustion chamber, fuel supply system, injector nozzle.*

Introduction

Diesel engine building is one of the main areas of mechanical engineering that has been developed recently in the Republic of Belarus. Minsk Motor Plant is the oldest enterprise in the Republic that has been producing multi-purpose diesel engines in a wide power range (Fig. 1) [1] for more than 55 years. The development strategy of the enterprise, 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 [2]. The Technical Regulations of the Customs Union [3], focused on the norms of the UNECE Regulations [4], establishes for diesel engines, newly manufactured or imported new tractors compliance with Stage 3A environmental standards, which should increase the demand for diesel engines of this ecological class [5, 6].

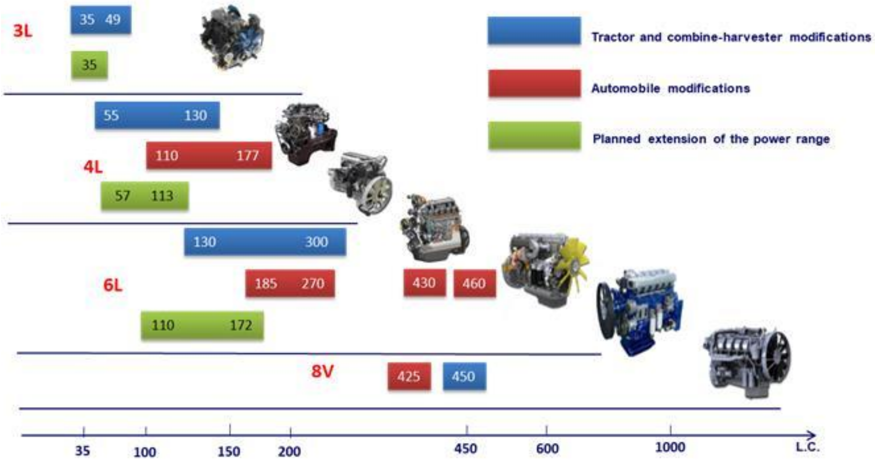
Marketing research shows that in the nearest future two modifications of six-cylinder tractor diesel engines D-260.1S3A with a power of 116 kW and D-260.4S3A with a power of 156 kW will be in demand.

Analysis of publications

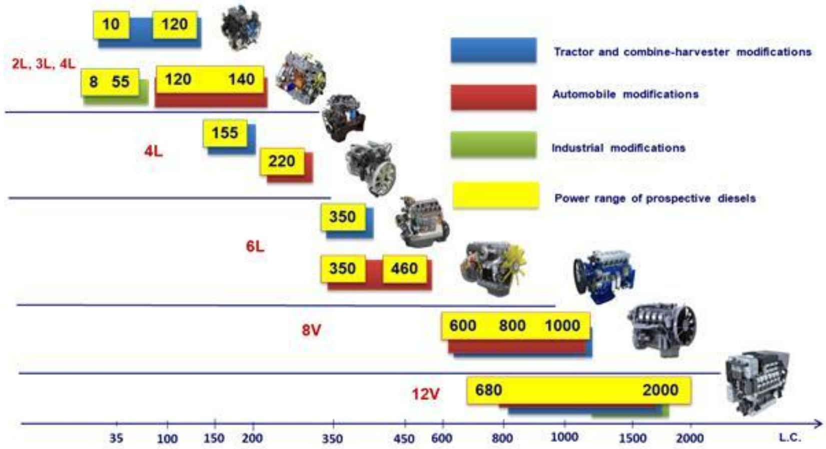
Achievement of environmental performance of the Stage 3A level is carried out mainly due to the coordination of the shape of the combustion chamber [7, 8], the parameters of the fuel supply equipment [9, 10], the swirl ratio of the inlet ports [8, 11], the valve timing [10] and the use of exhaust gas recirculation (EGR) [10, 11].

Theoretical research

The D-260 engines use cylinder heads with two valves per cylinder, which should ensure the simplicity of the design and maintenance of the gas distribution mechanism. The slightly increased resistance of the gas exchange channels is to some extent compensated by the engine boost. The inlet channels are dual-function - screw. When profiling the channels, the correctness of the adopted design solutions is checked by the method of 3D-modeling of the gas flow (Fig. 2) with the determination of the air flow rate and the mean rotation velocity of the air charge at the given pressure drops [12]. The mathematical model of the flow of a viscous heat-conducting fluid, widely used in solving engineering problems [13, 14, 15], is based on the Navier – Stokes system of equations, which combines the laws of conservation of mass, momentum and energy of a fluid in a nonstationary setting [16, 17].



