Abstract. Biofuels derived from vegetable oils are increasingly used in diesel engines. The article analyzes the physicochemical properties of petroleum diesel fuel and biofuels of various compositions. A technique has been developed to optimize the composition of multicomponent composite biofuels for diesel engines of agricultural machinery. The optimal composition of a mixture of petroleum diesel fuel, rapeseed oil and rapeseed oil methyl ester has been determined, providing the best combination of fuel efficiency and exhaust emissions. The optimization calculations made it possible to select the composition of a multicomponent mixed biofuel for the D-245.12S engine installed on domestic agricultural machines.

1. Introduction

In recent years an increased interest is shown in fuels derived from renewable energy resources of plant origin, the raw material reserves of which are practically unlimited due to the worsening energy crisis and the growing shortage of oil energy sources. Biofuels produced from vegetable oils are considered promising with regard to diesel engines for transport and agricultural purposes [1, 2, 3].

For the conditions of the European part of Russia, the most promising are fuels based on rapeseed oil. Rapeseed has a relatively good yield and rape is a desirable crop for improving crop rotation, from the agronomical point of view (it improves the structure and fertility of the soil). The use of biofuels based on rapeseed oil will allow not only replacing petroleum motor fuels with alternative fuels, but also improve indicators of exhaust gases toxicity. As a rule, there is a noticeable decrease in the emission of toxic exhaust gases components when diesel engines run on biofuels. First of all, this refers to the exhaust smokiness and emissions of other products of incomplete combustion of fuel, which are reduced by 1.5–2 times when using biofuels [1]. In addition, the use of plant-based fuels provides carbon dioxide circulation in the atmosphere, since during the combustion of biofuels in internal combustion engines; approximately the same amount of carbon dioxide is released into the atmosphere. It is absorbed in the process of growing raw materials for biofuel production. This leads to a decrease in greenhouse gas emissions.

However, biofuels have physicochemical properties that differ from the properties of petroleum diesel fuel [1, 4, 5]. Therefore, when converting engines, initially adapted to work on diesel fuel, to biofuels, a number of problems arise associated with the organization of work processes. Primarily these processes are fuel injection, atomization of fuel, mixture formation and combustion. In this case, it is possible that the initial adjustments of the engine are disturbed, the number of performance...
indicators of diesel engines is deteriorated, the wear of engine parts is increased, and their service life is reduced. Therefore, it is necessary to adapt the engines to operate on this type of fuel. One of the most effective ways to adapt engines to work on biofuels is the use of mixed biofuels (mixtures of diesel fuel and rapeseed oil). The greatest approximation to the properties of petroleum diesel fuel gives the use of multicomponent petroleum biofuels containing three or more components. It is able to get the best combination of diesel engines indexes of agricultural machines during the composition optimization of multicomponent mixed biofuels [6, 7, 8].

The problem of ensuring the necessary physicochemical properties of biofuels is also relevant in relation to vegetable oils and their derivatives (vegetable oil esters). An important feature of these fuels is the ability to mix in any proportions with most organic solvents including petroleum products (gasoline, kerosene and diesel fuel). It should be noted a good compatibility of various vegetable oils and their esters among themselves. This feature of these fuels allows obtaining multicomponent biofuels with desired physicochemical properties by mixing the various components in the required proportions.

2.2. Physical-chemical properties of diesel fuel mixtures with rapeseed oil and rapeseed oil methyl ester
Numerous published works [1–4, 9–13] confirm the possibility of using “pure” vegetable oils as a fuel for diesel engines, as well as their mixtures with traditional petroleum diesel fuel, which reduce exhaust gases toxicity. But at the same time one of the most acute problems is the increased viscosity of vegetable oils. In particular, the viscosity-temperature characteristics presented in ‘figure 1a’ indicate that the viscosity of rapeseed oil is much higher at normal temperature \( t = 20 \, {\text{°C}} \) than petroleum diesel fuel [6]. In the studies presented below, diesel fuel “Z” was used according to GOST (State Standard) 305-82 and domestic rapeseed oil with kinematic viscosity, respectively, \( \nu = 2.37 \) and 75 mm\(^2\)/s (Table 1).

Mixtures of vegetable oils with petroleum diesel fuel have a significantly lower viscosity. Thus, according to the data of [6], the viscosity of a mixture containing 80% diesel fuel (by volume) and 20% rapeseed oil at \( t = 20 \, {\text{°C}} \) is \( \nu = 9 \) mm\(^2\)/s ‘figure 1a’. But even this viscosity of composite biofuels significantly exceeds the viscosity of petroleum diesel fuel (the summer diesel viscosity is \( \nu = 3…6 \) mm\(^2\)/s, in accordance with GOST 305-82).

