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The Use of Biodiesel as a Blend Component of Commercial Diesel Fuels

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Abstract

Biodiesel is synthesized from five different types of vegetable oils (sunflower, mustard, linseed, corn and camelina). The yields of the target product, the physicochemical and low-temperature properties of the obtained biodiesel fuels are determined. The effect of the additive on the low-temperature properties of biodiesel and its blends with petroleum diesel fuel is investigated. It is shown that the low-temperature additive for petroleum diesel fuels is ineffective for improving the low-temperature properties of biodiesel. It is established that the efficiency of the low-temperature additive decreases with an increase in the proportion of biodiesel in the blend with diesel fuel. The expediency of using biodiesel as a blend component of commercial diesel fuels is shown. Recommendations on the use of "biodiesel/diesel fuel/low-temperature additive" blends as commercial diesel fuels of the Summer grade and Off-Season grade according to GOST (State Standard) 305-2013 "Diesel fuel. Technical Specifications" are developed.

Keywords: biodiesel fuel, vegetable oils, physicochemical properties, low-temperature characteristics, diesel fuel, low-temperature additive

INTRODUCTION

Permanently increasing world demand for energy and the global climate change due to the emission of greenhouse gases caused the necessity in the search for solutions in the area of renewable and stable sources of energy. Biodiesel fuel (BioDF) is one of the most promising substituents of diesel fuel (DF) and may be manufactured from vegetable oil, animal fat, waste oil and other raw material resources through transesterification in the presence of an alcohol and a catalyst [1, 2].

The major countries leading in the production of biodiesel are the USA, Brazil, Germany, Indonesia and Argentina. In turn, the countries of the European Community are the major consumers of this kind of fuel, with the demand growing every year. In this connection, attention to upgrading and optimization of the technologies of alternative fuel production and to the improvement of fuel performance characteristics is increasing.

Undoubtful advantages of BioDF as a motor fuel include renewable nature of the raw material for production, as well as the possibility to use various household and industrial wastes as the raw material; a decrease in the emissions polluting the environment and the absence of sulphur in the composition; extension of the lifetime of engines due to a good lubricating capacity [3]. However, in spite of many advantages of BioDF, obstacles on the way to using it as a fuel in the pure form are high viscosity, lower thermal value, corrosion activity and the problems connected with pumping through the fuel filter at low temperatures [4].

At present, special attention is paid to the blends of petroleum diesel fuel (PDF)/BioDF because their application does not require any changes in the design of diesel engine (up to a definite content of biodiesel in the blend). The standards for compulsory BioDF content in blends with PDF have been introduced by present in many countries: from 1–2 to 20 vol. % [5]. The use of biodiesel as a blend component will allow substantial broadening of the raw material basis for the production of DF.

Analysis of the published data showed that a large number of works are dealing with the studies of the effect of biodiesel additive to PDF on the characteristics of engine operation and on the composition of exhaust gases formed during the combustion of the blends. For instance, the authors of [6] studied the emission of solid substances, total carbon and polycyclic aromatic hydrocarbons (PAH) from diesel generator operating on the blends of BioDF obtained from soya beans, and DF with BioDF content 0, 10, 20, 50 vol. %. It was stressed that fuel blends with biodiesel content 10 and 20 vol. % were characterised by the lowest emissions of solid particles and total carbon at different levels of generator power (0, 5, 7, 10 kW). In addition, for all the studied levels of generator power, PAH content in the emissions from blends with biodiesel content 10 and 20 vol. % was lower by 38 and 26 %, respectively, in comparison with that from the generator operating with pure PDF [6].

The authors of [7] carried out a similar investigation of the effect of the addition of BioDF, obtained from waste vegetable oils, to PDF on the content of solid particles, PAH and persistent organic pollutants (POP) in the emissions. Using a standard diesel engine, BioDF/PDF blends with BioDF content 0, 20, 40, 60, 80 and 100 vol. % were investigated. The results obtained in these studies showed that a decrease in the emission of solid particles and POP with an increase in BioDF content in the blend to 60 vol. % is observed (in comparison with pure PDF), however, the addition of more than 60 vol. % BioDF leads to an increase in the amount of emissions due to the high viscosity of the fuel, which has a negative effect on the combustion of fuel blend [7].

