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STUDYING MAIN TECHNICAL-OPERATING CHARACTERISTICS OF THE ALTERNATIVE FUELS FOR DIESEL ITERNAL COMBUSTION ENGINES

Today alternative fuels for engines, based on alcohols, oils and animal fats, are becoming widespread in Ukraine and all over the world. Therefore, intensive work is carried out on switching internal combustion engines to biofuel both in the countries with limited energy resources and in highly developed countries that have the possibility of purchasing liquid fuels.

The paper analyzes main alternative fuels for diesel internal combustion engines (ICE), gives their characteristics, investigates and evaluates main physical and chemical indicators of the most widespread biodiesel fuels and describes the conditions necessary for their application in ICE.

On the results of studying the cetane number such fuel types as RME B100 and SME B10 are recommended for use in high-speed diesel engines. It should be noted, however, that for SME B10 the cetane number is 49.4 and is very close to the standard value. Therefore, its application as a fuel will not have negative consequences for engines.

According to the research results on lower combustion heat value, biodiesel fuel SME B20 corresponds to the State Standard and, therefore, by this indicator it is recommended for use in diesel engines.

Densities of biodiesel fuels SME B20 and SME B40 correspond to the State Standard of Ukraine and so they are also recommended to be used in diesel engines.

Biodiesel fuels SME B20 and SME B40 correspond to the kinematic viscosity Standard as well.

According to the sulfur content, biodiesel fuels RME B100, SME B100, SME B20 and SME B40 correspond to the quality indicator of diesel fuels of the type II for high-speed diesels (ДСТУ 4840:2007).

Thus, the properties of the investigated biodiesel fuels RME B100, SME B100, SME B20 and SME B40, based on rapeseed and soybeans oils, correspond or are very close to the State Standards of Ukraine. At the same time, SME B20 and SME B40 are the ones that are the closest to the commercial diesel fuels and, therefore, their application in high-speed diesel engines does not require any changes in the supply system and will ensure stable operation and high performance indicators of the engine.

Key words: *biodiesel fuel, production technologies, cetane number, lower combustion heat, density, kinematic viscosity.*

Introduction

Today, alternative fuels for diesel engines, based on oils and animal fats, are becoming widespread. Therefore, intensive work is carried out on switching internal combustion engines (ICE) to biofuel both in the countries with limited energy resources and in highly developed countries that have the possibility of purchasing liquid fuel carriers.

Biodiesel fuels (biodiesel, MEPO, PME, RME, FAME, EMAG, Bio-oil and others) are ecologically clean fuel types, produced from animal fats and of vegetable origin, which are used for replacement of the oil diesel fuel DF [1 - 3].

In terms of chemistry, biodiesel fuel is a mixture of methyl (ethyl) ethers of saturated and unsaturated fatty acids and, correspondingly, changes in the fuel composition influences some physical and chemical indicators of a biodiesel fuel, regulated by the Standard, as well as the diesel parameters and its ecologic and operational indicators.

The aim of the paper is to investigate physical and chemical indicators of the most widespread biodiesel fuels and to determine the conditions required for their application in ICE.

Analysis of the main types of alternative fuels for diesel ICE and their characteristics

According to the legislation of Ukraine as to promoting production and application of biological fuel types, biodiesel fuels (biodiesels) are defined as methyl or ethyl ethers of higher organic acids obtained from vegetable oils or animal fat, which are used as biofuel or bio-components [5, 6].

Biodiesel fuel is produced from any vegetable oil (rapeseed, sunflower, soybean, hemp, palm, etc.).

By its physical and chemical properties, biodiesel is a yellow liquid (could be of different shades depending on the raw material and manufacturing method), almost not mixing with water, having high boiling point and low vapor tension. If biodiesel is produced from clean raw material, it is nontoxic.

Relatively high ignition temperature of biodiesel makes the fuel quite safe in terms of fire safety.

