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INVESTIGATION OF THE WORKING PROCESS AND ENVIRONMENTAL PERFORMANCE OF A DUAL-FUEL GAS ENGINE

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ABSTRACT

The paper provides the results of the research of the working process of gas engines running on lean fuel-air mixtures on a dual-fuel cycle with combined quantity and air/fuel ratio torque control. The ways of the achievement of the maximum fuel efficiency were shown. The ways to reduce the level of harmful substances in exhaust gases using integrated oxidation-reduction systems of exhaust gases aftertreatmentwere presented.

Keywords: dual-fuel gas engine, diesel, working process, exhaust gas aftertreatment systems.

1. INTRODUCTION

Natural gas is one of the most available automotive fuel in terms of creating an alternative to liquid petroleum-derived fuels, including diesel fuel. Diesel engines can be converted to run on gaseous fuel in two ways. The first way is to create single-fuel dedicated gas engines on the basis of a diesel engine. The second way is to equip a diesel engine with an additional gas supply system for running on two fuels simultaneously while maintaining the ability to run only on diesel fuel (Nwafor, 2000; Selim, 2001; Lukshoet *al.*, 2015; Luksho *et al.*, 2015; Panchishnyet *al*., 2015).

The research of the working processes of dual-fuel engines was carried out by many scientists and engineers. For example, the U.A.E. University Professor Mohamed Selim found that in contrast to a diesel engine, in which the rate of pressure rise almost doesn't change depending on load, in the dual-fuel mode there is a change in the pressure rise rate at various loads with a change in the rotational speed (Selim, 2004).

The researchers R.G. Papagiannakis and D.T. Hountalas (Papagiannakis and Hountalas, 2004) carried out experiments to identify operational and environmental performance of a diesel engine running on a dual-fuel cycle. They found that the total specific fuel consumption of a diesel engine running on a gas cycle is higher in all the modes as compared to a diesel engine. The dual-fuel mode is characterized by an increase in the duration of combustion at low engine loads and a reduction in the duration of the combustion at high engine loads. A decrease in the concentration of nitrogen oxides in exhaust gases and a sharp reduction in particulate emissions were observed, while the values of the emissions of CO and HC increased dramatically.

The aim of another group of researchers (Mansour C., Bounif A., Aris A., Gaillard F.) was to determine the impact of the rotational speed of the crankshaft on the concentration of emissions of harmful substances in exhaust gases and the efficiency of an engine operating in the dual-fuel mode (Mansour *et al*., 2001). The test results showed that an engine, operating on a dual-fuel cycle, ranks below a diesel engine in power and torque, while the emissions of HC and CO increase. The maximum pressure of combustion in a dual-fuel engine is higher than in a diesel engine.

The aim of the research of O.M.I. Nwafor was to study the impact of the timing angle and the delivery rate of a pilot fuel charge on the operational performance of an engine operating in the dual-fuel mode (Nwafor, 2002; Uma *et al*., 2004).

The experiment showed that the specific fuel consumption increased when the engine was operating on a dual-fuel cycle, and the engine power decreased, as compared to a diesel engine.

R.G. Papagiannakis, C.D. Rakapoulos, D.T. Hountalas and D.C. Rakapoulos carried out the experimental research of a diesel engine operating in the dual-fuel mode, aimed to study the impact of the overall excess air/fuel ratio on the operational performance of the engine and the emissions of harmful substances.

It was shown that a decrease in the overall reduced excess air/fuel ratio leads to decreasing in the net efficiency in the dual-fuel mode (Papagiannakis and Hountalas, 2004; Bakhmutov and Karpukhin, 2012).

All the researchers point out that in a dual-fuel engine there is a decrease in the emissions of nitrogen oxides and a significant reduction in particulate emissions for all of the studied engine operation modes. This becomes even more evident at heavy loads and increased gas delivery per stroke. At the same time, an increase in the concentration of CO and HC is observed (Sahoo, 2009; Luksho and Mironov, 2010; Kavtaradzeet *al*., 2012; Wagemakers and Leermakers, 2012; Lim and Iida, 2012; Shah and Thipse, 2011).