Research works throughout the world show that the addition of BioDF to PDF allows substantial improvement of the ecological safety of this motor fuel, however, the effect on the majority of regulated performance parameters of commercial fuel turns out to be not so positive. For the Russian Federation, as well for other countries having northern and Arctic territories, the most essential characteristics are low-temperature properties of BioDF/PDF blends and the possibility of their improvement with the help of additives.

The goal of the present work was to evaluate the reasonableness of the use of BioDF as a blend component of commercial DF and the choice of the optimal BioDF/PDF ratios.

To achieve the formulated goal, the following tasks are to be solved:

– to synthesize BioDF from different kinds of vegetable oil;

– to determine the yield of the target product, physicochemical and low-temperature properties of the obtained BioDF;

– to study the effect of the additive on the low-temperature properties of BioDF and its blends with PDF;

– to elaborate recommendations concerning the use of the blends of BioDF/PDF/low-temperature additive as the commercial fuel of different grades.

EXPERIMENTAL

Objects of investigation

The objects of the investigation were BioDF samples synthesized from five different oil-bearing crops: oil-yielding sunflower, mustard, linseed, corn, and camelina. Designations accepted for the synthesized BioDF kinds are: the product obtained from sunflower oil is marked as S_{BioDF}, from mustard oil – M_{BioDF}, from linseed oil – L_{BioDF}, from corn oil – CO_{BioDF}, from camelina oil – CA_{BioDF}.

To make BioDF/PDF blends, we used the PDF sample of the Summer grade.

To improve the low-temperature characteristics of the obtained products, we used a low-temperature additive to DF in the amount of 0.22 mL of the additive per 100 mL of fuel. The characteristics of the additive are shown in Table 1.

TABLE 1

Characterization of low-temperature additive

Parameter	Value
Composition	Oil distillates, active substances
Density at 20 °C, g/cm^3	0.811
Kinematic viscosity at 20 °C, mm^2/s	4.394
Molecular weight, g/mol	167.975

Synthesis of biodiesel fuel

The synthesis of BioDF was carried out using ethanol as a transesterifying agent (the molar ratio of vegetable oil to the alcohol was 1 : 9) and sodium hydroxide (KOH) as a catalyst (the solution of KOH in ethanol was prepared taking 1 % of dry KOH with respect to the total mass of vegetable oil and ethanol).

The reactor for the synthesis of BioDF was a heat-resistant beaker, the reaction mixture was heated with the electric furnace, a mixer was used to maintain the homogeneity of the mixture. The upper part of the beaker was isolated from the environment with the help of metal foil to prevent ethanol evaporation during transesterification.

The synthesis of BioDF was carried out according to the algorithm:

1) vegetable oil was poured into the heat-resistant beaker and heated to 75 °C under permanent mixing;

2) after the achievement of the necessary temperature, the solution of KOH in ethanol was added;

3) the reaction mixture was kept at a constant temperature under mixing for 6 h;

4) after the synthesis was complete, the reaction mixture was cooled to the room temperature;

5) glycerol in the amount of 25 % of the mass of vegetable oil was added (to simplify the separation of BioDF from the residues of unreacted components);

6) the mixture obtained after reaction was kept in the separating funnel for the visible interface to be formed, with the upper layer containing a mixture of the product and residual ethanol, the medium layer containing unreacted vegetable oil and the ethanol solution of the alkali, and the lower layer composed of the glycerol phase;

7) residual ethanol was distilled off using a rotary evaporator.

Methods used to determine the composition and properties

The composition and properties of the obtained BioDF, as well as BioDF/PDF blends, were studied using the following methods:

– fractional composition (FC) was determined in agreement with the procedure described in GOST ISO 3405–2013 "Petroleum products. Determination of distillation characteristics at atmospheric pressure" [8];

– density at 15 °C was determined using a Stanbinger SVM3000 viscosimeter (Anton Paar, Austria) according to the procedure described in ISO 12185:1996 "Crude petroleum and petroleum products. Determination of density. Oscillating U-tube method" [9];

– viscosity at 20 °C was determined using a Stanbinger SVM3000 viscosimeter (Anton Paar, Austria) in agreement with the procedure described in GOST 33–2016 "Petroleum and petroleum products. Transparent and opaque liquids. Determination of kinematic and dynamic viscosity" [10];

