Multicomponent Emulsified Biofuels for Transport Diesel Engines

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Abstract. Vegetable oils are a significant raw material resource for producing biodiesel fuels. But while using vegetable oils as fuels, the coking of the combustion chamber elements and injectors’ spraying nozzles. These problems can be solved by supplying water into the combustion chamber through the injectors. The article considers an opportunity of ensuring the stable operation of the diesel engine when it is powered by multicomponent emulsified biofuels. Emulsions of petroleum diesel fuel, rapeseed oil and water were investigated. The results of experimental studies of the automotive diesel engine running on these fuels are presented. According to the test results the efficiency of using these emulsions as fuels for diesel engines was evaluated. The favorable combination of characteristics of fuel efficiency and toxicity of diesel engine exhaust gases is obtained by using an emulsion containing 57% of petroleum diesel fuel, 30% of rapeseed oil and 13% of water (by volume). At the maximum power mode, the replacement of petroleum diesel fuel with this emulsion enabled to reduce exhaust smoke opacity from 16.0 to 7.5% according to the Hartridge scale. By the modes of the thirteen-mode cycle the integral specific emission of nitrogen oxides NO\textsubscript{x} decreases from 6,610 to 5,552 g/(kW\cdot h).

1. Introduction

At the present stage of engine-building development the intensive search for energy sources that can replace petroleum motor fuels is carried out. Various alternative fuels [1, 2, 3] are becoming more common. Biomass is a significant raw material supplies base for the production of motor fuels. Annually in the world 170–200 billion tons of biomass is formed (in terms of dry weight), which is equivalent to 70–80 billion tons of petroleum [4]. At present, only a small part of it is used for power industry needs. In relation to diesel engines, vegetable oils are a promising raw material resource. Currently, about 100 million tons of various vegetable oils are produced annually in the world. Rapeseed oil accounts for about a quarter of the total volume of vegetable oils produced [5, 6]. Moreover, technical, low-grade, expired and deep-frying vegetable oils can be used for the production of motor fuels [7, 8, 9].

Various vegetable oils and their derivatives – methyl, ethyl, and butyl ethers – are used as fuel for diesel engines [10, 11, 12, 13]. Despite the problems that arise when diesel engines run on vegetable
oils (their high viscosity, as well as the coking of spraying nozzles and elements forming the combustion chamber, the mobility degradation of the piston rings that occur during long-term work on these oils), research continues on the operation of diesel engines on these biofuels and their mixtures with other fuels [1, 5, 6, 14–17].

One of the important aspects of the use of vegetable oils and fuels based on them as a motor fuel is the possibility to improve the exhaust emission indexes of diesel engines operating on these fuels [10, 18, 19, 20]. This is due to the high content of oxygen atoms (10–12%) in the molecules of vegetable oils participating in the oxidation (combustion) processes of fuel, and the absence of sulfur and polycyclic aromatic hydrocarbons (PAHs) in them. Therefore, when diesel engines operate on vegetable oils or fuels produced from them, the exhaust gases contain a very small amount of incomplete combustion products (primarily soot), sulfur oxides (SO₂), PAHs and a number of other harmful substances. A further reduction in soot emissions, as well as a reduction in nitrogen oxides (NOₓ) emissions, can be achieved by adding water to biofuels. The use of water-fuel emulsions refers to few methods for reducing exhaust emissions, which simultaneously reduce the content of NOₓ and smoke [4, 6, 19]. In this regard, it is advisable to use emulsions of water and biofuels (vegetable oils and their derivatives) [21–24]. These biofuels, even in their pure form, are distinguished by good ecological qualities, and their emulsions with water have even better ecological characteristics. Furthermore, the addition of water to biofuels allows us to solve the problem of the coking of elements that form the diesel engine’s combustion chamber and the coking of the injectors’ spraying nozzles.

This is confirmed by studies of diesel engines on emulsions of vegetable oils and their derivatives with water [25, 26, 27]. However, in these studies, insufficient attention was paid to the issues of how the properties of these emulsions influence the exhaust emission indexes of diesel engines.

2. Experimental studies of transport diesel on multicomponent emulsified biofuels

One of the tasks of water-fuel emulsification is the need to use special emulsifying devices. To obtain an emulsion containing 70% (vol.) of rapeseed oil (RO) and 30% water, an emulsifying device was used. Its work is based on electromagnetic oscillations of the moving elements. To obtain stable emulsions of RO and water, urine alkenylsuccinimide was used as an emulsifier. It is produced by mixing these components. Physico-chemical properties of the studied fuels are presented in Table 1.