2. MAIN PART

The Central Scientific Research Automobile and Automotive Engine Institute "NAMI" has a vast experience in the development of such engines. In the first half of the 1980s, an original fuel feed system GD-NAMI with ratio power control was developed at the Institute with the participation of "KAMAZ" and the production association "Diesel Equipment". The experience of the operation of engines with a dual-fuel system with ratio torque control made it possible to identify the strengths and weaknesses of this system.

The main advantages of an engine operating on a dual-fuel cycle include:

- replacement of up to 60-75% of liquid fuel with gaseous fuel in the mixed mode of motion;
- reducing particulate emissions 1.5-2 times;
- extending the service period of motor oil 2.5 times;
- reducing the wear of cylinder-piston group 1.5 times;
- maintaining power ratings in the dual-fuel mode at the level of the base diesel engine;
- retaining the possibility of an engine operation on diesel fuel (if necessary) and a rapid transition from one fuel to another.

The main drawback was the deterioration of fuel efficiency and the increase in the emissions of unburned hydrocarbons (more than 90% of which is methane) and carbon monoxide, due to the deterioration of the gas combustion process at low loads (Papagiannakis, 2009; Luksho and Terenchenko, 2013).

The further improvement of fuel efficiency and environmental performance of a dual-fuel engine can be achieved by extending the zone of optimal control (the composition of the fuel-air mixture, the volume of a pilot fuel charge, timing angle), the use of multiple port gas injection and mixed quantity and ratio torque control. The optimization of these parameters is the aim of the research carried out in this paper.

In the FSUE "NAMI", the authors developed an engine with a dual-fuel supply system. Base diesel engine: 6-cylinder, V-type, engine capacity 11 l, compression ratio 17.5, maximum power 200 kW at 1900 min^{-1}, maximum torque 1120 Nm at 1100-1500 min^{-1}. Diesel supply system is common rail with an electronic control system.

The engine is equipped with a gas supply system and a control system, ensuring the operation on a dual-fuel cycle with the ignition of the air-gas mixture by a pilot charge of diesel fuel. A port distributed gas fuel supply was used (6 gas injectors); the quantity torque control was carried out using an electronic throttle.

3. RESEARCH METHODS

The test methodology provided for the determination of engine mapping (on the basis of the composition of the fuel-air mixture, injection timing, the volume of a pilot fuel injection) for operation on a dual-fuel cycle in different modes with the evaluation of power ratings, fuel efficiency and environmental performance.The characteristics of optimal control were determined with maintaining a constant torque.The in-cylinder pressure measurementwas carried out. The optimization of the composition of the fuel-air mixture involved choosing the values of the excess air/fuel ratio, ensuring the minimum values of fuel consumption and the minimum concentration of HC.

Figure-1 shows a diagram of the test banch with an indication of the location of temperature sensors and measuring equipment.