10 % higher density and 1.5 times higher kinematic viscosity, compared to those of diesel fuel, contribute to longer range of the fuel torch and increased diameter of the sprayed fuel droplets, which can result in intensive biodiesel hitting the walls of combustion chamber. Reduced values of compressibility coefficient of biodiesel fuel causes increased actual fuel injection advance angle and maximal pressure in the nozzle. High cetane number of biodiesel fuel (51 and higher values) reduces the ignition delay period and "stiffness" of engine operation. Almost 3-time higher temperature of biodiesel fuel ignition in a closed crucible (120 ºC and more) ensures high fire safety [4 – 5].

Oxygen (~ 10%) in the methyl ether molecule acts as follows. Availability of oxidizer directly in the fuel molecule intensifies the combustion process and provides higher temperature in the diesel cylinder. On the one hand, this increases indicative and absolute engine efficiency and on the other, leads to a somewhat higher content of the nitrogen oxide (NOx) [6 – 8].

Smaller percentage (~ 77%) of carbon in the biodiesel fuel molecule results in the reduction of the lower combustion temperature (by 13 – 15%) and increases time and specific efficient fuel consumption. To maintain the engine nominal parameters, when it is switched to biodiesel fuel, adjustment of the fuel equipment is required (fuel rack stop of the high-pressure fuel pump is reset to an increased fuel injection rate).

Biodiesel fuel application makes it possible to reduce discharge of harmful substances with exhaust gases. For diesel engines with turbulence chamber (pre-chamber) and direct injection the reduction is as follows: CO – from 12 to 10 %, C_nH_m – from 35 to 10 %, PM (solid particles) – from 36 to 24 %, soot – increases from 50 to 52 % [9, 10, 11].

Certain growth of NOx discharge can be compensated by implementation of the following measures: reduction of the actual fuel injection advance angle, recirculation of the exhaust gases, water supply at the input.

When running diesel engines operating with the use biodiesel fuel attention should be paid to the following factors (Table 1):

Table 1

Potential failures of diesel, fuel equipment and its systems in the process of operation with biodiesel fuel application

Fuel characteristic components	Influence	Failure
1	2	3
Methyl ethers of fatty acids	Drying, hardening and fracture of rubber products, getting into the motor oil	Fuel leakage. Necessity for frequent changes of motor oil
Free methanol	Corrosion of aluminum and zinc	Corrosion of fuel equipment. Low ignition temperature in a closed container
Free water in the fuel	Conversion of methyl ethers of vegetable oil into fatty acids. Corrosion. Increase of fuel electric conductivity. Development of microorganisms	Clogging of the filter. Corrosion of the fuel equipment.
Free glycerin	Corrosion of non-ferrous metals. Sediment formation on movable parts and on lacquer-and-paint coating	Clogging of filters. Clogging of nozzles of fuel injectors
Mono- and diglycerides	The same as for glycerin	
Free fatty acids	Electrolyte formation and acceleration of zinc corrosion. Formation of salts of fatty acids, of organic compounds	Corrosion of fuel equipment. Clogging of the filter. Formation of sediment on the components
Increase of fuel density	Higher injection pressure	Reduction of the fuel equipment resource
High viscosity at low temperature	More stringent conditions of operation of the high-pressure fuel pump. Increased wear of the parts	Increased wear of the parts of the high-pressure fuel pump. Worsening of the fuel injection indicators. Necessity for using additives
Solid particles	Worsening of the fuel lubrication properties	Reduction of the fuel equipment resource
Ant and acetic acids	Corrosion of all metal parts	Corrosion of the fuel equipment
High molecular weight organic acids	The same as for free fatty acids	Corrosion of the fuel equipment. Clogging of the filter. Sediment formation on the parts
Products of polymerization	Sediment formation, especially in fuel mixtures	Clogging of the filter
Phosphor	Clogging of neutralizers and catalysts of the diesel discharge system	Failure of the diesel exhaust gases discharge system and reduction of its environmental safety level

Thus, before starting the engine with the use of biodiesel fuel, it is important to rinse fine and coarse fuel filters. Due to high aggressiveness of such fuel, it is necessary to replace fuel tubes and gaskets with those made of biofuel-resistant material as well as to carefully remove biodiesel fuel from lacquer-and-paint coating. In certain cases more frequent changes of the motor oil are required because of its possible dilution by biodiesel fuel [1 – 6].