Rapeseed oil has a higher density than petroleum diesel fuel. So, if the density of the investigated below rapeseed oil was 913 kg/m\(^3\), then the density of diesel fuel of the “Z” brand in accordance with GOST 305-82 is 805 kg/m\(^3\). In addition, rapeseed oil has a greater surface tension. The surface tension of petroleum diesel fuel is 27.1 mN/m, and rapeseed oil is 33.2 mN/m. These differences in the physical properties of rapeseed oil from the properties of petroleum diesel fuel have a significant impact on the parameters of the diesel fuel injection process. It leads to the transformation of the characteristics of injection and atomization of these fuels, subsequent processes of mixture formation and combustion, fuel economy and exhaust gases toxicity indicators [6].

An effective way to improve the quality of these processes is to approximate the properties of biofuels based on vegetable oils to the properties of petroleum diesel fuel. But the possibilities of this method are limited when using only two components of mixed biofuels (for example, diesel fuel and rapeseed oil). The use of a larger number of components with different physicochemical properties (for example, diesel fuel, rapeseed oil and rapeseed oil methyl ester, see Table 1) allows one to purposefully influence these properties by optimizing the composition of biofuels. Thus, the use of multicomponent biofuels allows us to provide an approximation of the physicochemical properties of these fuels to the properties of petroleum diesel fuel. In particular, the multicomponent biofuels studied below (mixtures of diesel fuel, rapeseed oil and rapeseed oil methyl ester) have a viscosity corresponding to the viscosity of summer diesel fuel according to the GOST 305-82 (\( \nu = 3..6 \) mm\(^2\)/s, see ‘figure 1b’).

It should be noted that during the operation of vehicles and agricultural equipment (tractors, combines, etc.), multicomponent biofuels can be formed during their refueling. If a diesel engine, besides traditional diesel fuel, also operate on biofuels (on rapeseed oil and rapeseed oil methyl ester),
then during refueling the fuel remaining in the tank is mixed with the refueled fuel, and a sufficiently long operation of diesel engines on mixtures of these fuels is possible. In this case, the fuel in the fuel tank becomes multicomponent.

**Table 1.** Physicochemical properties of the studied fuels.

| Physicochemical properties | Fuels | 90% diesel fuel, 5% rapeseed oil and 5% rapeseed oil methyl ester | 80% diesel fuel, 10% rapeseed oil and 10% rapeseed oil methyl ester | 60% diesel fuel, 20% rapeseed oil and 20% rapeseed oil methyl ester |
|----------------------------|-------|---------------------------------------------------------------|---------------------------------------------------------------|---------------------------------------------------------------|
| Density at 20 °C, kg/m³    | 805   | 913                                                          | 877                                                          | 815                                                          | 821                                                          | 840                                                          |
| Kinematic viscosity at 20 °C, mm²/s | 2.37  | 75.0                                                         | 8.0                                                          | 4.661                                                        | 5.421                                                        | 5.477                                                        |
| Surface tension coefficient at 20 °C, mN/m | 27.1  | 33.2                                                         | 30.7                                                         | –                                                            | –                                                            | –                                                            |
| Net calorific value, kJ/kg | 42,500| 37,300                                                        | 37,800                                                        | 42,000                                                       | 41,500                                                       | 40,500                                                       |
| Cetane number              | 45    | 36                                                           | 48                                                           | –                                                            | –                                                            | –                                                            |
| Autoignition temperature, °C | 250   | 318                                                          | 230                                                          | –                                                            | –                                                            | –                                                            |
| Cloud point, °C            | -25   | -9                                                           | -13                                                          | –                                                            | –                                                            | –                                                            |
| Solidification point, °C   | -35   | -20                                                          | -21                                                          | –                                                            | –                                                            | –                                                            |
| The amount of air needed to burn 1 kg of substance, kg | 14.3  | 12.5                                                         | 12.6                                                         | 14.2                                                         | 14.0                                                         | 13.6                                                         |
| Content, percentage by weight |       |                                                               |                                                               |                                                               |                                                               |                                                               |
| C                         | 87.0  | 77.0                                                         | 77.6                                                         | 86.0                                                         | 85.1                                                         | 83.1                                                         |
| H                         | 12.6  | 12.0                                                         | 12.2                                                         | 12.6                                                         | 12.5                                                         | 12.4                                                         |
| O                         | 0.4   | 11.0                                                         | 10.2                                                         | 1.4                                                          | 2.4                                                          | 4.5                                                          |

Note: “–” – properties were not defined; volumetric percentage of components is indicated for mixtures.

