Research Study of Diesel Engine Operation on Biogas with the Ignition Dose of Methyl Ester of Rapeseed Oil

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Abstract. The types of biofuels used in internal combustion engines are considered. The advantages of using gaseous biofuels are shown. The organization of the diesel engine working process on biogas with the ignition dose of rapeseed oil methyl ester is presented. The results of experimental studies of a diesel engine operating on biogas with the ignition dose of methyl ester of rapeseed oil are presented. The possibility of improving the environmental performance of the diesel engine with such organization of its working process is shown.

1. Biofuels Types and Directions of Their Use in Diesel Engines

The directions and tendencies of the further power industry development are largely determined by its provision with primary energy resources and their ecological characteristics. Currently, petroleum fuels are mainly used in internal combustion engines. More than 50% of the total amount of produced oil is spent for these purposes [1]. It should be noted that gradual depletion of the world's oil reserves is inevitable. Oil is presently used for motor fuels production. A significant depletion of liquid hydrocarbon deposits may occur in the next 50-70 years with the current level of energy consumption [2]. Ubiquitous operation of internal combustion engines, primarily in transport power plants, leads to significant atmosphere contamination by hazardous substances formed during the combustion of petroleum motor fuels [3]. It is necessary to search for alternative environmentally friendly motor fuels. Among such alternative fuels, biofuels produced from renewable raw materials are the most promising [2]. These are, primarily, bioethanol [4] and biodiesel fuels [5], and gaseous biofuel - biogas, generator (pyrolysis) gases. These biofuels are produced on an industrial scale and are widely used in transport in a number of countries (USA, Germany, Brazil, etc.).

The peculiarity of using gaseous biofuels is that they are in the same aggregate state as the oxidizer (air). This facilitates the organization of the mixture formation, allows to produce a homogeneous fuel-air mixture, and ensures its complete combustion. Fuel ingress to the cylinder walls and to the engine oil is prevented, what happens when liquid fuels are used. This allows to reduce wear of of engine parts and increase the service life of engine oil. But when transferring internal combustion engines to gaseous fuels, it is necessary, as a rule, to introduce additional design changes in their configuration. These are related to the need to organize the engine working process that provides the required quality indices of the spontaneous combustion processes and combustion of these fuels.

The production of biogas from livestock waste in specialized devices (fermenters – methane tanks) is the most widely used technology. A similar technology is used for food waste fermentation. Another
technology for producing biogas is collecting of the so-called landfill waste (solid domestic waste – SDW), the process of decomposition of which happens in an unregulated mode.

2. Production and Properties of Biofuels

The composition and quality of biogas largely depends on the feedstock used, the temperature regime of fermentation, and the speed of the processes that take place. The fermentation period varies from 12 to 60 days and decreases with the increase of the fermentation temperature. Table 1 presents the comparison of the compositions of biogas produced using different wastes and technologies. The presence of hydrogen sulphide (H₂S), ammonia (NH₃), as well as sulfur dioxide (SO₂), silicon (Si), and some other substances and compounds in biogas composition hinders the direct use of biogas (without purification) in internal combustion engines.

| Biogas Components | Origin of Biogas |
|-------------------|------------------|
|                   | Gas from Food    |
|                   | Methane Tanks    |
| Methane CH₄       | 60-65%           |
| Carbon dioxide CO₂| 16-34%           |
| Nitrogen N₂       | 0-3%             |
| Hydrogen H₂       | –                |
| Carbon monoxide CO| –                |
| Hydrogen sulphide H₂S| – up to 1.0%  |
| Ammonia NH₃       | –                |
| Nitrogen monoxide NO| – 35 mg/m³    |

It should be noted that gas engines are usually created on the basis of mass-produced engines operating on liquid fuel. When converting internal combustion engines to work on gaseous fuels, both gasoline engines (engines with forced ignition of the working mixture from the spark plug) and diesel engines (engines with ignition of the working mixture from the heat of compression) can be used as gasoline engines [6, 7]. It is reasonable to burn biofuels in diesel engines, which differ from engines with forced ignition of the working mixture by higher compression ratios (ε) and excess-air coefficients (α) [6, 7]. The possibility of using a particular fuel as diesel fuel is determined by its physical and chemical properties. Properties of some liquid and gaseous motor fuels are given in Table 2.