Certain increase in noise and smokiness levels during cold start is possible. At low temperatures additives should be used. It is necessary to control water content in biodiesel fuel (due to its high hygroscopicity) in order to avoid the danger of development of microorganisms, formation of peroxides and corrosive influence of water, including influence on the fuel equipment components [6 – 8].

The technology of producing biodiesel fuel by the example of that based on rapeseed oil is presented in Fig. 1.

In accordance with the technology, the initial raw material (rapeseed) is supplied to the oil press where oil is extracted from rapeseed, which could further be used for producing feed for cattle. The next stage is the process of esterification in special reactors. For obtaining methyl ether, methanol and small amount of catalyst are added to the rapeseed oil in the reactor. As a catalyzer, sodium hydroxide or potassium hydroxide are mostly used. Fat molecules that are part of the oil consist of triglycerides – combinations of trivalent glycerol alcohol with three fatty acids. As a result of chemical reaction, methyl ether (biodiesel) is formed as well as glycerol as a by-product.

Time required for the reaction is from 1 to 8 hours. The fastest reaction occurs at 70°C – the boiling point of alcohol. As temperature decreases by 10°C, reaction rate decelerates twice. However, it is believed that it is safer if reaction occurs at a temperature in the range of 50 – 55°C [6, 7].

Depending on the production capacity, two technologies of obtaining biodiesel fuel are distinguished:

- “cold” technology, used at low-capacity enterprises. According to this technology, biofuel is obtained at a temperature of 20 – 70°C with the application of alkaline catalysts.
- “hot” technology, used at powerful enterprises. It requires reaction of transesterification at a temperature of 240°C under pressure of 10 MPa. Such technology requires access to a source of cheap heat as well as large amount of methanol that after one cycle can be re-directed to the process.

The use of described technologies is determined by organizational solutions of the production process. The process of biofuel production with the application of “cold” technology can be implemented at small processing enterprises with annual biofuel output of 500 ton. “Hot” technology can be implemented at large enterprises, chemical and oil-extraction plants. The choice of technology determines the cost of rapeseed oil processing into biofuel.

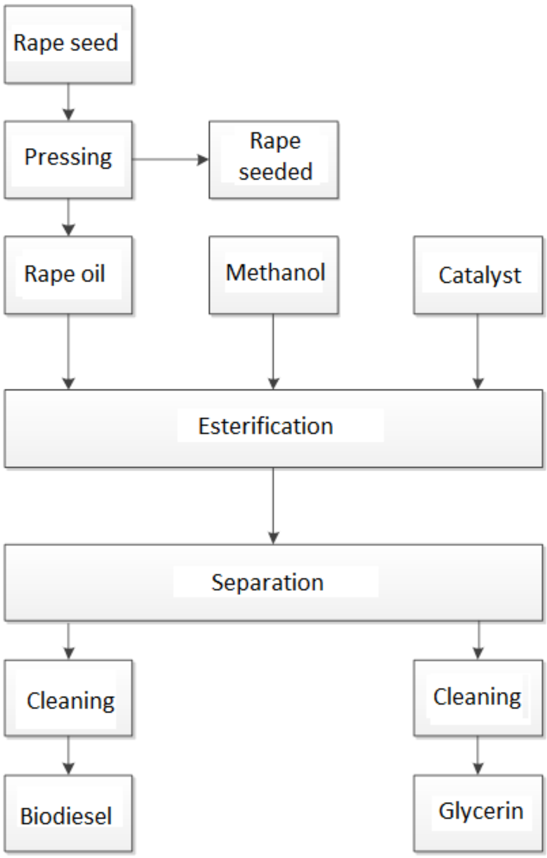


Fig. 1. Technology of biofuel production

Thus, rapeseed oil may be used as diesel biofuel in the form of (Fig. 2):
- pure cold-pressed rapeseed oil (RO);
- modified esterified rapeseed oil (MRO).

Biodiesel production is a two-stage process that combines known mechanical technologies, used in oil-extraction industry, with technologies used in chemical industry.