3. Experimental studies of the diesel engine operating on mixtures of diesel fuel with rapeseed oil and rapeseed oil methyl ester

Evaluation of the composition influence of multicomponent biofuels on the indicators of fuel efficiency and exhaust gases toxicity is carried out using the results of experimental studies of the diesel engine type D-245.12S (4 CN 11/12.5) produced by Minsk Motor Corp., conducted on a motor stand [6]. Diesel D-245.12S had a fuel system that included the Motorpal PP4M10U1 type fuel injection pump assembly with diameter of plungers \(d_{pl} = 10\) mm and their full speed \(h_{pl} = 10\) mm, high-pressure fuel lines of length \(L = 540\) mm and FDM-22 nozzles, which were adjusted to injection start pressure \(p_{inj} = 21.0\) MPa. The installation angle of fuel injection advance equal to \(\theta = 13^\circ\) of crankshaft rotation to the top dead center (TDC) and the position of the maximum fuel delivery stop remained unchanged during the tests. The motor stand was equipped with a set of necessary measuring equipment. Exhaust gases smokiness was measured using an MK-3 smoke meter produced by Hartridge (UK) with a measurement error of ±1%. The concentrations of \(NO_x\), CO, \(CH_x\) in exhaust gases were determined with a SAE-7532 gas analyzer from the Japanese company YANACO with components measurement errors of ±1%.
Figure 1. Viscosity-temperature characteristics of two-component (a) and multicomponent (b) composite biofuels: 1 – rapeseed oil; 2 – 50% diesel fuel and 50% rapeseed oil; 3 – 80% diesel fuel and 20% rapeseed oil; 4 and 5 – diesel fuel; 6 – 90% diesel fuel+5% rapeseed oil+5% rapeseed oil methyl ester; 7 – 80% diesel fuel+10% rapeseed oil+10% rapeseed oil methyl ester; 8 – 60% diesel fuel+20% rapeseed oil+20% rapeseed oil methyl ester; 9 – rapeseed oil methyl ester.

At the first stage of research, tests of the diesel type D-245.12S were performed on full-load curve on petroleum diesel fuel, as well as on the mixture of 90% diesel fuel, 5% rapeseed oil and 5% rapeseed oil methyl ester (biofuel №1), the mixture of 80% diesel fuel, 10% rapeseed oil and 10% rapeseed oil methyl ester (biofuel №2), and mixtures of 60% diesel fuel, 20% rapeseed oil and 20% rapeseed oil methyl ester (biofuel №3). Some physical-chemical properties of these fuels are given in Table 1. The test results of the diesel engine on full-load curve regimes are shown in ‘figure 2’ and in Table 2. At the second stage, the engine was examined on the 13-regime test modes of the UNECE Regulation 49. The results of these tests are shown in ‘figure 3’ and are presented in Table 2.

The data presented above confirm the possibility of improving the exhaust gases toxicity indicators of the diesel engine D-245.12S type when it is transferred from petroleum diesel fuel to multicomponent biofuels. But this raises the problem of the composition optimization of these fuels.

4. Composition optimization of multicomponent biofuels

The results analysis of experimental studies of the D-245.12S diesel engine, operating on petroleum diesel fuel and its mixtures with rapeseed oil, shows that the task of choosing the optimal composition of composite biofuels is quite complex and does not have a univocal solution. This is due to the fact that the operation of the diesel engine is characterized by a whole set of indicators (criteria) of exhaust gases toxicity: normalized emissions of nitrogen oxides NOx, carbon monoxide CO, light unburned hydrocarbons CHx and particulate matter or soot (carbon) C (exhaust gases smokiness). Requirements for the choice of the optimal fuel composition according to these criteria often contradict each other. As a result, the task of choosing the optimal composition of mixed biofuels becomes a multi-criteria optimization problem [4, 14–17].
The article proposes the method for optimizing the composition of mixed biofuels (mixtures of petroleum diesel fuel with rapeseed oil and rapeseed oil methyl ester), based on the compilation of a generalized additive optimality criterion as a sum of partial criteria characterizing the emission of two main toxic components of exhaust gases: nitrogen oxides and soot (exhaust gases smokiness). In this case, the main operating modes of the diesel engine are the modes of maximum power and maximum torque. Thus, the task of optimizing the composition of mixed biofuels for the diesel engine is reduced to finding the generalized criterion $J_o$. It is defined as the sum of individual criteria characterizing the concentration of nitrogen oxides $J_{NOx}$ in the exhaust gases and the exhaust opacity on the Hartridge scale $J_{Kx}$ in two main modes (maximum power $N_{max}$ and maximum torque $M_{max}$). The expression of the generalized criterion takes the form:

$$J_o = J_{NOx\_max} + J_{NOx\_max} + J_{Kx\_max} + J_{Kx\_max},$$

(1)

where $J_{NOx\_max}$, $J_{NOx\_max}$, $J_{Kx\_max}$ are partial criteria of optimality (concentration of nitrogen oxides in exhaust gases and exhaust smokiness on the Hartridge scale) in the specified modes. Since in the proposed method, the concentration of nitrogen oxides $C_{NOx}$ and smoke opacity $K_x$ on the Hartridge scale, having different dimensions, are used as partial criteria for the optimality of expression (1), it is reasonable to apply them in relative values as follows:
\[ J_{NOx} N_{max} = \frac{C_{NOx} N_{max}}{C_{NOx} N_{DF}}; \]
\[ J_{NOx} M_{max} = \frac{C_{NOx} M_{max}}{C_{NOx} M_{DF}}; \]
\[ J_{KX} N_{max} = \frac{KX N_{max}}{KX N_{DF}}; \]
\[ J_{KX} M_{max} = \frac{KX M_{max}}{KX M_{DF}}. \]  \hspace{1cm} (2)

where the parameters with the “DF” index correspond to the work on petroleum diesel fuel, and the parameters with the “i” index correspond to the work on the mixed biofuel of the i-th composition.

The generalized optimality criterion (1) is also convenient to use in relative form given below:

\[ J_0 = \frac{J_{oI}}{J_{oDF}}. \]  \hspace{1cm} (3)

**Table 2.** Indexes of diesel type D-245.12S during the operation on the studied fuels.

| Diesel indicators | Composition of fuel |
|-------------------|---------------------|
|                   | 90% diesel fuel + 5% rapeseed oil methyl ester (mixture №1) | 80% diesel fuel + 10% rapeseed oil + 10% rapeseed oil methyl ester (mixture №2) | 60% diesel fuel + 20% rapeseed oil + 20% rapeseed oil methyl ester (mixture №3) |
| Hourly fuel consumption \( G_F \), kg/h | 19.50/249.0 | 19.79/224.3 | 19.98/228.7 |
| Diesel torque \( M_e \), N·m | 12.70 | 312/361 | 12.60 | 311/351 |
| Specific effective fuel consumption \( g_e \), g/(kW·h) | 312/249.0 | 12.00 | 311/224.3 |
| Effective efficiency of the diesel \( \eta_e \) | 0.378 | 0.338 | 0.340 |
| Exhaust gases smokiness \( KX \), % by Hartridge scale | 0.378 | 0.338 | 0.340 |
| Integral indicators of diesel fuel economy on the modes of 13-mode cycle: | | | |
| – effective fuel consumption \( g_e^{\text{cond},} \), g/(kW·h) | 247.89 | 251.72 | 253.89 |
| – effective efficiency \( \eta_e^{\text{cond}} \) | 0.342 | 0.341 | 0.342 |
| Integral specific emissions of toxic components on 13-mode cycle, g/(kW·h): | | | |
| – nitrogen oxides \( e_{NOx} \) | 6.862 | 6.875 | 6.662 | 7.182 |
| – carbon monoxide \( e_{CO} \) | 2.654 | 2.489 | 2.496 | 2.662 |
| – unburned hydrocarbons \( e_{C_{Hx}} \) | 0.719 | 0.687 | 0.677 | 0.690 |

Note: the parameters obtained at the maximum power mode are given in the numerators; the parameters obtained at the maximum torque mode are given in the denominators.
Figure 3. Dependency of hourly fuel consumption $G_F$ (a), volumetric concentrations of nitrogen oxides $C_{NOx}$ in exhaust gases (b), carbon monoxide $C_{CO}$ (c), unburned hydrocarbons $C_{CHx}$ (d) from rotational speed $n$ and torque $M_e$ of the diesel type $D$-245.12S: 1 – diesel fuel; 2 – mixture 90% diesel fuel + 5% rapeseed oil + 5% rapeseed oil methyl ester; 3 – mixture 80% diesel fuel + 10% rapeseed oil + 10% rapeseed oil methyl ester; 4 – mixture 60% diesel fuel + 20% rapeseed oil + 20% rapeseed oil methyl ester.