In order to assess the possibility of improving the fuel economy and exhaust toxicity using multicomponent emulsified biofuels, experimental studies of the diesel engine model “D-245.12S” (4/In Line, 4-Stroke, Turbocharged, 110mm/125mm) were carried out. It was manufactured by the OJSC “Minsk Motor Plant” Holding Managing Company” and installed on light trucks ZiL-5301 “Bychok”. In this diesel engine, which has a semi-separated combustion chamber of the CNIDI type, volume-film mixing is organized. Diesel model “D-245.12S” had a fuel system that included a high-pressure fuel pump (HPFP) model “PP4M10U1f” manufactured by “Motorpal” of with plungers’ diameter \( d_\text{p} = 10 \text{ mm} \) and their full stroke \( h_\text{p} = 10\text{mm} \), high-pressure fuel lines of length \( L_\text{p} = 540\text{mm} \) and nozzles model “FDM-22” (two-stage small nozzles), which were adjusted to the pressure of the start of injection \( p_\text{s} = 21.0 \text{ MPa} \).

The diesel engine was tested on pure diesel fuel (DF) and on multi-component emulsions. At the same time two types of multicomponent emulsions were investigated. The first of them was obtained by mixing two volume parts of summer grade DF according to GOST 305-2013 (Russian National Standard) and one volume part of the emulsion containing 70% (vol.) RO and 30% water. As a result, the emulsion №1 contained 67% DF (vol.), 23% RO and 10% water. The second multicomponent emulsion consisted of a mixture of four volume parts of summer grade DF according to GOST 305-2013 and three volume parts of the emulsion containing 70% (vol.) RO and 30% water. Emulsion №2 contained 57% DF (vol.), 30% RO and 13% water. It is necessary to notice that the initial emulsion of RO and water mixed well with petroleum diesel fuel without the involvement of additional devices for mixing these components. Physico-chemical properties of the studied fuels are presented in Table 1.
Table 1. Physico-chemical properties of petroleum diesel fuel, water and emulsified fuels.

| Physico-chemical properties | Fuel | DF | RO | Water | Emulsion № 1 (67% DF, 23% RO and 10% water) | Emulsion № 2 (57% DF, 30% RO and 13% water) |
|-----------------------------|------|----|----|-------|-------------------------------------------|-------------------------------------------|
| Density at 20 °C, kg / m³  |     | 830| 916| 998.2 | 866.6                                    | 877.7                                    |
| Kinematic viscosity at 20 °C, mm² / s  |     | 3.8| 75.0| 1.006 | 8.4                                      | 9.5                                      |
| Surface tension coefficient at 20 °C, mN / m  |     | 27.1| 33.2| 72.7 | -                                        | -                                        |
| Lower heat value, MJ / kg  |     | 42.5| 37.3| -    | 36.75                                    | 35.07                                    |
| Cetane number  |     | 45 | 36 | -    | -                                        | -                                        |
| The amount of air required for combustion of 1 kg of substance, kg  |     | 14.3| 12.5| -    | 12.46                                    | 11.92                                    |
| Content, % by weight |    | C  | 87.0| 77.0| 74.8 | 71.4                                    |
|                              |    | H  | 12.6| 12.0| 11.0 | 10.5                                    |
|                              |    | O  | 0.4 | 11.0| 2.7 | 3.4                                    |
|                              |    | H₂O| 0  | 0 | 100 | 11.5                                    |
|                              |    |  |   |   |   | 14.7                                    |

Note: “-” - properties were not defined; for mixtures of DF, RO and water the volume percentage of components is indicated.

It should be noted that the addition of water to the mixture of petroleum diesel fuel and rapeseed oil reduces the viscosity of such emulsified biofuel. This allows us to bring the properties of emulsified biofuels to the properties of traditional petroleum diesel fuel. This, in turn, simplifies the organization of fuel feeding, spraying of fuel, mixing and subsequent combustion processes.