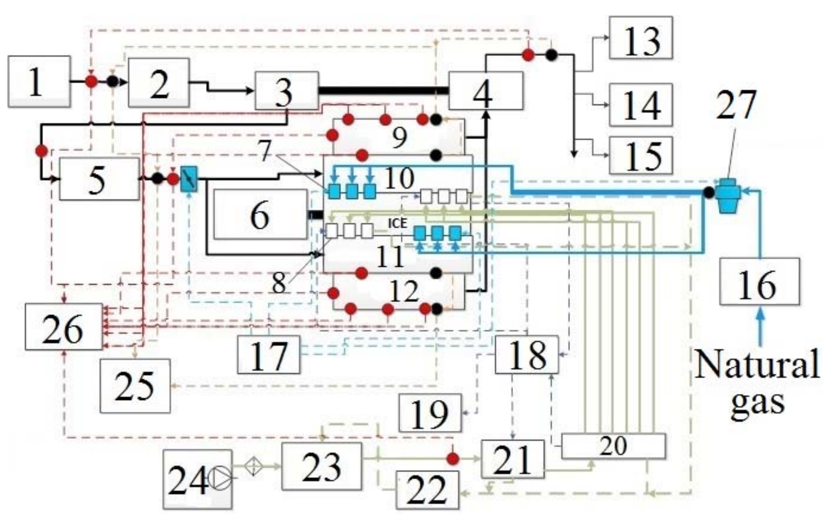

Figure-1. Diagram of the test banch with a dual-fuel engine.
1- Air filter; 2- Air-flow meter; 3- Compressor; 4- Turbine; 5- Intercooler; 6- Brake motor; 7- Gas injectors; 8- Diesel injectors; 9- Right exhaust manifold; 10- Right intake manifold; 11- Left intake manifold; 12- Left exhaust manifold; 13- O_2 Sensor; 14- Exhaust gas analyzer: CO, HC, NO_x; 15- Smoke analyzer; 16- Gas flowmeter; 17- ECU Gas; 18- ECU Diesel; 19- Computer; 20- Fuel Rail; 21- High pressure fuel pump; 22- Heat-exchange unit; 23- Fuel flowmeter; 24- Fuel tank; 25- Pressure measurement unit; 26- Temperature measurement unit; 27- Electronic gas pressure regulator.

To determine the mass-flow rate of gas fuel, the flow meters YokogawaRotamasswere used. The values of the excess air/fuel ratio were determined using the device Innovate Motorsports LC-1 O_2 Sensor. The opacity of exhaust gases was measured by the opacimeter MK-4 (YDA309).The NO/NO_x concentrations were measured using the chemiluminescence analyzer "Beckman".The concentration of HC was measured using the FID

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analyzer"Beckman". The concentration of CO was measured using the NDIR analyser "Beckman".For the indexing of the working process, the multichannel high-speed equipment AVL IndiSet Advanced GigaBit 642 was used.

4. RESULTS AND DISCUSSIONS

The dual-fuel working process is characterized by the fact that two types of fuel, different in their physical and chemical properties, participate in the process of combustion. The differences are not only in different values of octane and cetane numbers of these fuels, but also in the specifics of the combustion process. The combustion process of diesel fuel allows for ratio power control. In case of organizing the combustion of the homogeneous methane-air mixture, quantity power control is required. In this work, the working process of a dual-fuel engine was considered as a working process with the positive ignition of the methane-air mixture by a pilot injection of diesel fuel. The share of gas fuel, participating in the combustion process and in ensuring efficient operation, is significantly higher than the share of diesel fuel. Therefore, the optimization of the working process of the engine was aimed at improving the efficiency of the combustion of a gas-air charge in the engine cylinder.

It is known that the optimal and efficient combustion of the homogeneous air-gas mixture is achieved in a fairly narrow range of values of the excess air/fuel ratio (α = 1.05-1.4). But in engines with ratio torque control at idle speed and low loads, the excess air/fuel ratio can reach much larger values (more than 3). This characteristic of the working process in an engine with ratio torque control leads to the deterioration of the performance characteristics of a dual-fuel engine. The research focused on the selection of the optimal values of the excess air/fuel ratio (α) with a choice of an appropriate throttle position for maintaining the torque. On the one hand, it was required to ensure efficient combustion of the gas-air mixture, with the excess air/fuel ratio not exceeding 1.4. On the other hand, it was necessary to ensure reliable ignition of the minimum volume of a pilot diesel fuel charge at throttling, which is accompanied by a decrease in pressure and temperature at the end of the compression stroke.

Figure-2 shows the dependencies of the change in the corrected efficient fuel consumption on the value of the delivery rate of pilot injection of diesel fuel for different loads and different values of the reduced excess air/fuel ratio. The mass of the pilot injection of diesel fuel (Q_p) was determined as a percentage of maximum diesel fuel supply for a given speed mode (n = 1200 min^{-1}).