a



b

Fig. 1. Power range of the engines manufactured by MMP: a) serial engines [1]; b) promising

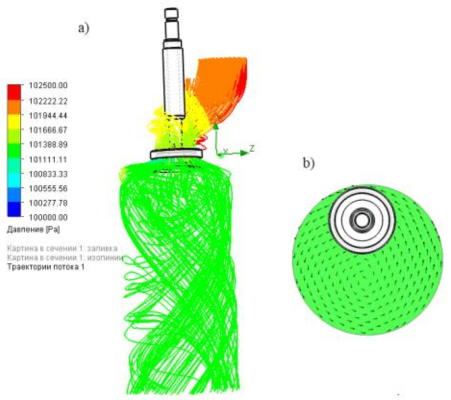


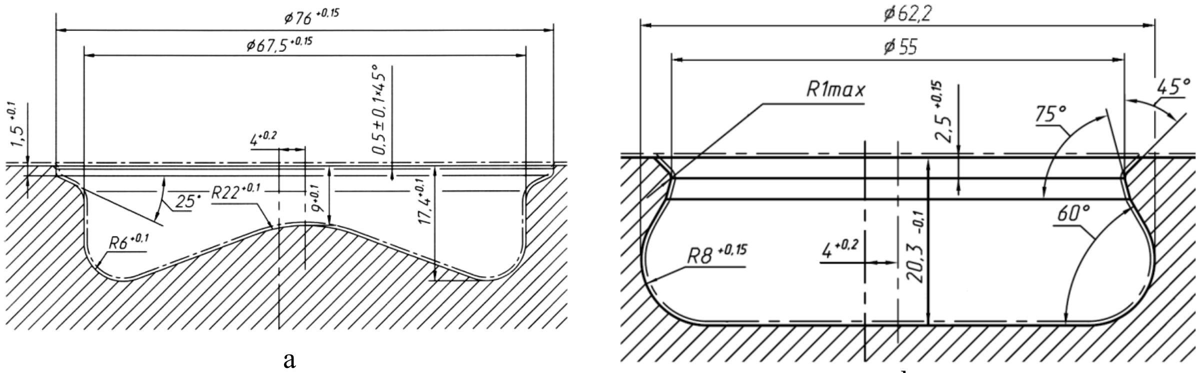
Fig. 2. Results of the inlet channel virtual purge: a – pressure distribution; b – velocity field in the outlet section

To control the parameters of the inlet channels of the cast heads, a motorless blow off stand with a straightening grid is used [12, 18]. Usually, the data of virtual and full-scale blow off differ by no more than 5 %. For D-260 engines, head designs have been developed that ensure the generation of an air swirl at the inlet with a swirl ratio of 3–4 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. 3.a) [19, 20]. Large swirl ratios are used for engines with direct-action fuel equipment and a semi-open combustion chamber (Fig. 3.b) [21].

Serially produced six-cylinder diesel engines D-260, which meet Stage 3A environmental standards, are equipped with fuel supply equipment with electronic control "Common Rail" manufactured by "Bosch"; pistons with an open combustion chamber; a cylinder head with a screw inlet channel providing a swirl ratio H = 3 – 4; unregulated turbocharging. Low pressure EGR is used to reduce NOx emissions [22].

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-action pump and a mechanical regulator manufactured by Motorpal.



a

b

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

The fuel supply system layout with a direct-acting pump is shown in Fig. 4.

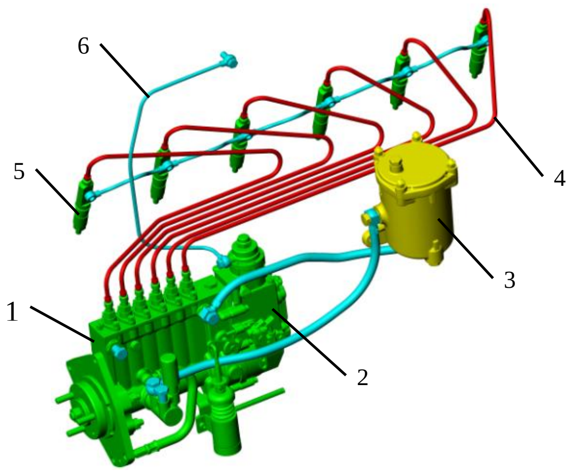


Fig. 4. Fuel supply system layout with a Motorpal pump: 1 – high pressure fuel pump; 2 – speed governor; 3 – fuel filter; 4 – high pressure fuel line; 5 – injector; 6 – tube to the corrector for charge air pressure

The fuel pump 6M4330ZT (Motorpal, Czech Republic) with a diameter of 10 mm and a plunger stroke of 14 mm is equipped with a mechanical governor and a fuel supply 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 DOP147P528 nozzles (μf = 0.22 mm^2) (Motorpal, Czech Republic) (Fig. 5.a) (for an open combustion chamber);
- injectors AZPI 172.1112010-11.01 with nozzles AZPI 172.1112110-12.01 (μf = 0.23 ... 0.25 mm^2);
- injectors VA70P360 with sac-less nozzles DOP140P528 (μf = 0.18 ... 0.2 mm^2) (Motorpal, Czech Republic) (Fig. 5.b).