As it follows from the data of Table 2, biogas has a high auto-ignition temperature, which complicates its use as gas-engine fuel for diesel engines. However, its ignition in the diesel combustion chamber is possible from the ignition dose of high-cetane fuel, which is highly flammable in the combustion chamber of the diesel engine. Typically, natural gas is used as the main fuel in the gas-diesel cycle, and diesel oil is used as ignition fuel. The use of liquid biofuel as ignition fuel is advisable for complete substitution of petroleum motor fuels with biofuels. For instance, rapeseed oil methyl ester, having a higher cetane number than oil diesel fuel (48 and 45, respectively, see Table 2).

Such organization of the diesel working process on biogas with the ignition dose of rapeseed oil methyl ester allows to ensure reliable ignition of low-cetane biogas in the combustion chamber of the diesel engine. And also, it helps to ensure complete replacement of natural gas and diesel fuel with biofuels (biogas and rapeseed oil methyl ester). At the same time rapeseed oil methyl ester is produced by direct etherification of fatty acids of rapeseed oil with methanol at the temperature of +80…+90°C in the presence of catalyst (potassium hydroxide KOH) [8, 9].
Table 2. Physicochemical Properties of Motor Fuels

| Physical and Chemical Properties | Gaseous Fuels | Liquid Fuels |
|---------------------------------|--------------|--------------|
|                                 | Natural Gas  | Biogas       | Diesel Fuel | Rapeseed Oil Methyl Ester |
| Density of the gaseous phase at 0°C and 0.1 MPa, kg/m³ | 0.72 | 1.17 | - | - |
| Density of the liquid phase at 20°C, kg/m³ | - | - | 830 | 877 |
| Net calorific value, MJ/kg | 49.9 | 34.8 | 42.5 | 37.8 |
| Net calorific value, MJ/m³ | 33.8 | 20.2 | - | - |
| Cetane number | 3 | 0 | 45 | 48 |
| Auto-ignition temperature, °C | 550 | 650 | 250 | 230 |
| Amount of air required for combustion of 1 kg of substance, kg | 17.2 | 12.0 | 14.3 | 12.7 |

Note: Natural gas contains 95% of methane CH₄, the rest are ethane C₂H₆, propane C₃H₈, butane C₄H₁₀, and other impurities; some data are presented on biogas containing 70% of CH₄, 25% of CO₂, 1% of H₂, 1% of H₂S, 3% of other admixtures (volume content of the components is indicated).

3. Methods of Conducting Experimental Studies

Studies at the experimental stand were carried out to assess the parameters and characteristics of diesel with a dual-fuel fuel supply system (biogas and ignition dose of the rapeseed oil methyl ester). Its main element was D-243 diesel (4Ch11/12.5) produced by Minsk Motor Plant (MMZ). This diesel is converted to biogas, ignited from the ignition dose of the rapeseed oil methyl ester. A diesel-generator set commercially manufactured at the MMZ was used when creating the experimental stand. The generator produces an alternating electric current. The mentioned diesel engine of 4Ch 11/12.5 type is used as the prime mover in this generating set. A fuel injection pump assembly was developed to convert this engine to gas fuels. And it is equipped with a regulation system of gas- and ignition fuel supply. This system includes a regulator of liquid fuel (rapeseed oil methyl ester) supply, a biogas feed regulator, and an air-gas mixer installed in the gas diesel intake system.

The unsupercharged tested diesel of 4Ch 11/12.5 type had a nominal power of \( N_e = 36 \text{ kW} \) at the crankshaft rotating speed of \( n = 1,500 \text{ rpm} \). Some parameters of the diesel are given in Table 3. In this engine, as noted above, the main fuel was biogas, fed through the engine's intake system into its cylinders. Ignition of biogas in the combustion chamber occurred from the ignition dose of the rapeseed oil methyl ester injected into the cylinders by a regular fuel delivery system.