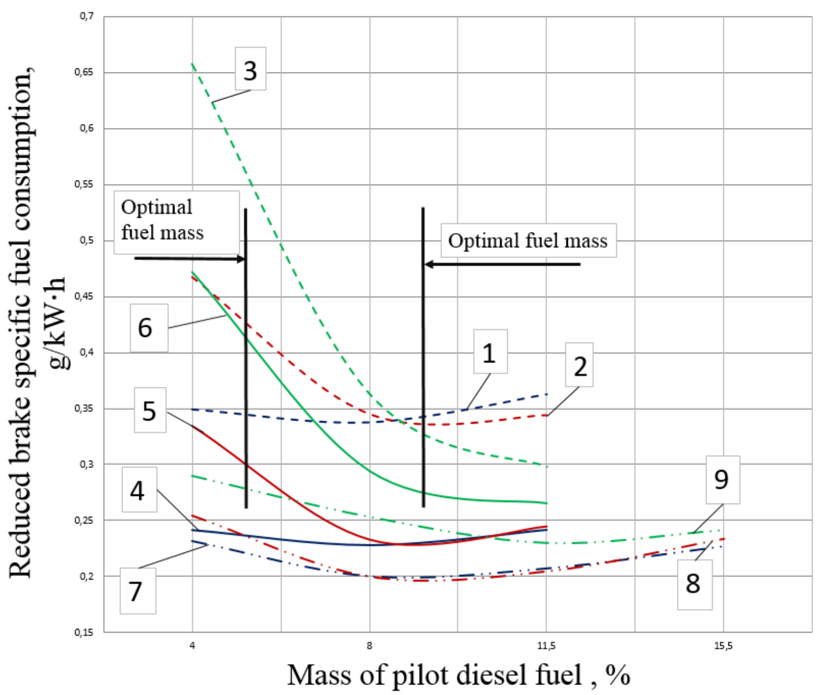

Figure-2. Determination of the optimal values of the delivery rate of a pilot charge of diesel fuel in per cent of the maximum delivery rate at full load.
1 – α = 1.4, M_k = 150 Nm; 2 – α = 1.65, M_k = 150 Nm; 3 – α = 2, M_k = 150 Nm; 4 – α = 1.4, M_k = 350 Nm; 5 – α = 1.65, M_k = 350 Nm; 6 – α = 2, M_k = 350 Nm; 7 – α = 1.4, M_k = 550 Nm; 8 – α = 1.65, M_k = 550 Nm; 9 – α = 2, M_k = 550 Nm.
(where α is the excess air/fuel ratio of the fuel-air mixture, M_k is the torque)

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As a result of these studies, the volume of the pilot fuel charge for further tests was taken to be within the range of 6-11 mg/cycle (5-10%).

The study of the specifics of the working process of a dual-fuel engine was carried out on the basis of the in-cylinder pressure diagrams obtained in the course of the tests.

The heat release characteristics were obtained as a result of the mathematical processing of the experimental data using the software AVL Boost – Burn.

The authors carried out tests to study the impact of the delivery rate of a pilot charge of diesel fuel on the performance of an engine operating on a dual-fuel cycle. The tests were conducted at a rotational speed *n* = 1200 min^{-1}, the torque was set to be 650-700 Nm. Fuel pressure in the fuel rail was set to be within the range of 50-60 MPa.

It should be noted that the combustion of a fuel-air charge in the dual-fuel mode has a pronounced multi-stage nature. This is related to the presence of the phases of the delay of ignition of both diesel and gas fuel, different in duration main phases of combustion of the two fuels and after-burning phases of the two fuels. Combustion phases of one fuel influence combustion phases of another one, and all of these processes depend on the volume and conditions of delivering diesel fuel, on the composition of the gas-air mixture and other parameters.

The results showed (Figure-3) that with an increase in the delivery rate of a pilot charge of diesel fuel the maximum gas pressure in the cylinder also increases - from 7.14 to 8.09 MPa.

The changes in the heat release rate at different delivery rate of a pilot fuel injectedare shown in Figure-4.