– sulphur content was determined with the help of X-ray fluorescence energy-dispersive analysis using SPEKTROSKAN S (NPO SPEKTRON, Russia) according to the procedure described in GOST 32139–2013 "Petroleum and petroleum products. Determination of sulphur content by method of energy-dispersive X-ray fluorescence spectrometry" [11];

– cetane index (CI) was calculated using the procedure described in ISO 4264:2018 "Petroleum products – Calculation of cetane index of middle-distillate fuels by the four-variable equation" [12]. This procedure was chosen as the most accurate calculation procedure [13];

– molecular weight was determined using a set-up for the cryoscopic determination of molecular mass KRION-1 (LC TERMEKS, Russia) according to the procedure described in ASTM D2224-78 "Method of Test for Mean Molecular Weight of Mineral Insulating Oils by the Cryoscopic Method" [14];

– cloud point (CP) was determined using a liquid low-temperature thermostat KRIO-T-05-01 (LC TERMEKS, Russia) according to the procedure described in GOST 5066–91 "Motor fuel. Methods for determination of cloud, chilling and freezing points" [15];

– cold filter plugging point (CFPP) was determined using a liquid low-temperature thermostat KRIO-T-05-01 and the set-up for the determination of the limiting temperature of diesel fuel filterability on the cold filter according to the procedure described in GOST EN 116–2013 "Diesel and domestic heating fuels. Test method of determination of plugging point" [16];

– pour point (PP) was determined using liquid low-temperature thermostat KRIO-T-05-01 according to the procedure described in GOST 20287–91 "Oil products. Methods to determine pour point and cloud point" [17].

Preparation of the blends of biodiesel fuel with oil diesel fuel

To evaluate the reasonableness of the use of BioDF as an additive to PDF and to study the ef-