The diesel generator set also included an electric alternator of ECO-ECP type from RINA (Italy). Electric power generated by the alternator was consumed by three heaters in experimental studies. The maximum power of each of them is 12 kW (these heaters can also work under the electrical load of 6 kW). Thus, it is possible to implement six load modes with an effective output of 0 kW (idling mode), 6 kW, 12, 18, 24, 30 kW, and 36 kW (maximum power mode).

The research studies were carried out under normal climatic conditions at ambient temperature \((20\pm10)°\text{C}\), relative air humidity of 45% to 80%, and atmospheric pressure of 630 to 800 mm Hg (84 to 107 kPa). Standard diesel parameters, smoke and toxicity of its exhaust gases, and a number of limiting parameters were determined during the experiments. The smokiness of the exhaust gases was measured with the help of Infrakar D1.01 smokemeter by Zapadpribor enterprise (Moscow) with a measurement error of \(\pm 1\%\). The concentrations of normalized toxic components (nitrogen oxides NOx, carbon monoxide CO, light unburned hydrocarbons CHx) were determined in the exhaust gas with Infrakar SM-3.01 gas analyzer by Zapadpribor enterprise (Moscow) with measurement errors of these components \(\pm 1\%\).
Table 3. The Main Design and Exploitation Parameters of the Diesel Engine of 4Ch 11/12.5 Type, Operating on Biogas with the Ignition Dose of the Rapeseed Oil Methyl Ester

| Parameters                                | Value                                      |
|-------------------------------------------|--------------------------------------------|
| Number of cylinders                       | 4                                          |
| Cylinder bore \(D\) / piston stroke \(S\), \(\text{mm}\) | 110/125                                    |
| Common working volume \(iV_h\), \(\text{liter}\) | 4.32                                       |
| Compression ratio \(\varepsilon\)          | 16.0                                       |
| Mixing mode                               | Volume-film (combustion chamber in the piston) |
| Supply system                             | Divided type                               |
| Fuel injection pump assembly              | Row type \(PP4M10U1f\) by \(\text{Motorpal}\) with centrifugal regulator |
| Plungers diameter \(d_p\) / plungers stroke \(h_p\), \(\text{mm}\) | 10/10                                       |
| Delivery fuel line length \(L_T\), \(\text{mm}\) | 540                                        |
| Nozzles                                   | FDM-22 type produced by \(\text{JSC Kuroaparatura (Vilnius)}\) |
| Sprayers of nozzles                       | \(\text{Motorpal type DOP 119S534 with five nozzle holes with the diameter of } d_n = 0.34 \text{ mm and the flow area of } \mu_n f_n = 0.250 \text{ mm}^2\) |

The diesel engine of 4Ch 11/12.5 type was studied on the motor stand at the maximum modes of regulatory characteristics, formed with the regulator at the crankshaft speed of \(n = 1,500 \text{ rpm}\). During the tests, the fuel injection advance angle was set equal to \(\theta = 13^\circ\) of the crankshaft rotation to the top dead center.

4. Experimental Studies of Diesel Operating on Biogas with an Ignition Dose of Rapeseed Oil Methyl Ester

During the tests of the diesel, its work was studied both in a purely diesel cycle (operation only on oil diesel fuel) and in a gas-diesel cycle (operation on biogas with an ignition dose of the rapeseed oil methyl ester). Biogas generated by agricultural production waste (from cattle manure) was researched. And also, the rapeseed oil methyl ester oil produced by etherification of rapeseed oil with ethanol was studied. The properties of these fuels are given in Table 2. When converting diesel to biogas, the developed regulator of the fuel injection pump assembly maintained an approximate constancy of the hourly consumption of the ignition rapeseed oil methyl ester at 1.93 kg/h (Table 4); i.e. the approximate constancy of the ignition dose of the rapeseed oil methyl ester was at the level of \(q_c = 12.2 \text{ mm}^3\).