To determine the lower heat value of emulsions, an empirical formula of D.I. Mendeleev in the form [1] is applied

\[ H_U = [81 \cdot C + 246 \cdot H - 26 \cdot (O - S) - 6 \cdot W] \cdot 4.1868 [kJ / kg], \]

where C, H, O, S, W - the content of carbon, hydrogen, oxygen, sulfur and water, % (mass.). The last formula, written for mass fractions of C, H, O, S, W, takes on the form

\[ H_U = 33.913 \cdot C + 102.995 \cdot H - 10.886 \cdot O + 10.886 \cdot S - 2.512 \cdot W [kJ / kg]. \]

The amount of air required to burn 1 kg of fuel is determined from the expressions

\[ L_o = \left(1 / \mu_o \right) \cdot \left(C / 12 + H / 4 - O / 32\right) [kmol of air / kg of fuel], \]

\[ L_o = L_o \cdot \mu_o [kg of air / kg of fuel], \]

where \( \mu_o = 28.93 \) – air molecular weight.

Diesel model “D-245.12S” was investigated on the engine stand. The fuel injection advance angle was constant and equal to \( \theta = 13^\circ \) of the crankshaft rotation to the top dead center. The stop position of the full fuel delivery of the high-pressure fuel pump (HPFP) was also unchanged. The motor stand was equipped with a set of necessary measuring equipment. Exhaust smoke opacity was measured using the Hartridge Smoke Meter MK-3 (Great Britain) with a measurement error of ± 1%. The concentration of NOx, carbon monoxide (CO), light unburned hydrocarbons (CHx) in the exhaust
gases was measured by SAE-7532 Gas Analyzer of the Japanese company Yanaco with measurement errors of the specified components ± 1%.

At the first stage of experimental studies of the diesel engine model “D-245.12S”, its tests were carried out on the full-load curve mode with maximum fuel delivery. At the second stage of testing, the load modes of the UN/ECE R49 13-mode test cycle were investigated. This cycle ‘figure 1’ includes thirteen steady-state modes: three idling modes at a minimum rotation speed \( n = (0.25 – 0.3)n_{\text{nom}} \), five load modes (10, 25, 50, 75, 100% of load) at a nominal rotation speed \( n_{\text{nom}} \) and five load modes (10, 25, 50, 75, 100% of load) at a rotation speed \( n_{\text{max}} = (0.6 – 0.7)n_{\text{nom}} \), corresponding to the maximum torque. The obtained experimental data on the diesel engine model “D-245.12S” operating on the 13-mode cycle were used to determine specific mass emissions of nitrogen oxides \( e_{\text{NOx}} \), carbon monoxide \( e_{\text{CO}} \) and unburned hydrocarbons \( e_{\text{CNx}} \). Conventional average specific effective fuel consumption \( g_{e \text{ conv}} \) for the modes of this cycle and conventional effective efficiency of the diesel engine \( \eta_{e \text{ conv}} \) were calculated. Table 2 shows the results of the research.

Figure 1. Stationary European 13-mode cycle (UN/ECE R49 standards), used to assess the exhaust emissions of diesel engines of medium and heavy duty vehicles – with a gross weight of over 3.5 tones. Next to each mode, indicated by a circle, there are its number and the time share given as a percentage of the total operating time; \( n \) – the number of revolutions of the engine shaft, which characterizes the speed mode; \( M_e \) – the torque on the engine shaft, which characterizes the load mode; \( n \) and \( M_e \) parameters are expressed as a percentage of the full speed and load modes.

The data presented in Table 2 prove the possibility of improving the environmental performance of a transport diesel engine during its operation on the studied multicomponent emulsified biofuels. In this case, emissions of nitrogen oxides \( e_{\text{NOx}} \) and exhaust smoke opacity \( K_H \) (soot emission \( C \)) are considered to be the main environmental indexes. It is these two toxic components of diesel exhaust gases that are the most toxicologically significant [18, 19].

A favorable combination of fuel efficiency and exhaust toxicity of the diesel engine model “D-245.12S” was obtained using the emulsion containing 57% of petroleum diesel fuel, 30% of rapeseed oil and 13% of water (by volume). When the diesel engine operated on the modes of the 13-mode cycle and switched from diesel fuel to this emulsion, the specific mass emission of nitrogen oxides \( e_{\text{NOx}} \) decreased from 6.610 to 5.552 g/(kW·h). At the same time, at the maximum power mode, the exhaust smoke opacity decreased from 16.0 to 7.5% on the Hartridge scale, and at the maximum torque mode, from 28.0 to 15.5% on the Hartridge scale. At the same time, the conventional effective efficiency of the diesel engine \( \eta_{e \text{ conv}} \) increased from 0.341 to 0.374, or by 9.7%, which shows an increase in the efficiency of the combustion process of the emulsified biofuel under investigation.