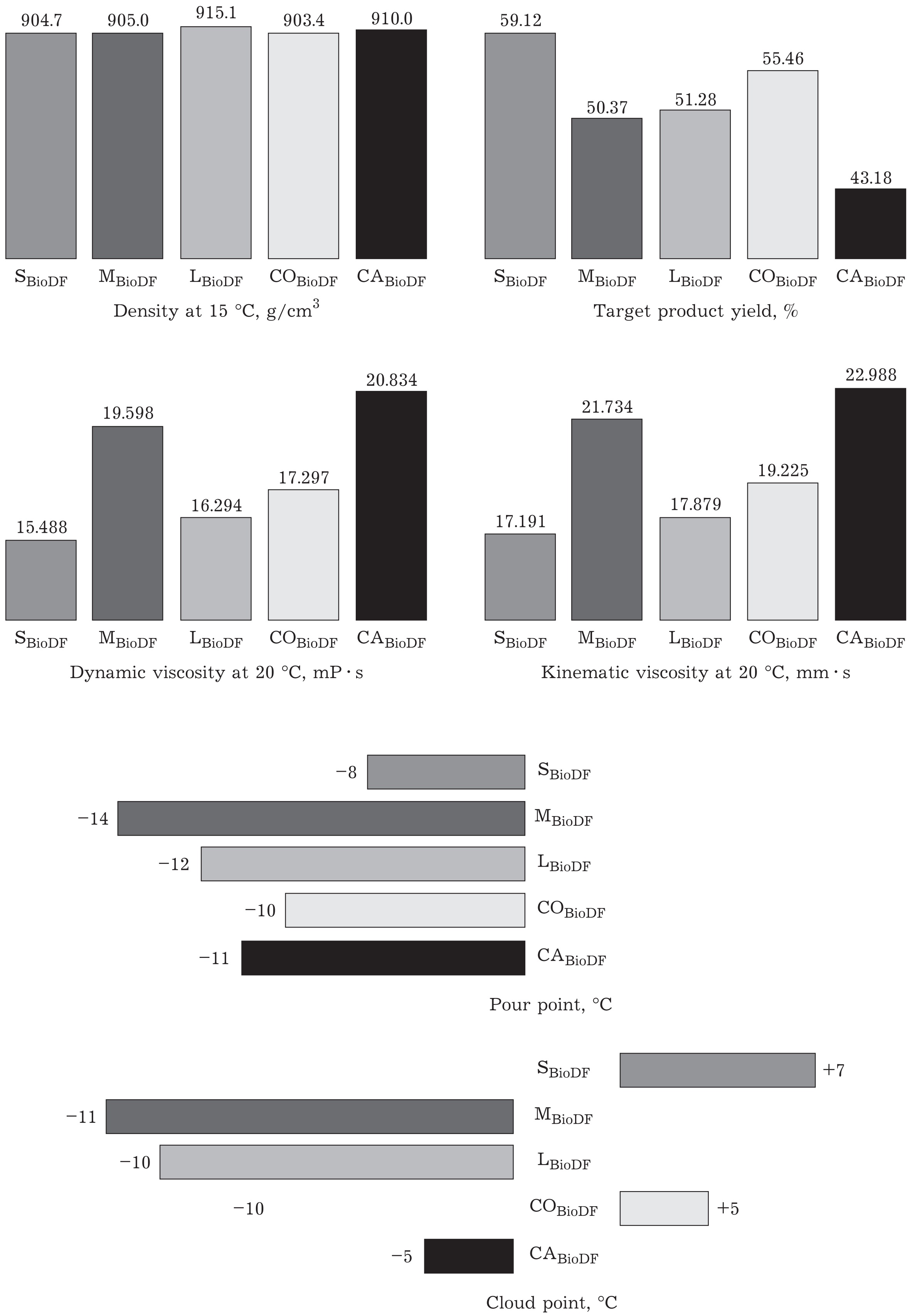

Fig. 1. Characteristics of the obtained BioDF.

fect of the addition of BioDF on the characteristics of BioDF/PDF blends, the indicated blends were prepared with different ratios of blend components.

According to the data reported in [3, 4, 18], the most widespread blends are:

1) B5 – a blend of 5 vol. % BioDF and 95 vol. % PDF;

2) B10 – a blend of 10 vol. % BioDF and 90 vol. % PDF;

3) B20 – a blend of 20 vol. % BioDF and 80 vol. % PDF.

These ratios are widespread because the use of BioDF/PDF blends with BioDF content exceeding 20 vol. % will cause the necessity to introduce changes in the design of the diesel engine.

Blends B5, B10, B20 were prepared on the basis of the synthesized BioDF characterized by the best (M_{BioDF}) and worst (S_{BioDF}) low-temperature characteristics (Fig. 1).

RESULTS AND DISCUSSION

Yield and properties of the obtained biodiesel fuels

The synthesis of BioDF from different kinds of vegetable oil was carried out according to the described procedure.

For the synthesized BioDF samples, the key performance characteristics (viscosity and density) were determined, because these parameters provide normal fuel supply, fuel spraying in the combustion chamber, and the operability of fuel filters; low-temperature properties characterizing the operation of the fuel system at negative environmental temperatures were also determined. The density and viscosity of fuel determine the process of blend formation. The use of fuel with increased density and viscosity leads to the excessive consumption of fuel, a decrease in power, an increase in exhaust opacity [19]. The yields of the target product and the results of the determination of physicochemical and low-temperature characteristics of the obtained BioDF are presented in Fig. 1.

One can see that the highest BioDF yield is observed for sunflower oil, and the lowest one for camelina oil. The difference in the yields of products may be explained by the differences in oil composition. It is known that unsaturated fatty acids possess higher reactivity than saturated ones [20]. Investigations show that sunflower and corn oils contain the largest amount of unsaturated fatty acids [20], which explains the highest yield of BioDF obtained from these oil-bearing crops.

According to the data presented in Fig. 1, the highest viscosity is characteristic of BioDF obtained from camelina oil, and the lowest one – BioDF from sunflower oil. The highest density is characteristic of BioDF obtained from linseed oil, and the lowest one – of BioDF from corn oil. It may be stressed that the density and viscosity of BioDF exceed the permissible values for PDF (density – not more than 863.4 kg/m^3, kinematic viscosity – 3–6 mm^2/s [21]), which explains impossibility to use BioDF without blending with PDF as commercial fuel.

According to the obtained data (see Fig. 1), the best low-temperature properties are characteristic of BioDF obtained from mustard oil, and the worst ones – of BioDF from sunflower oil. For these BioDF kinds, the reasonableness to use them as the blend components for commercial DF was evaluated.