Only ignition rapeseed oil methyl ester was fed into the engine in the entire range of load modes at idle speed because of the approximate constancy of the hourly consumption of the rapeseed oil methyl ester at the level of \(G_{ROME} = 1.93 \text{ kg/h}\). The biogas feed was maximal and equal to \(G_{\text{biog}} = 9.00 \text{ kg/h}\) in the full load mode, and the hourly consumption of rapeseed oil methyl ester was \(G_{\text{DME}} = 1.92 \text{ kg/h}\). As a result, the supply of the ignition rapeseed oil methyl ester turned out to be equal to 17.6 % of the total flow in the maximum power mode (where \(G_{\text{fuel 2}} = G_{ROME} + G_{\text{biog}} = 10.92 \text{ kg/h}\)). The total flow is the common supply of the hourly consumption of liquid and gaseous fuels \((G_{\text{fuel 2}})\). According to Table 4, the values of the excess air factor “\(\alpha\)” and the fuel economy indices of the diesel are determined. Therefore, the methods of work [2] were used.
Table 4. Hourly Consumptions of Air Flow $G_{\text{air}}$, Oil Diesel Fuel $G_{\text{DF}}$, Rapeseed Oil Methyl Ester $G_{\text{ROME}}$, and Biogas $G_{\text{biog}}$; Air Temperatures in the Intake Manifold $t_{\text{air in}}$ and Coolant Air of the Generator $t_{\text{air gen}}$, Air Excess Ratio $\alpha$ of Diesel Engine $4Ch 11/12.5$

| Diesel Cycle | Mode number | $n$, rpm | $N_e$, kW | $G_{\text{DF}}$, kg/h | $G_{\text{biog}}$, kg/h | $G_{\text{air}}$, kg/h | $t_{\text{air in}}$, °C | $t_{\text{air gen}}$, °C | $\alpha$ |
|--------------|-------------|----------|-----------|---------------------|----------------------|---------------------|-----------------|------------------|-------|
| 1            | 1,450       | 34.4     | 9.33      |                    | –                    | 185                 | 32.0            | 28               | 1.39  |
| 2            | 1,473       | 28.8     | 7.45      | –                   | 195                  | 29.0                | 26              | 1.83             |
| 3            | 1,491       | 23.2     | 6.03      | –                   | 198                  | 27.2                | 24              | 2.30             |
| 4            | 1,509       | 15.4     | 4.35      | –                   | 200                  | 34.7                | 30              | 3.22             |
| 5            | 1,520       | 7.7      | 2.82      | –                   | 202                  | 35.2                | 30              | 5.01             |
| 6            | 1,557       | 0        | 1.50      | –                   | 204                  | 33.4                | 30              | 9.51             |

| Gas-diesel Cycle | Mode number | $n$, rpm | $N_e$, kW | $G_{\text{ROME}}$, kg/h | $G_{\text{biog}}$, kg/h | $G_{\text{DF}}$, kg/h | $t_{\text{air in}}$, °C | $t_{\text{air gen}}$, °C | $\alpha$ |
|------------------|-------------|----------|-----------|---------------------|----------------------|---------------------|-----------------|------------------|-------|
| 1                | 1,434       | 33.7     | 1.92      | 9.00                | 174                  | 37.6                | 35              | 35               | 1.31  |
| 2                | 1,440       | 28.5     | 1.92      | 6.83                | 182                  | 36.6                | 33              | 29               | 1.70  |
| 3                | 1,455       | 23.5     | 1.93      | 5.27                | 190                  | 33.6                | 30              | 2.16             |
| 4                | 1,475       | 15.6     | 1.94      | 3.17                | 194                  | 32.5                | 29              | 3.05             |
| 5                | 1,490       | 7.9      | 1.93      | 1.44                | 198                  | 34.2                | 31              | 4.70             |
| 6                | 1,515       | 0        | 1.92      | –                   | 200                  | 33.0                | 30              | 8.43             |

The data of Table 5 show that the total specific effective fuel consumption ($g_{e \text{ total}}$) was generally higher than in the purely diesel cycle when the gas-diesel cycle was fulfilled. The lowest specific effective fuel consumption $g_e = 258.7 \text{g/(kW-h)}$ corresponds to the regime of the diesel cycle with the power of $N_e = 28.8 \text{kW}$ at $n = 1,473$ rpm.

The values of the effective efficiency $\eta_e$ calculated in accordance with the methods of work [2] are presented in Table 5. The diesel and gas-diesel cycles of diesel are close to each other on the efficiency of the combustion process.