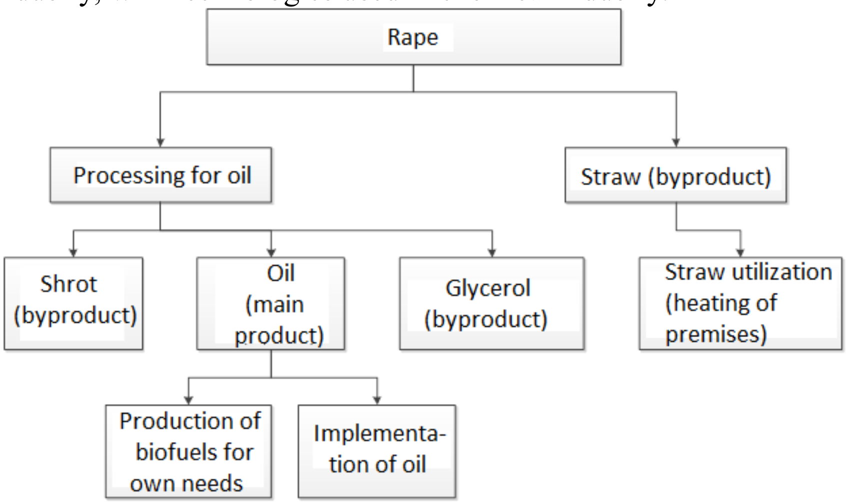


Fig. 2. Classical biodiesel production technology of agricultural industry

Principal modern technological block-diagram of the installation for producing modified biodiesel RMO consists of the following stages (Fig. 2):
- cold rapeseed pressing;

- oil filtration;
- two stages of re-esterification by ethanol with the use of KOH catalyst (obtaining RMO and glycerin);
- glycerin separation;
- removal of soap;
- removal of methanol;
-final removal of soap
- refining methylester;
- biodiesel standardization by cetane number.

In accordance with US Standard definition, under biodiesel fuel we mean mono-alkyl ethers of fatty acids, obtained from vegetable oils or animal fat, which are intended for use in diesel engines. The main task to be fulfilled is replacement of oil processing products with natural renewable resources.

Rapeseed, sunflower, palm and other vegetable oils as well as pork fat serve as raw material for biodiesel fuel (Fig. 2).

Introduction of unprocessed oils into the fuel is undesirable as they are characterized by high viscosity, relatively low thermal power, which results in 15 % engine power reduction on the average. Besides, they have poor starting capacity at low temperatures and due to the presence of free acids, they are combined poorly with structural and sealing materials as well as have a tendency to oxidation during storage. Alkalization products have better low-temperature properties and low viscosity with cetane number increase from 30 – 40 to 50 – 80 units.

The most widespread fuel of this type is the so-called rape-methyl ether (RME) which is quite often used in Sweden, Germany, France and other countries. It can be added to diesel fuel in a concentration of up to 30 % without additional adjustment of the engine.

In Western European countries, a decision was adopted about obligatory addition of 5 % RME into the diesel fuel but in some countries (e.g. Sweden) it is used directly.

The current cost of RME production at the European market is about twice as high as that of hydrocarbon diesel fuel. It could, however, be assumed that the production volumes of methylated vegetable oils will grow, agricultural technologies improve, which will lead to their cost reduction to an acceptable level.

Testing RME and its additives to diesel fuel in the USA and in Europe have shown that RME application reduces emission of hydrocarbons and hydrogen oxide while the intensity of formation of nitrogen oxides remains unchanged. A certain increase in the discharge of ozone-forming components (aromatic hydrocarbons, olefins and aldehydes) was observed. Therefore, engines operated with the use of biofuel should be equipped with catalytic neutralizers. Increased formation of solid particles is also observed but their nature differs from that of the particles formed during operation with diesel fuel. Actually, soot contains a small amount of solid particles. Their main part consists of soluble organic compounds – mostly unburned biofuel particles. Investigation of mutagenic activity of solid particles has shown that it is lower than that of the particles formed during diesel fuel combustion.

In the presence of monoalkyls, ethers of vegetable acids improve the properties of low-sulfur ecologically clean diesel fuels. This is a very important circumstance, since in the general case sulfur content reduction in the fuel leads to the loss of its lubrication properties.