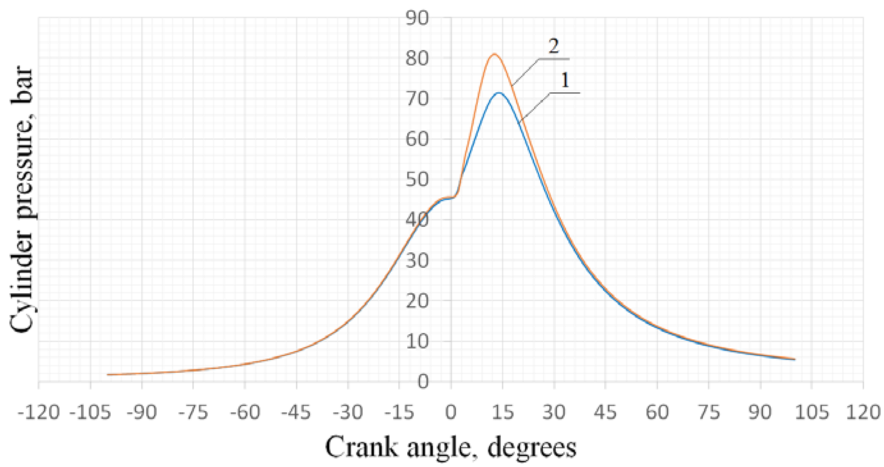

Figure-3. Comparison of pressure diagrams (n = 1200 min^{-1}, M_k = 650-700 Nm, Q_{p2} = 5 mg/cycle (curve 1) and Qp_2= 10 mg/cycle (curve 2).

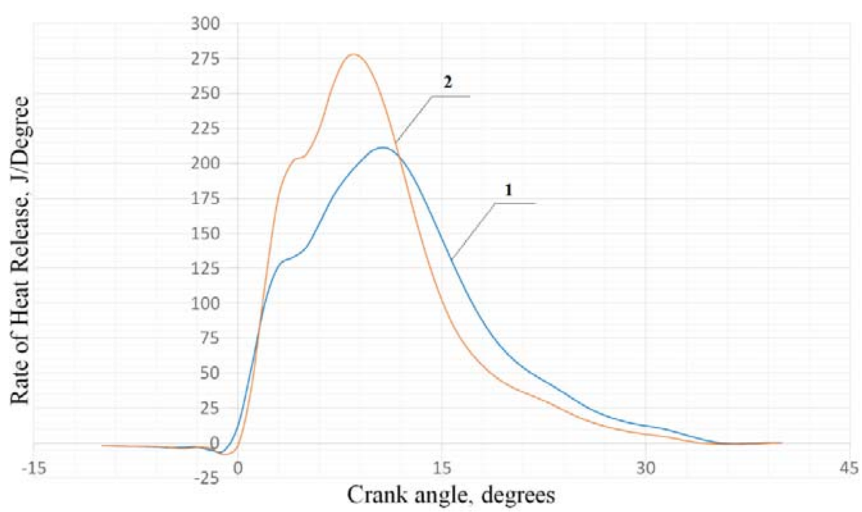

Figure-4. Comparison of the characteristics of the change in heat release rate(n = 1200 min^{-1}, M_k = 650-700 Nm, Q_{p2} = 5 mg/cycle (curve 1) and Q_{p2}= 10 mg/cycle (curve 2).

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Heat release rate increases by about 25%, with an increase of the delivery rate of a pilot fuel charge from 5 mg/cycle to 10 mg/cycle.

The selected volume of the pilot fuel injection (5-10% of the maximum fuel supply) was adopted in view of the conditions for achieving the maximum economic feasibility. But at such values of fuel delivery rate, at heavy loads there is a problem of high heat density of the injection nozzle. There are two possible ways to reduce the thermal load on the injection nozzle. The first way is to increase the diesel fuel delivery rate (in this case, the method is not acceptable). The second is to increase the expiration time of the minimum value of fuel delivery rate. The second way can be implemented by reducing the pressure in the fuel rail.

The change in the pressure in the fuel rail is known to have a major impact on the structure of fuel spray and the degree of its atomization. Therefore, in the process of the optimization of fuel injection parameters, aimed at improving the efficiency of the dual-fuel process, two factors should be taken into account. The first one is setting the minimum pressure in the fuel rail to increase the duration of injection and create the best conditions for nozzle cooling. The second one is not to reduce the pressure below the level at which signs of the deterioration of the working process appear.

In view of this, the following series of tests was carried out with the aim of studying the impact of fuel pressure in the fuel rail on the working process of an engine (Figure-5), operating in a dual-fuel cycle. The tests were conducted at a rotational speed n = 1200 min^{-1}; the torque was set to be 700-720 N·m, the delivery rate of a pilot fuel charge was set to be within 10 mg/cycle, and the fuel pressure in the fuel rail increased from 50 to 90 MPa.