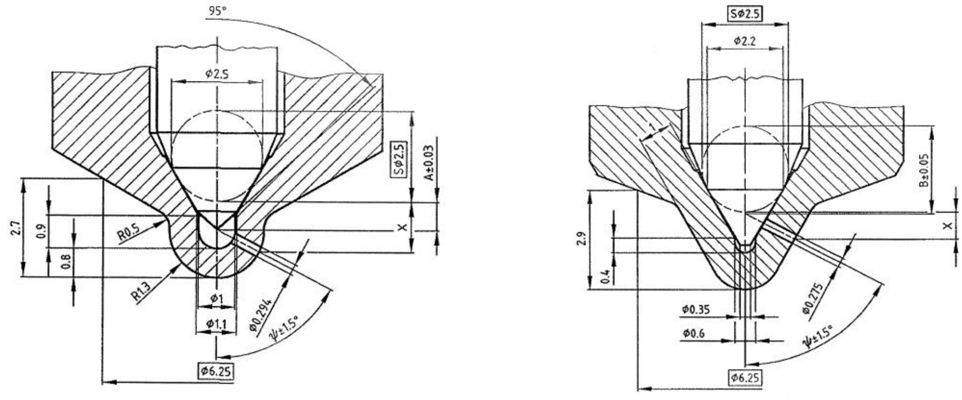
Matching of the combustion chamber form and the location of the fuel flares were coordinated using 3D models [20, 23]. The meeting points of the axes of the fuel jets with the walls of the combustion chamber are shown in Fig. 6.

Experimental research

The comparative tests (results in table 1) for the NRSC cycle showed the possibility of achieving emission standards for Stage 3A.

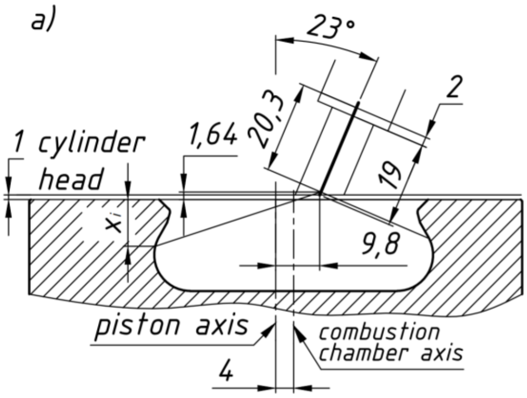
The use of sac-less nozzles led to a decrease in fuel leakage and, as a consequence, to a decrease in nozzles coking, soot and CH_x hydrocarbons emissions [12, 28].

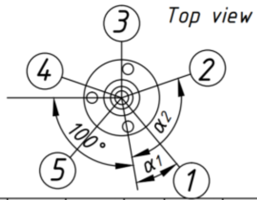
Tests of the D-260.4S3A diesel engine with direct-acting fuel equipment showed a high exhaust smoke level while ensuring the target NO_x emissions (table 1) using the EGR. As a result, achieving the Stage3A level for particulate emissions on a D-260.4 engine with a direct-acting fuel system with semi-open and open combustion chambers is not possible at this stage. Therefore, the proposed use of the type Low Cost "Common Rail" accumulator system.



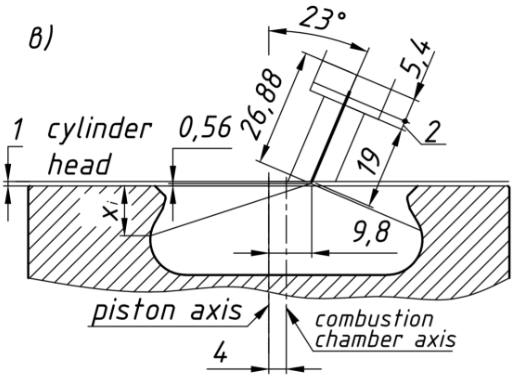
a b

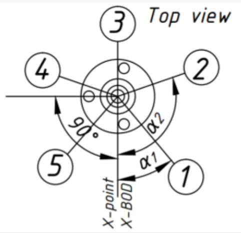
Fig. 5. Nozzle cone shapes: a – with a blind-hole (with a dead volume); b – with the exit of nozzle holes to the surface of the locking cone (sac-less nozzle)