For alkalizing oils, not only methanol could be used but other available alcohols as well. Ethanol is prospective in this relation. In particular, cetane numbers of ethyl ethers of fatty acids are 10 – 15 units higher than those of corresponding methyl ethers.

A method of transesterification of vegetable and animal fats, which are triglycerides of carboxylic acids with the use of methanol in the presence of catalysts (alkyls or acids), is becoming widespread. In the case of using alkyli, the degree of conversion of fats is higher and reaches 98 %. The process temperature is 60 – 70 °C and pressure – up to 0.15 MPa. The alkali consumption is about 1% of the oil.

Requirements to the raw materials are rather strict: content of free acids should not exceed 0.5 % and acid number – maximum 1 mg KOH / g. Absence of water is also required. Otherwise, soap formation begins, which will increase alkali consumption and prevent glycerin separation from the reaction mass. As a transesterification agent, methanol is commonly used, but ethanol is also of interest as a plant raw material. In harsh conditions (pressure above 300 atm. and temperature 350°C), when methanol is in supercritical condition, strict requirements to the raw material may not be necessary. The process itself takes several minutes and could be implemented in a continuous manner. The method is rather promising but not widespread yet as it is complex in terms of technological implementation.

Thus, world production of biodiesel in the recent years amounted to about 1.7 million tons, in particular, in European Union – 1.5, in Eastern Europe – 0.1 and in the USA – 0.07 million tons. According to the forecast, by 2020 it will increase to 23 million ton per year.

An interest to this type of fuel is also observed in Ukraine, which is explained, primarily, by the initiative of agricultural producers. Rapeseed, soybeans and sunflower in some regions are considered as the main sources of oils. The main difficulties are low yield, prolonged terms of harvesting and processing the seeds. At the same time, taking into account domestic production and application of biodiesel, economic effect could turn to be rather high

Calculations show that in the case of optimal organization of rapeseed oil production in the Ukrainian farms the biodiesel fuel cost could be lower than that of hydrocarbon diesel fuel.

Taking into account the prospects of biodiesel fuel application, there is a necessity for studying and assessing basic characteristics of this fuel as compared to commercial diesel fuel.

Investigation of the basic technical and operational characteristics of the alternative fuels for diesel ICE

To achieve the goal of the research, the following fuels were used:
- RME B100;
- SME B100;
- SME B20;
- SME B40.

Assessment of the possibility to use the above fuel types for ICE was conducted according to the following indicators: the cetane number, lower combustion temperature, sulfur content, density, kinematic viscosity.

The cetane number. Self-ignition of diesel fuels is assessed according to the cetane number, determined by the method of comparing the fuel ignition with the ignition of reference mixture. The mixture includes cetane, the self-ignition delay period of which is short and the cetane number (CN) is assumed to be 100, and α-methylnaphthalene, the self-ignition delay period of which is long and the cetane number is 0.

The cetane number can be determined according to the Standard (ГОСТ 3122-67) using a special installation УДП-3М with a single-cylinder engine, designed so that it provides the change in the compression measure in the range of 7 – 23.

The cetane number is determined in the following way. The engine is started with the use of test fuel and by changing the compression degree such conditions are achieved when self-ignition of the fuel begins at the upper dead point, i.e. the self-ignition delay period is 13º. Then such mixture of n-cetane and α-methylnaphthalene is found, which at the same compression degree would also ignite at the upper dead point, i. e. would have the same delay period (130) as the test fuel [12].

The cetane number is the content of n-cetane in the mixture with α-methylnaphthalene, self-ignition of which is similar to that of the test fuel.

To increase the cetane number of diesel fuels, different additives can be used, e.g. alkylates, peroxides. Peroxides have not received practical application because these additives decompose during storage and their efficiency is reduced. As an additive to diesel fuels, isopropyl nitrate is most commonly used. Adding it in an amount of 1.0 % increases the cetane number by 10 units. Along with increasing the cetane number, additives improve starting properties of the fuels. However, application of additives is limited due to the flash point reduction and increased coking.