The results showed that with the increase of the pressure in the fuel rail the maximum gas pressure in the cylinder slightly increases -from 8.09 to 8.14 MPa, which gives ground for choosing the optimal pressure in the fuel rail proceeding from the need to cool the injection nozzle of the diesel injector.

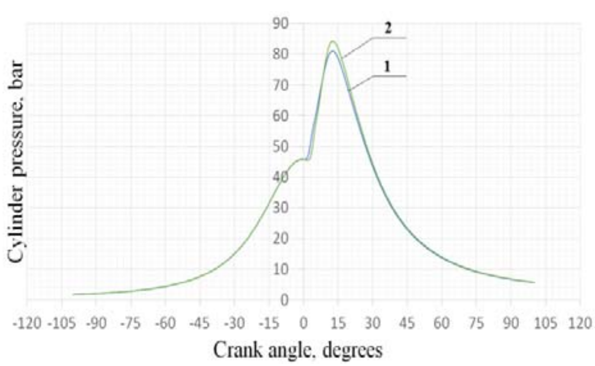

Figure-5. Comparison of pressure diagrams (n = 1200 min^{-1}, M_k = 700-720 Nm,Q_p = 10 mg/cycle, P_{t1} = 60 MPa (curve 1), P_{t2} = 90 MPa (curve 2)).

The changes in the heat release rate at different fuel pressure in the fuel rail are shown in Figure-6.

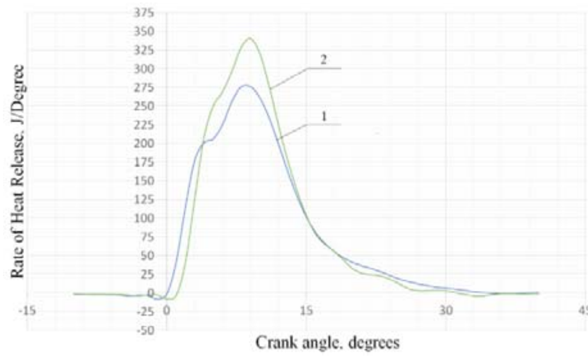

Figure-6. Comparison of the characteristics of the change in heat release rate (n = 1200 min^{-1},M_k = 700-720 Nm, Q_p = 10 mg/cycle, P_{t1} = 60 MPa (curve 1), P_{t2} = 90 MPa (curve 2)).

Heat release rate increases by about 20% with the increase of the pressure in the fuel rail.

According to the results of the studies, the optimal pressure is considered to be within the value of 60 MPa.

Figure-7 shows the dependence of the reduced specific fuel consumption on the excess air/fuel ratio.

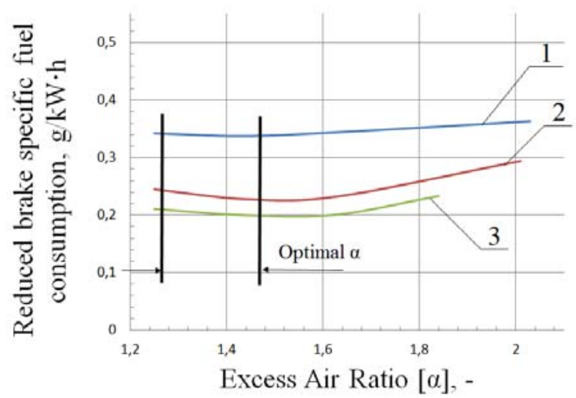

Figure-7. Dependence of the reduced specific fuel consumption on the excess air/fuel ratio (1- M_k = 150 Nm; 2- M_k = 350 Nm; 3 – M_k = 550 Nm).

It was found that the efficiency of the engine operation on a dual-fuel cycle with the minimum values of g_e^{red} is achieved when α is maintained within the range of 1.35-1.5.