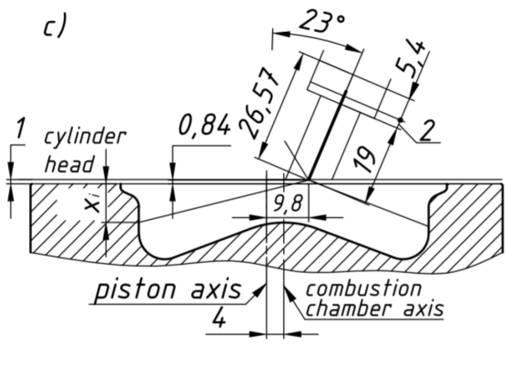


	1	2	3	4	5
α, °	30	99	170	241	309
φ, °	84,5	62,5	51	62,5	84,5
x_{i},mm	9,2	9,1	8,8	9,1	9,0





	1	2	3	4	5
α, °	40	109	180	251	319
φ, °	84,5	62,5	51	62,5	84,5
x_{i},mm	10,6	10,3	9,9	10,3	10,5



	1	2	3	4	5
α, °	40	109	180	251	319
φ, °	88,5	65,5	53	65,5	88,5
x_{i},mm	9,2	9,1	9,0	9,1	9,1

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_{eTmax}, g/(kW·h)	N_{RP}, %HSU	N_{Tmax}, %HSU
D-260.1S3AM	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)		0,3	-			
D-260.4S3AM	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)		0,2	-			

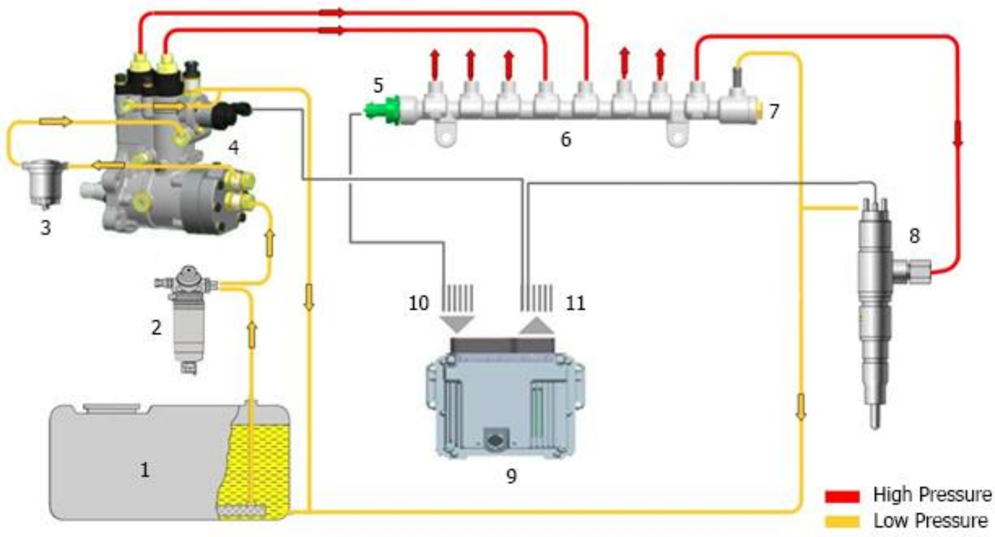


Fig. 7. Diagram of the common rail fuel system: 1 – fuel tank; 2 – coarse filter; 3 – fine filter; 4 – fuel pump; 5 – fuel pressure sensor; 6 – fuel rail; 7 – pressure-relief valve; 8 – injector; 9 – electronic control unit; 10 – signals from sensors; 11 – signals to actuators

The schematic diagram of "Common Rail" type Low Cost is shown in fig. 7. It consists of:

- fuel pump CB 28;
- injectors CRIN2 with 7-hole nozzles with a tent opening angle δ = 147.6° and a flow of 500 cm3 / 30 s at a pressure of 100 bar,
- pressure accumulator LWRN18 with a maximum injection pressure of 1400 bar;
- the control unit EDC17CV54 with software version P_1142.3.0.0 for Low Cost system.

To increase the reliability of the units, the recirculation and turbocharging systems, they switched to a high-pressure recirculation system, the diagram of which is shown in Fig. 8 [22, 25, 26]. 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.

Tests of six-cylinder diesel engines with the high-pressure EGR system showed the problem of organization the EGR gas flow into 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 Stage3A level for exhaust emissions. The test results of the engine D-260.4S3A are shown in table 2.