The lower the cetane number, the rougher engine operation. The value of cetane number influences other indicators of engine operation: its start, maximum combustion pressure, specific fuel consumption (Fig. 3, 4), the exhaust temperature, deposition in the engine, smokiness and toxicity of the exhaust gases. An increase in the cetane number facilitates the engine start and increases maximum combustion pressure, the engine performance improves.

Modern high-speed diesel engines require the use of fuels with cetane numbers 45 – 50 that ensure soft operation of the engine. If cetane number is 40 and lower, diesel operation is rough, wear of the engine components increases as well as fuel consumption, toxicity and smokiness of exhaust gases.

If cetane number increases above 50, it has no significant influence on the improvement of diesel operation. At the same time, specific fuel consumption and its production cost are increased. It is explained by the fact that at high cetane numbers self-ignition delay period is very short and fuel combustion is incomplete. This leads not only to excessive fuel consumption but also to increased toxicity and smokiness of the exhaust gases as well as to the oil overconsumption [12].

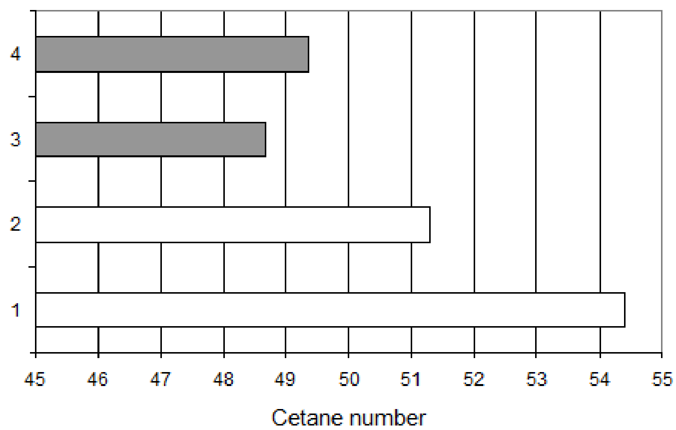
On the results of studying the cetane number of biodiesel fuels the diagram of Fig. 3 was built.

According to the Standard (ДСТУ4840:2007), cetane number of biodiesel fuels for high-speed engines should not be below 51. In our case, among the test fuels biodiesel fuels 1 and 2 correspond to this indicator.

Thus, according to the cetane number, fuels RME B100 and SME B100 are recommended for use in high-speed diesel engines. It should be noted, however, that for SME B40 cetane number is 49.4 that is very close to the standard value and so its application as a fuel will not have negative consequences for ICE.

Lower combustion heat. Fuel combustion heat influences its consumption and engine power. The more heat is obtained during fuel combustion, the higher engine power can be achieved and the lower specific fuel consumption will be.

Combustion heat is the amount of heat released during complete combustion of 1kg of liquid or solid fuel (kJ / kg).



1- RME B100; 2 - SME B100; 3 - SME B20; 4 - SME B40

Fig. 3. Cetane number indicators of biodiesel fuels

Two values of the combustion heat are distinguished – upper (Q_u) and lower (Q_l) ones. In engineering practice lower combustion heat is used, which does not take into account condensation of the water vapors since the exhaust gas temperature is much higher than the temperature of vapor condensation.

Hydrocarbon fuels do not differ much as to their combustion heat. Their lower combustion heat is in the range of 41000 – 44000 kJ / kg.

According to the State Standard of Ukraine, for diesel fuels this indicator is not regulated but must be about 42600 kJ / kg.

Fig. 4 presents the results obtained from studying lower combustion temperature of biodiesel fuel.