Effect of the additive on the low-temperature properties of biodiesel fuel

Results of the determination of CP and PP for the blends of BioDF with the additive characterized by the best and worst low-temperature properties (M_{BioDF} and S_{BioDF}, respectively) are shown in Table 2.

One can see that the additive had almost no effect on PP of both kinds of BioDF, and on CP of M_{BioDF}. The effect of the additive on CP of S_{BioDF} is higher. Over the entire set of characteristics, it should be stressed that the low-temperature additive to PDF turned out to be of low efficiency for the improvement of low-temperature characteristics of BioDF.

This effect is explained by the mechanism of additive action: the substances included in low-temperature additives are to react with the incipient crystals of *n*-paraffins present in PDF being adsorbed on their surface [22]. In the absence of *n*-paraffins in the fuel, the efficiency of

TABLE 2

Low-temperature properties of BioDF blends with the additive, °C

Designation	CP	ΔCP	PP	ΔPP
S_{BioDF}	+1	6	−9	1
M_{BioDF}	−11	0	−14	0

these additives is insignificant. Therefore, it is promising to develop special low-temperature additives for BioDF.

The obtained results also allow us to assume that the efficiency of the low-temperature additive with respect to BioDF/PDF blends will be lower in comparison with the use of the additive for pure PDF because of the presence of BioDF.

Composition and properties of the petroleum diesel fuel sample

Results of the determination of the major controlled characteristics for the PDF sample according to the above-described procedures are presented in Tables 3, 4, and in Fig. 2. According to the data obtained, the PDF sample corresponds to the requirements of GOST 305–2013 “Diesel fuel. Specifications” [21] for DF of the Summer grade and Inter-season grade in density (not more than 863.4 kg/m^3), kinematic viscosity (3–6 mm^2/s), sulphur content (not more than 2000 mg/kg), CI (not less than 45 points), $FC_{50\%}$ (not higher than 280 °C), CFPP (not higher than −5 °C for the Summer grade and not higher than −15 °C for the Inter-season grade). However, with respect to $FC_{95\%}$ (not higher than 360 °C), the PDF sample under consideration does not meet the requirements [21].

Relying on the characteristics of the PDF sample, blending with BioDF appears promising because PDF has a substantial quality margin with respect to CI and CFPP in addition, blending with BioDF will allow us to decrease $FC_{95\%}$.

TABLE 3

Characterization of PDF sample

Parameter	Value
Density at 15 °C, kg/m^3	844.8
Dynamic viscosity at 20 °C, mPa · s	3.825
Kinematic viscosity at 20 °C, mm^2/s	4.546
Sulphur content, mg/kg	238
CI, points	47.18

Composition and properties of the blends of biodiesel fuel with petroleum diesel fuel

The application of BioDF as a blend component with DF is first of all limited by unsatisfactory low-temperature properties of BioDF, so the products with the best and worst low-temperature characteristics (see Fig. 1) were chosen to prepare BioDF/PDF blends: BioDF obtained from mustard oil and sunflower oil (M_{BioDF} and S_{BioDF}, respectively).

Results of the determination of FC of the prepared blends BioDF/PDF B5, B10, B20 based on S_{BioDF} and M_{BioDF} are presented in Table 5.

It may be stated through a comparison of the FC of the Summer grade PDF sample (see Table 4) and the prepared BioDF/PDF blends (see Table 5) that the addition of BioDF causes a substantial decrease of initial boiling point (IBP) of the fraction (nearly by a factor of 2 as average), but this has no effect on the possibility to use BioDF/PDF blends as a fuel for diesel engines. Besides, the addition of BioDF to PDF causes an increase in $FC_{50\%}$ by 8–11 and 11–18 °C, a decrease in $FC_{90\%}$ by 35–83 and 46–49 °C for S_{BioDF} and M_{BioDF}, respectively. It may be as-

TABLE 4

Fraction composition of PDF sample

Forerunning fraction, vol. %	Temperature, °C	Forerunning fraction, vol. %	Temperature, °C
IBP	137	50	268
10	186	60	279
20	228	70	292
30	243	80	308
40	254	90	369

Note. Here and in Table 5: IBP is the initial boiling point.