As a result of the optimization of the composition of the fuel-air mixture, the volume of a pilot quantity of diesel fuel and the pressure of diesel fuel in the fuel rail, the settings of the control system were selected, and the load characteristics of an engine, operating on a dual-fuel cycle with mixed quantity and ratio torque control, were obtained. Figures 8 and 9 show the load characteristic of the dual-fuel engine at a rotational speed of 1450 min^{-1}.

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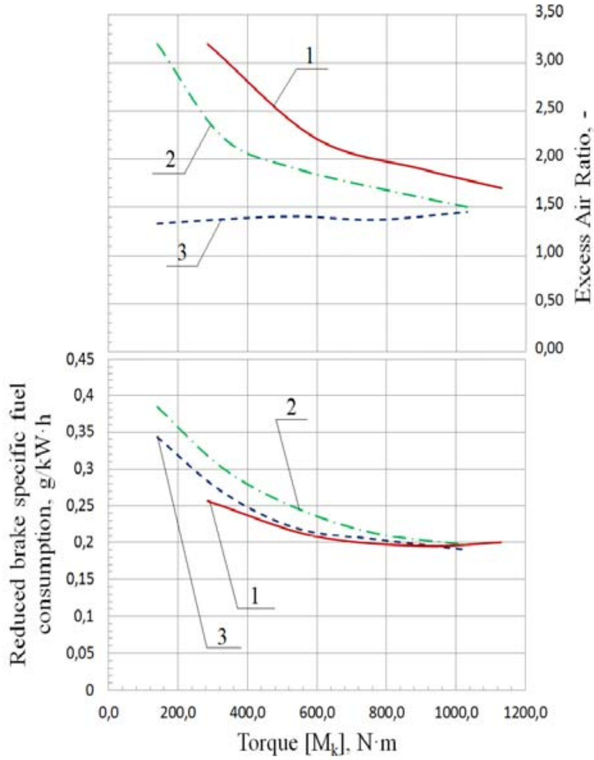

Figure-8. Comparison of the corrected specific fuel consumption on the basis of the load characteristic for dual-fuel and diesel engines (n = 1450 min^{-1}, 1- Diesel; 2-Dual-fuel (ratio control); 3- Dual-fuel (quantity and ratio control)).

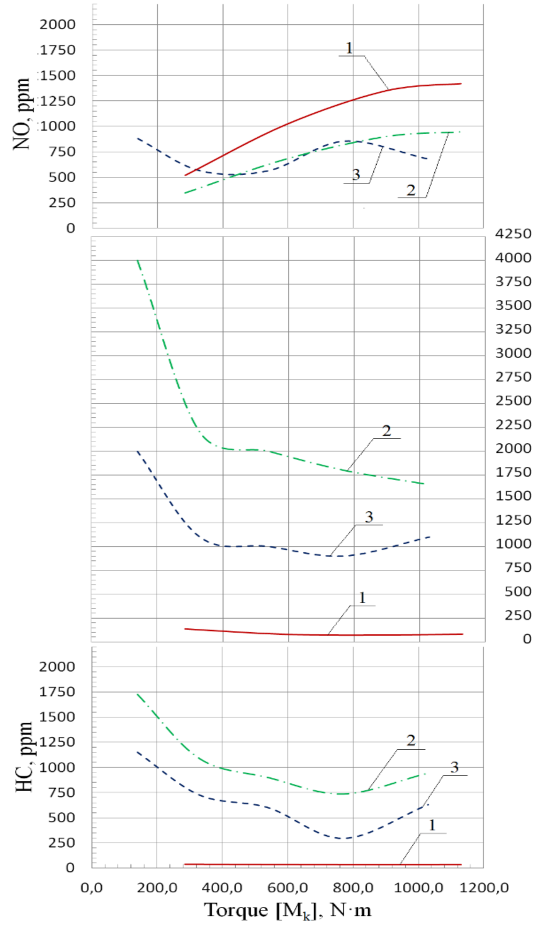

Figure-9. Concentrations of nitrogen oxides, carbon monoxide and hydrocarbons on the basis of the load characteristic for dual-fuel and diesel modes (n = 1450 min^{-1}, 1- Diesel; 2-Dual-fuel (ratio control); 3-Dual-fuel (quantity and ratio control)).