The proposed method has been applied to optimize the composition of mixtures of petroleum diesel fuel with rapeseed oil and rapeseed oil methyl ester for the $D$-245.12S diesel engine. At the same time the experimental data of ‘figure 2’, ‘figure 3’ and Table 2 are used. The results of the calculation of partial optimality criteria for expressions (2) and the generalized optimality criterion for the formulas (1) and (3) are given in Table 3.

The data of Table 3 indicate that all considered mixed biofuels significantly improve the exhaust gases toxicity indicators of the $D$-245.12S type diesel engine. From the point of view of the generalized criterion of the proposed optimization technique, the best results were achieved using the mixture of 60% diesel fuel, 20% rapeseed oil and 20% rapeseed oil methyl ester.

5. Conclusion

The complex of experimental and computational studies has confirmed the effectiveness of using mixtures of petroleum diesel fuel with rapeseed oil and rapeseed oil methyl ester as fuel for car-and-tractor diesel engines. Experimental studies of the $D$-245.12S diesel engine were carried out on petroleum diesel fuel and on its mixtures with rapeseed oil and oil methyl ester. The concentration of rapeseed oil and rapeseed oil methyl ester was up to 20% of each of them (by volume). The technique has been developed to optimize the composition of petroleum diesel fuel mixtures with rapeseed oil and rapeseed oil methyl ester. This method has been based on the compilation of the generalized additive optimality criterion as a sum of partial criteria characterizing the emission of two main toxic components of exhaust gases: nitrogen oxides and soot (exhaust opacity). It occurred during diesel operation in two main operating modes of the diesel engine: maximum power and maximum torque.
The best results on the environmental performance of the diesel engine were achieved using the mixture of 60% diesel fuel, 20% rapeseed oil and 20% rapeseed oil methyl ester. The transfer of the D-245.12S diesel engine from petroleum diesel fuel to the indicated mixture reduced the opacity of exhaust gases from 16.0 to 9.0% on the Hartridge scale at maximum power mode and from 23.0 to 9.5% at maximum torque mode. At the same time, the specific emission of unburned hydrocarbons $e_{\text{CH}_x}$ integrated on the 13-mode modes, decreased from 0.719 to 0.690 g/(kW h). The specific mass emission of carbon monoxide $e_{\text{CO}}$ and the integral (conditional) effective efficiency $\eta_{\text{e cond}}$ remained almost unchanged. The integral specific emission of nitrogen oxides $e_{\text{NOx}}$ increased from 6.862 to 7.182 g/(kW h). But it can be effectively reduced by optimizing the fuel injection advance angle.

### Table 3. Composition optimization of mixtures of petroleum diesel fuel, rapeseed oil and rapeseed oil methyl ester for D-245.12S diesel engine.

| Fuel type | $C_{\text{NOx}}$ | $J_{\text{NOx}}$ | $C_{\text{NOx}}$ | $J_{\text{NOx}}$ | $K_X$ | $J_X$ | $K_{X M\text{max}}$ | $J_{X M\text{max}}$ | $J_o$ | $\overline{J}_o$ |
|-----------|----------------|----------------|----------------|----------------|-------|-------|----------------|----------------|-------|-------------|
| Diesel fuel | 565 | 1.000 | 650 | 1.000 | 16.0 | 1.000 | 23.0 | 1.000 | 4.000 | 1.000 |
| 90% diesel fuel+5% rapeseed oil+5% rapeseed oil methyl ester | 570 | 1.009 | 640 | 0.985 | 10.0 | 0.625 | 11.0 | 0.478 | 3.097 | 0.774 |
| 80% diesel fuel+10% rapeseed oil+10% rapeseed oil methyl ester | 550 | 0.973 | 625 | 0.962 | 11.0 | 0.688 | 12.5 | 0.543 | 3.166 | 0.792 |
| 60% diesel fuel+20% rapeseed oil+20% rapeseed oil methyl ester | 600 | 1.062 | 650 | 1.000 | 9.0 | 0.563 | 9.5 | 0.413 | 3.038 | 0.760 |

In conclusion of the results analysis of the research conducted on the operation of the diesel engine on multicomponent biofuels, it should be noted that the use of these fuels not only provided an improvement in the engine’s exhaust gases toxicity indicators, but also made it possible to bring the properties of biofuels closer to traditional petroleum diesel fuel. This, in turn, facilitates the organization of the fuel feeding processes, atomization of fuel, mixing and subsequent combustion. In addition, the adaptation of engines to work on multicomponent biofuels simplifies the supply of vehicles and agricultural equipment with the necessary motor fuels.

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