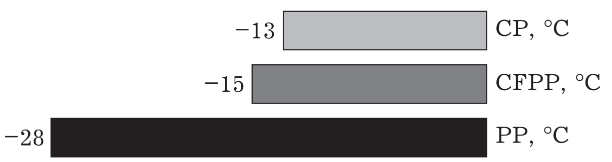

Fig. 2. Low-temperature properties of PDF sample.

TABLE 5

Fraction composition of S_{BioDF}/PDF и M_{BioDF}/PDF blends

Fractional composition, vol. %	Temperature, °C					
	B5 S_{BioDF}	B10 S_{BioDF}	B20 S_{BioDF}	B5 M_{BioDF}	B10 M_{BioDF}	B20 M_{BioDF}
IBP	70	71	73	70	71	73
10	210	196	207	201	196	200
20	231	227	227	222	214	229
30	250	244	251	246	249	254
40	263	262	267	264	266	271
50	276	276	279	279	274	286
60	288	288	285	283	291	302
70	301	304	300	303	301	313
80	319	318	302	320	314	323
90	334	329	304	323	328	325

Note. See Table 4.

sumed that all the obtained blends correspond to the requirements [21] concerning $FC_{95\%}$ (not higher than 360 °C), but one can see that B20 M_{BioDF} blend does not meet the requirements [21] concerning $FC_{50\%}$ (not higher than 280 °C).

For the prepared BioDF/PDF blends, in addition to density and viscosity, other key regulated performance characteristics were measured: sulphur content, which determines the corrosion activity of DF and the toxicity of exhaust gases from fuel combustion; CI, characterizing the power and economic parameters of engine operation. Results of the determination of the major regulated characteristics for BioDF/PDF blends are presented in Fig. 3, 4.

One can see that the addition of BioDF to PDF sample causes an increase in the density of the latter by 3.0–12.4 and 3.3–13.6 kg/m^3, and an increase in kinematic viscosity by 0.299–1.442 and 0.302–1.892 mm^2/s for S_{BioDF} and M_{BioDF}, respec-