The application of quantity control of a dual-fuel engine made it possible to significantly improve fuel economy (by 20-30%) and reduce the emissions of HC and CO at low and medium loads as compared to a dual-fuel engine with ratio torque control.

To meet the requirements of the modern standards for the emissions of harmful substances in exhaust gases, an engine should be equipped with an oxidation catalyst and selective catalytic reduction converters of nitrogen oxides (SCR) (Luksho and Mironov, 2010; Bakhmutov and Karpukhin, 2012; Luksho, 2013).

A diagram of the aftertreatment system is shown in Figure-10.

The installation of ancomplexaftertreatment system of exhaust gases ensures refining HC, CO and NO_x up to 65-88%, which ensures meeting the EURO-5 requirements by a dual-fuel engine with mixed torque control, and after further improvement of the control system – meeting the requirements of EURO-6.

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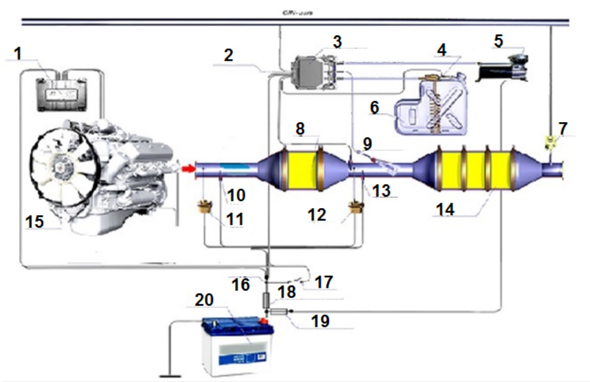

Figure-10. Diagram of the complexaftertreatmentsystem of exhaust gases SNOGMET.
1 – engine controller; 2 – ambient temperature sensor; 3 – SCR supply module with a controller; 4 – fluid level sensor and temperature sensor AdBlue; 5 – compressor (0.6 MPa); 6 – tank AdBlue ; 7 – pressure sensor; 8 – thermofor catalytic cracking (TCC) unit; 9 – injector AdBlue (0.5 MPa); 10 – TCC unit inlet temperature sensor; 11 – TCC unit inlet pressure sensor; 12 – TCC unit outlet pressure sensor; 13 – TCC unit inlet temperature sensor; 14 –SCR catalyst module; 15 – engine; 16 – contact +24V; 17 – key; 18– fuse 20 A; 19 – fuse 20 A; 20 – battery

5. CONCLUSIONS

During testing, it was determined that the maximum efficiency of the dual-fuel process with minimum values of the specific brake fuel consumption and the minimum emissions of HC and CO is achieved at the excess air/fuel ratio equal to 1.35-1.5 and maintained in engine operation modes from 100% to 10% of the full load. At loads of less than 10%, ratio power control is applied. It should be noted that under no-load conditions the excess air/fuel ratio should not exceed 1.75-1.9 at throttling not less than 10% of wide open throttle.

It was experimentally determined that a change in the pressure of diesel fuel in the rail has little impact on the fuel efficiency of the operation of an engine in the dual-fuel mode. The optimal value of the pressure of diesel fuel in the fuel rail is within the value of 60 MPa. Such pressure ensures a reliable protection of the nozzles from overheating and high efficiency of the engine operation.

In order to increase the degree of replacement of liquid fuels with gaseous ones, the mass of the pilot portion of diesel fuel was taken to be equal to 6-11 mg/cycle (5-10% of the maximum fuel supply).

The operation in the dual-fuel mode is accompanied by a significant increase in the emissions of CO and HC as compared to the diesel version of the engine. The emissions of nitrogen oxides in this case show a downward trend.

To meet the modern standards for emissions of harmful substances into the atmosphere, an engine must be equipped with ancomplexaftertreatment system, including an oxidation unit and a selective catalytic reduction (SCR) unit for reducing the emissions of nitrogen oxides.

The results of the conducted experimental research suggest that using the optimal algorithms of controlling the working process of a dual-fuel engine at different operation modes provides the improvement of the fuel efficiency of an engine and significantly reduces the emissions of particulate matter and nitrogen oxides.

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