The obtained data on the smoke emission of the diesel engine (Table 5) show that the use of biogas results in a noticeable decrease in the emission of carbon $C$ (reducing smoke emission). There is a significant reduction in the exhaust smokiness at the modes with high loads, compared with the diesel cycle. The biggest smoke emission was observed at the full load mode: in the diesel cycle $K_X = 57.3\%$ on the Hartridge scale, and in the gas-diesel cycle $K_X = 8.7\%$ on the Hartridge scale. Thus, the transition from the diesel cycle to the gas-diesel cycle results in reduction of the exhaust smokiness by about 6.6 times at this regime. The transition from the diesel to the gas-diesel cycle influences the content of other toxic components in the exhaust.

A decrease in oxygen concentration $C_{O_2}$ in the exhaust gases of the diesel engine is observed during the transition from the diesel cycle to the gas-diesel cycle. And also, there is an increase of carbon dioxide content $C_{CO_2}$ in the exhaust (Table 6). It should be noted that there is a tendency for a smaller content of $NO_x$ in the exhaust gases in the gas-diesel cycle compared with the diesel cycle. Another point to be mentioned is that for the gas-diesel cycle of the studied diesel engine the products content of incomplete fuel combustion are characteristic: carbon monoxide $CO$ and light unburned hydrocarbons $CH_x$ (Table 6).
Table 5. Total Specific Effective Fuel Consumption $g_{e, \text{total}}$, Total Net Calorific Value of the Rapeseed Oil Methyl Ester and Biogas $H_{U, \Sigma}$, Effective Efficiency $\eta_e$, Exhaust Smokiness $K$ [m$^{-1}$] and $K_e$ [% on Hartridge scale] of the Diesel Engine 4Ch 11/12.5.

| Mode Number | $n$, rpm | $N_e$, kW | $g_{e, \text{total}}$, g/(kW·h) | $H_{U, \Sigma}$, MJ/kg | $\eta_e$ | $K$, m$^{-1}$ | $K_e$, % (Hartridge) |
|-------------|----------|-----------|---------------------------------|-----------------------|---------|-------------|------------------|
| Diesel cycle | 1 | 1,450 | 34.4 | 271.2 | 42.5 | 0.312 | 1.979 | 57.3 |
| | 2 | 1,473 | 28.8 | 258.7 | 42.5 | 0.327 | 0.294 | 11.9 |
| | 3 | 1,491 | 23.2 | 259.9 | 42.5 | 0.326 | 0.094 | 4.0 |
| | 4 | 1,509 | 15.4 | 282.5 | 42.5 | 0.300 | 0.068 | 2.9 |
| | 5 | 1,520 | 7.7 | 366.2 | 42.5 | 0.231 | 0.04 | 1.8 |
| | 6 | 1,557 | 0 | – | 42.5 | – | 0.03 | 1.3 |

| Mode Number | $n$, rpm | $N_e$, kW | $g_{e, \text{total}}$, g/(kW·h) | $H_{U, \Sigma}$, MJ/kg | $\eta_e$ | $K$, m$^{-1}$ | $K_e$, % (Hartridge) |
|-------------|----------|-----------|---------------------------------|-----------------------|---------|-------------|------------------|
| Gas-diesel cycle | 1 | 1,434 | 33.7 | 324.0 | 35.3 | 0.315 | 0.211 | 8.7 |
| | 2 | 1,440 | 28.5 | 307.0 | 35.4 | 0.331 | 0.110 | 4.9 |
| | 3 | 1,455 | 23.5 | 306.4 | 35.6 | 0.330 | 0.090 | 3.8 |
| | 4 | 1,475 | 15.6 | 329.8 | 35.9 | 0.306 | 0.068 | 2.8 |
| | 5 | 1,490 | 7.9 | 426.5 | 36.5 | 0.231 | 0.04 | 1.7 |
| | 6 | 1,515 | 0 | – | 37.8 | – | 0.03 | 1.2 |