The increase in the efficiency of the combustion process (the increase in the diesel’s effective efficiency \( \eta_e \)) and the reduction of the exhaust smoke opacity \( K_X \) when running on emulsified fuels are explained by the improvement in the quality of the mixing process due to the occurrence of so-called “micro-explosions” observed at elevated temperatures in the diesel combustion chamber [4]. They
appear due to the fact that emulsified fuel droplets consist of fuel particles, inside of which there are a large number of randomly moving water inclusions. At temperatures exceeding the water boiling point (at t>100°C), these inclusions evaporate quickly, which leads to microturbulation of the air-fuel mixture, the reduction of fuel consumption and soot particles in the exhaust gases. In addition, the presence of a significant amount of water vapor in the combustion chamber areas with a lack of oxygen prevents fuel from cracking at high temperatures, and also contributes to the gasification of previously formed carbon, which also leads to a significant decrease in soot formation.

### Table 2. Characteristics of diesel engine model “D-245.12S”, running on petroleum diesel fuel and on multicomponent emulsified biofuels.

| Diesel characteristics | Fuel type | Emulsion № 1 (67% DF, 23% RO and 10% water) | Emulsion № 2 (57% DF, 30% RO and 13% water) |
|------------------------|-----------|---------------------------------------------|---------------------------------------------|
| Fuel consumption per hour $G_F$, kg/h | DF                         | 17.42/12.25 | 18.07/12.01 |
| Torque $M_e$, N·m       | DF                         | 271/355    | 254/327     |
| Smoke opacity $K_{Ht}$, % by Hartridge scale | DF                         | 16.0/28.0  | 10.0/19.0   |
| Specific effective fuel consumption $g_{e, e}$, g/(kW·h) | DF                         | 255.5/219.7| 283.1/233.9 |
| Specific effective fuel consumption $g_{e, conv}$, g/(kW·h) | DF                         | 248.12     | 260.79      |
| Diesel effective efficiency $\eta_e$ | DF                         | 0.332/0.386| 0.346/0.419 |
| Conventional (average) characteristics of diesel’s fuel efficiency on the modes of the 13-mode cycle: | | | |
| Effective fuel consumption $g_{e, conv}$, g/(kW·h) | DF                         | 248.12     | 260.79      |
| Effective efficiency $\eta_{e, conv}$ | DF                         | 0.341      | 0.376       |
| Integral specific emissions of toxic components on the modes of the 13-mode cycle $g$/kW·h: | | | |
| Nitrogen oxides, $e_{NOx}$ | DF                         | 6.610      | 6.153       |
| Carbon monoxide, $e_{CO}$ | DF                         | 3.612      | 2.988       |
| Unburned hydrocarbons, $e_{CHx}$ | DF                         | 1.638      | 2.543       |
| Note: The numerator indicates diesel parameters at maximum power mode, in the denominator - at maximum torque mode |

When water is supplied to diesel cylinders, a decrease in combustion temperatures is observed, which is caused by increased heat of water vaporization ($Q_v = 2260$ kJ/kg at $t = 100^\circ$C; for diesel fuels, $Q_v = 220–300$ kJ/kg). This has a beneficial effect on reducing emissions of nitrogen oxides from exhaust gases. The increase in emissions of unburned hydrocarbons observed in the tests of the diesel engine model “D-245.12S” can be easily eliminated when a catalytic converter is installed in the exhaust system of the diesel engine, which effectively purifies exhaust gases from carbon monoxide and unburned hydrocarbons contained in them.