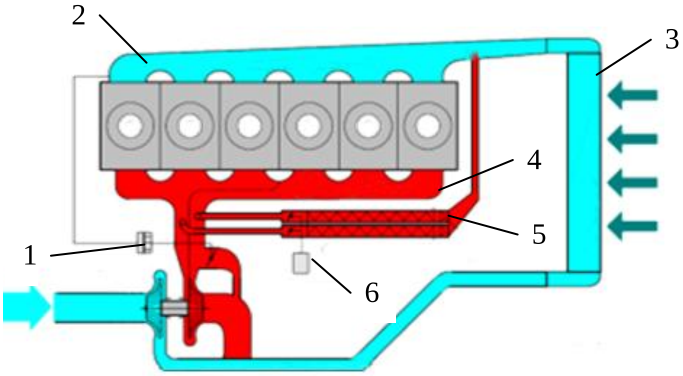


Fig. 8. Schematic diagram of the high-pressure EGR system: 1 – bypass valve; 2 – inlet manifold; 3 – charge air cooler; 4 – exhaust manifold; 5 – EGR cooler; 6 – rotary EGR valve

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	-
$M_к$. 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
$g_{(SC)}$. г/(кВт·ч)		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

Conclusions

Measures have been developed to organize the working process of six-cylinder tractor diesel engines of ecological level Stage 3A with exhaust gas recirculation along the high-pressure circuit.

It has been established that the achievement of emission standards for harmful substances on diesel engines with a capacity of 116 kW is possible with the use of direct-action fuel equipment and a semi-open combustion chamber. Achieved total nitrogen oxides and unburned hydrocarbon emissions of 3.91 g/(kWh). 2 % less than the adopted Stage 3A emission level.

To meet Stage 3A standards on 156 kW diesel engines. it is necessary to use the Low Cost Common Rail fuel supply system and an open combustion chamber.

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Забезпечення екологічних норм Stage3A шестициліндровим тракторним дизелем

Анотація. Проблема. Стратегія розвитку Мінського моторного заводу, що реалізується в межах заводських і державних науково-технічних програм, спрямована на виготовлення конкурентоспроможної продукції, яка відповідає сучасним технічним вимогам міжнародних стандартів і якості. Обов’язковою умовою успішного просування дизелів на ринку позашляхової техніки є забезпечення необхідних екологічних показників за умови низької витрати палива й невисокої вартості двигуна. Відомі технічні рішення, спрямовані на досягнення екологічних показників рівня Stage3A, істотно підвищують вартість дизелів. Тому досягнення необхідних екологічних норм без значного подорожчання двигунів можна вважати актуальним завданням. ***Мета.*** Забезпечення екологічних норм Stage3A шестициліндровим тракторним дизелем. ***Методологія.*** Експериментальні дослідження проводилися для дизелів, укомплектованих акумуляторною системою подачі палива Common Rail BOSCH із тиском упорскування 140 МПа, форсунками, що мають сім соплових отворів; системою подачі палива безпосередньої дії з паливним насосом MOTORPAL, що забезпечує максимальний тиск упорскування 100 МПа, форсунками MOTORPAL і АЗПІ з п’ятьма сопловими отворами; камерами згоряння двох типів з діаметрами горловин 55 і 67,5 мм; головками блока циліндрів. що забезпечують вихрові відношення 3–4 і 3,5–4,5; системою рециркуляції відпрацьованих газів по контуру високого тиску. Випробування проводилися по характерних точках циклу NRSC на трьох частотах обертання колінчастого вала: мінімального холостого ходу 800 хв$^{-1}$, максимального крутного моменту 1600 хв$^{-1}$ і максимальної потужності 2100 хв$^{-1}$. ***Результати.*** Встановлено, що досягнення норм викидів шкідливих речовин Stage 3А на дизелях потужністю 116 кВт можливе з використанням паливної апаратури безпосередньої дії та з напіввідкритою камерою згоряння, на дизелях потужністю 156 кВт з використанням системи подачі палива «Common Rail» типу Low Cost і з відкритою камерою згоряння. ***Наукова новизна.*** Результати вибору форми камери згоряння, параметрів паливоподавальної апаратури, вихрового відношення впускних каналів, фаз газорозподілу й параметрів системи рециркуляції відпрацьованих газів, що дозволяють організувати протікання робочого процесу дизеля екологічного рівня Stage 3А. ***Практична значущість.*** Розроблено й впроваджено на Моторному заводі елементи конструкції шестициліндрових дизелів.

Ключові слова: *дизель, вихрове відношення, камера згоряння, система подачі палива, розпилювач палива.*

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