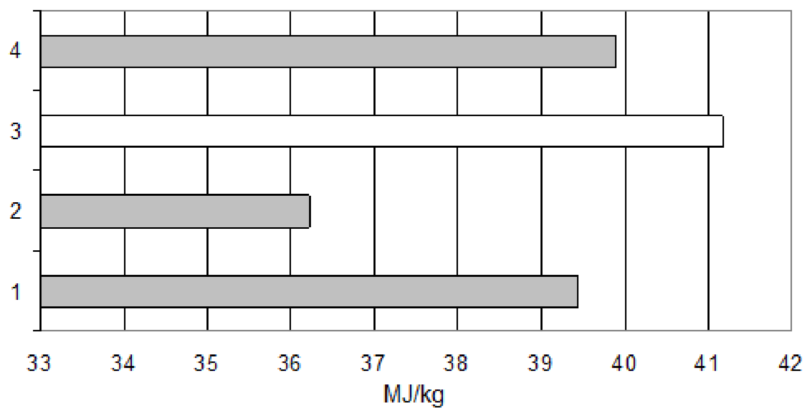
In accordance with Fig. 4, among the test fuels biodiesel fuel 3 corresponds to the above lower combustion heat indicator and, therefore, can be recommended for use in diesel engines.

At the same time, practically all test fuels, with the exception of SME B100, have the lower combustion heat values, which are very close to this indicator.

Kinematic viscosity and density of the fuel. Fuel pumping, failure-free operation of the high-pressure fuel pump, wear of the precision pairs, continuous fuel supply to the cylinders, spraying fineness and completeness of the fuel combustion, its consumption, composition of exhaust gases depend, to a great extent, on the viscosity and density of diesel fuels.

For diesel fuels, kinematic viscosity is determined at the temperature of 20 ºC. Fuel having very high viscosity can cause problems in its supply to the pump due to resistance to its flowing via supply system through the filters and openings of the nozzles. With the reduction of fuel viscosity lubrication of the high-pressure fuel pump precision pairs is observed as well as leakage of the fuel through sealing gaps between the plunger and the sleeve [12].

Viscosity, density, surface tension of the fuel affect spraying fineness and fuel consumption. The smaller the value of these indicators, the better spraying, the smaller diameter of the droplets created during the fuel spraying process and the better evaporation. However, the jet range is reduced as small droplets have small kinetic energy reserve. The fuel mixes unevenly with the air, burns mainly near the nozzle and therefore the combustion chamber volume is not used completely. As a result, fuel combustion is incomplete, engine power is reduced and fuel overconsumption occurs, nozzles are overheated and deformed.



1 - RME B100; 2 - SME B100; 3 - SME B20; 4 - SME B40

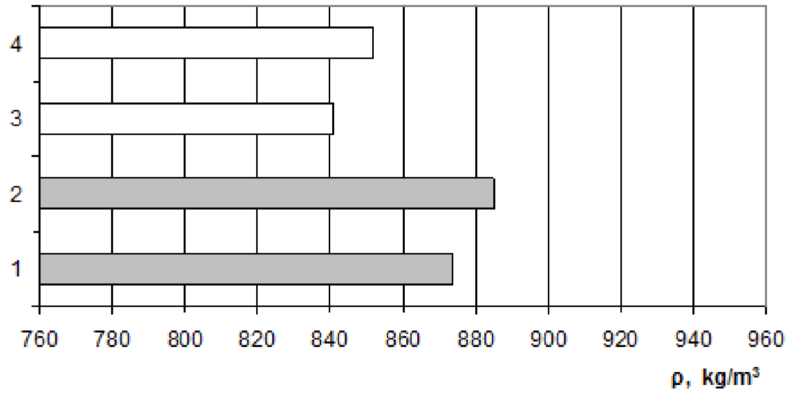
Fig. 4. Indicators of the lower combustion heat of biodiesel fuels

According to the State Standard, fuel density for high-speed engines should be in the range of 820 – 845 kg / m^3.

With the growth of fuel viscosity the depth of jet penetration increases as large-diameter droplets are formed, homogeneity of the fuel mixture improves. However, fuel evaporation and completeness of the fuel combustion are worse. This leads to fuel overconsumption, reduced power, higher smokiness and toxicity of the exhaust gases. Optimal viscosity values of diesel fuels depend on the design of fuel pumps, combustion chamber, season of their application. The lower the temperature at which the fuel is used, the lower its viscosity. For diesel fuels, both maximal and minimal viscosities are regulated. According to the State Standard, for summer fuel kinematic viscosity should be in the range of 2.0 – 4.5 sSt.

On the results of studying density and viscosity of biodiesel fuels dependencies shown in Fig. 5 and Fig. 6 are built.