### 3. Comparative analysis of the environmental performance of the transport diesel engine running on mixtures of petroleum diesel fuel with rapeseed oil and on multicomponent emulsified biofuels

To assess the effect of the presence of water in the studied fuels on the environmental performance of a diesel engine, a comparative analysis of the data obtained for mixtures of petroleum diesel fuel with rapeseed oil and for multicomponent emulsified biofuels was carried out. The results of this analysis are presented in Table 3 and Figure 2. From the above data it follows that the reduction of NOx emissions from the exhaust gases of the studied diesel engine running on multicomponent emulsions is
due to the presence of rapeseed oil and water in their composition. At the same time, the addition of 30% RO to petroleum diesel fuel leads to a decrease in NOx emissions from 6.610 to 6.186 g/(kW·h), i.e. by 6.4%, and the conversion of diesel from petroleum diesel fuel to emulsion № 2 is accompanied by a decrease in NOx emissions from 6.610 to 5.552 g / (kW·h), i.e. by 16.0%. Thus, the presence of water in a multicomponent emulsified biofuel has a much greater effect on the emission of nitrogen oxides than the presence of rapeseed oil in it.

**Figure 2.** Dependence of specific mass emissions of nitrogen oxides $e_{\text{NOx}}$ on the modes of the 13-mode cycle (UN/ECE R49 standards) and exhaust smoke opacity $K_H$ on the maximum power mode of the diesel engine model “D-245.12S” on the composition of the fuels used: $a$ – diesel engine running on mixtures of petroleum diesel fuel with rapeseed oil; $b$ – diesel engine running on emulsions of petroleum diesel fuel, rapeseed oil and water; $C_O$ – volume content of rapeseed oil in mixed fuel; $C_w$ – volume water content in emulsified fuel.

**Table 3.** Ecological performance of the diesel engine model “D-245.12S” running on petroleum diesel fuel, mixtures of petroleum diesel fuel with rapeseed oil and on multicomponent emulsified biofuels.

| Diesel characteristics | Fuel type | Integral specific emissions of nitrogen oxides, $e_{\text{NOx}}$, of the 13-mode test cycle g/(kW·h) | Smoke opacity $K_H$, % by Hartridge scale |
|------------------------|-----------|--------------------------------------------------|----------------------------------------|
| DF                     | DF        | 6.610                                            | 16.0                                  |
| Mixture of 90% DF and 10% RO | 6.505 | 15.0                                            |
| Mixture of 80% DF and 20% RO | 6.357 | 13.5                                            |
| Mixture of 70% DF and 30% RO | 6.168 | 12.0                                            |
| Emulsion №1 (67% DF, 23% RO and 10% water) | 6.153 | 10.0                                            |
| Emulsion №2 (57% DF, 30% RO and 13% water) | 5.552 | 7.5                                             |

To a lesser degree, this refers to the exhaust smoke opacity. When the investigated diesel engine is operating at maximum power mode, its conversion from petroleum diesel fuel to a mixture of 70% DF
and 30% RO is accompanied by a decrease in smoke opacity from 16.0 to 12.0% on the Hartridge scale, i.e. by 25%. Replacing petroleum diesel fuel with emulsion № 2 on this mode leads to a decrease in smoke from 16.0 to 7.5% on the Hartridge scale, i.e. by 53.1%. Thus, the influence of the content in the emulsion No. 2 of rapeseed oil and water on the exhaust smoke opacity turned out to be comparable.

4. Conclusion
In general, the complex of experimental and computational studies confirmed the possibility and efficiency of using multicomponent emulsified fuels containing petroleum diesel fuel, rapeseed oil and water in transport diesel engines. Adaptation of the diesel engine model “D-245.12S” running on these emulsions allowed to increase the effective efficiency of the diesel engine and to improve its environmental performance. The use of these fuels not only provided an improvement in the engine's exhaust emission indexes, but also made it possible to bring the properties of biofuels closer to those of traditional petroleum diesel fuel. For instance, the addition of water to the mixture of petroleum diesel fuel and rapeseed oil reduces the viscosity of such emulsified biofuels. This, in turn, facilitates the organization of fuel feeding processes, fuel spraying, mixing and subsequent combustion.

The presence of water and rapeseed oil in the studied multicomponent emulsified biofuels can significantly improve the environmental performance of a diesel engine. While testing, there was a decrease in emissions of the most significant toxic components of diesel engine exhaust gases – nitrogen oxides and exhaust smoke opacity. Moreover, it is the water contained in multicomponent emulsified biofuels that has a much greater effect on the emission of nitrogen oxides than the presence of rapeseed oil in them. The influence of the content of rapeseed oil and water in these emulsions on the exhaust smoke opacity turned out to be comparable. It should be noted that the adaptation of diesel engines to operation on multicomponent biofuels simplifies the supply of vehicles and agricultural machinery with the necessary motor fuels.

5. References

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