Table 6. Volumetric Concentrations of Oxygen $C_{O2}$, Carbon Dioxide $C_{CO2}$, Nitrogen Oxides $C_{NOx}$, Carbon Monoxide $C_{CO}$, Light Unburned Hydrocarbons $C_{CHx}$ in the Exhaust Gases of Diesel Engine 4Ch 11/12.5.

| Mode Number | $n$, rpm | $N_e$, kW | $C_{O2}$, % | $C_{CO2}$, % | $C_{NOx}$, ppm | $C_{CO}$, ppm | $C_{CHx}$, ppm |
|-------------|----------|-----------|-------------|-------------|----------------|--------------|----------------|
| Diesel cycle | 1 | 1,446 | 34.6 | 6.11 | 10.76 | 1,112 | 819 | 64 |
| | 2 | 1,464 | 28.6 | 8.98 | 8.47 | 1,284 | 487 | 102 |
| | 3 | 1,485 | 23.2 | 11.25 | 6.82 | 1,168 | 395 | 123 |
| | 4 | 1,503 | 15.7 | 13.86 | 4.92 | 740 | 364 | 146 |
| | 5 | 1,516 | 7.9 | 16.07 | 3.34 | 371 | 380 | 162 |
| | 6 | 1,557 | 0 | 17.41 | 2.01 | 196 | 431 | 181 |

| Mode Number | $n$, rpm | $N_e$, kW | $C_{O2}$, % | $C_{CO2}$, % | $C_{NOx}$, ppm | $C_{CO}$, ppm | $C_{CHx}$, ppm |
|-------------|----------|-----------|-------------|-------------|----------------|--------------|----------------|
| Gas-diesel cycle | 1 | 1,434 | 34.5 | 5.51 | 11.35 | 950 | 1,158 | 93 |
| | 2 | 1,449 | 28.7 | 8.29 | 9.09 | 1,120 | 764 | 160 |
| | 3 | 1,462 | 23.4 | 10.62 | 7.36 | 1,008 | 641 | 224 |
| | 4 | 1,479 | 15.5 | 13.31 | 5.22 | 557 | 578 | 264 |
| | 5 | 1,491 | 7.5 | 15.65 | 3.12 | 215 | 549 | 219 |
| | 6 | 1,505 | 0 | 17.96 | 1.88 | 151 | 526 | 193 |

Note: Volumetric percentage content is indicated for $C_{O2}$ and $C_{CO2}$ in exhaust gases; ppm (part per million) is millionth volume proportions of $C_{NOx}$, $C_{CO}$, $C_{CHx}$. 
5. Conclusion
When diesel engine is transferred from the diesel cycle to the gas-diesel cycle, there is a marked improvement in its environmental performance. In general, this was revealed by the analysis of the characteristics of toxic components in the emissions of the diesel engine. There was a significant reduction in the emissions of two major toxic components of exhaust gases in the gas-diesel cycle: nitrogen oxides and soot (exhaust gas smokiness). At the same time, an increase in the emissions of two other standardized toxic components of exhaust gas was registered: carbon monoxide \( CO \) and unburned hydrocarbons \( CH_x \). Wherein the toxicological significance of carbon monoxide \( CO \), nitrogen oxides \( NO_x \), unburned hydrocarbons \( CH_x \), and soot (solid particles) is estimated as the ratios of 1:41; 1:3; 16:200 [3, 10]. It also should be noted according to the tests of the diesel, that the increase in the emissions of carbon monoxide \( CO \) and unburned hydrocarbons \( CH_x \) is eliminated in the gas-diesel cycle in comparison with the conventional diesel cycle by using a catalytic converter. It effectively purifies the exhaust gases of the products of incomplete fuel combustion [3, 7, 11].

The conducted experimental studies confirmed once again the prospects of using biogas for fuel-feeding diesel engines. It is expedient to fulfil the gas-diesel cycle when biofuel is used as motor fuel. In this cycle biogas ignites from a firing dose of the rapeseed oil methyl ester, which has better flammability in comparison with petroleum diesel fuel in the conditions of the diesel engine combustion chamber. The implementation of such dual-fuel cycle allows to completely stop using fuels produced from fossil raw materials and replace them with biofuels.

6. References

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