According to Fig. 5, densities of biodiesel fuels 3 and 4 correspond to the State Standard and so by this indicator they are recommended for use in diesel engines.



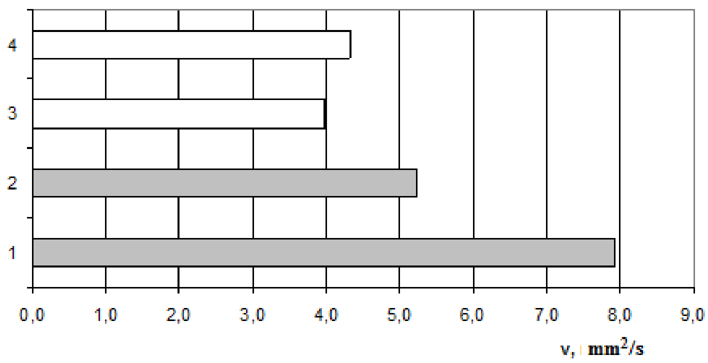
1- RME B100; 2 - SME B100; 3 - SME B20; 4 - SME B40

Fig. 5. Density values of biodiesel fuels

According to the kinematic viscosity indicator (Fig. 6), biodiesel fuels 3 and 4 correspond to the State Standard. It should be also noted that viscosity of SME B100 is very close to the above ones and its application in ICE will not cause significant changes in its operation.

Content of sulfur compounds in fuels. Corrosive properties of diesel fuels, like those of gasoline, depend on the content of water-soluble acids and alkalis, organic acids and sulfur compounds in them.

Corrosive aggressiveness of diesel fuels is determined not so much by total sulfur content in the fuel but by the content of mercaptans. Wear of plunger pairs during engine operation with the use of fuel with 0.025 % content of mercaptan sulfur is increased two times as compared with the wear when fuels without mercaptans are used [12].

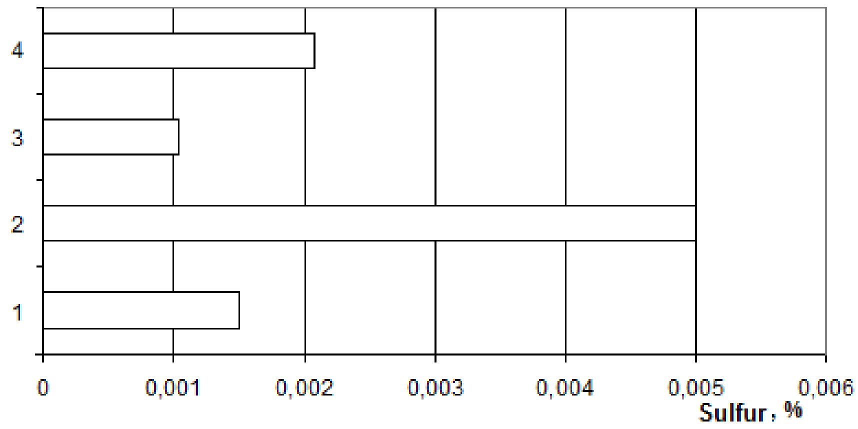


1- RME B100; 2 - SME B100; 3 - SME B20; 4 - SME B40

Fig. 6. Kinematic viscosity values of biodiesel fuels

According to the State Standard, for high-speed engines sulfur content for fuel of type I is

0.001% and for type II – 0.005 %.



RME B100; 2 - SME B100; 3 - SME B20; 4 - SME B40

Fig. 7. Percentage of sulfur content in biodiesel fuels

As it is evident from Fig. 7, by sulfur content biodiesel fuels 1, 2, 3, 4 correspond to the quality indicator for diesel fuels of type II for high-speed diesels (ДСТУ 4840:2007).

Conclusions

On the whole, the properties of test biodiesel fuels RME B100, SME B100, SME B20 and SME B40, based on rapeseed and soybean oils, correspond or are very close to the State Standard of Ukraine.

It should be noted, however, that fuels SME B20 and SME B40 are the closest to the commercial diesel fuel and therefore their use for high-speed diesels does not require changes in the supply system and ensures stable operation of the engine and high technical and operational indicators.

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