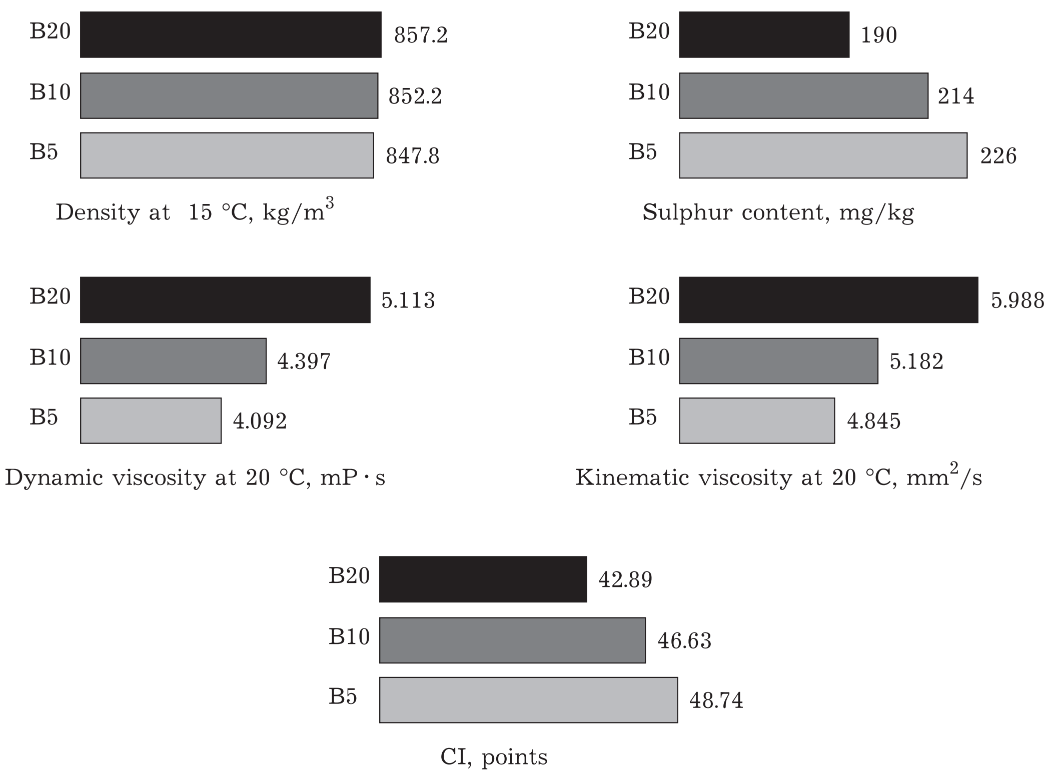

Fig. 3. Characteristics of S_{BioDF}/PDF blends.

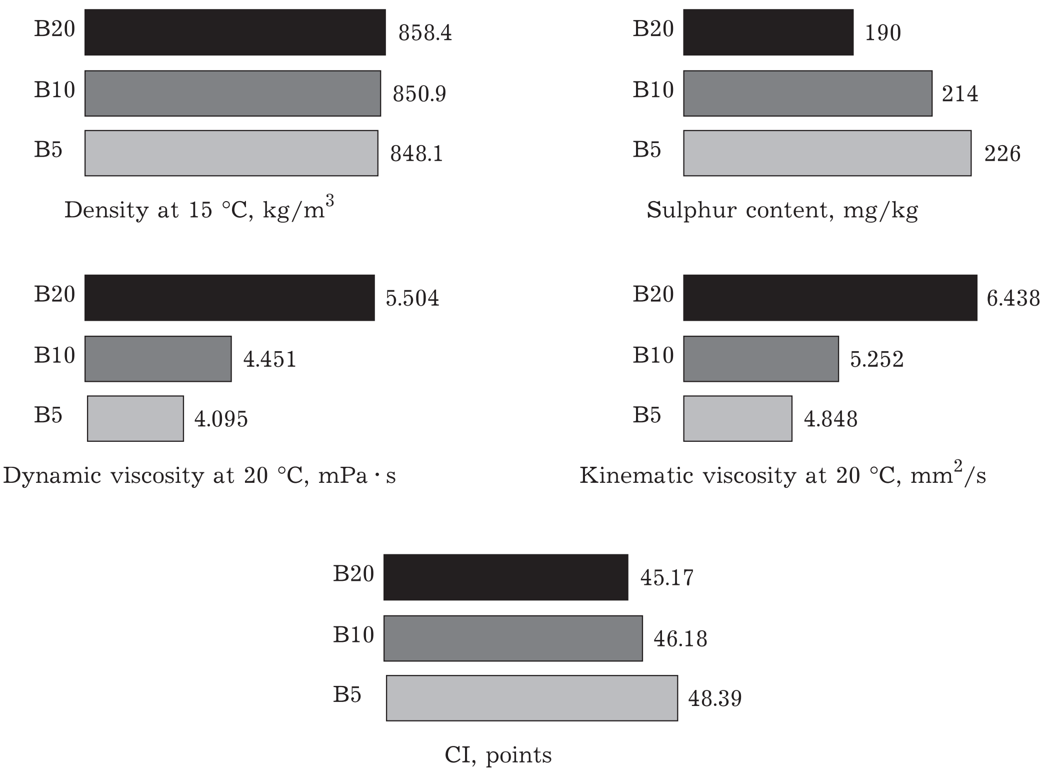

Fig. 4. Characteristics of M_{BioDF}/PDF blends.

tively. With respect to density, all the obtained blends corresponded to the requirements [21] (not more than 863.4 kg/m^3) for the Summer grade and Inter-season grades; with respect to kinematic viscosity, all blends except B20 M_{BioDF} meet the requirements [21] (3–6 mm^2/s).

The addition of BioDF to PDF leads to a decrease in sulphur content (by 12–48 mg/kg) because sulphur is absent from BioDF. All blends meet the requirements [21] with respect to sulphur content (not more than 2000 mg/kg).

The CI of DF changes nonlinearly after the addition of 5, 10 and 20 vol. % BioDF: the addition of a small amount of BioDF (5 vol. %) allows increasing CI by 1.6 and 1.2 points for S_{BioDF} and M_{BioDF}, respectively. However, a further increase in the fraction of BioDF in the blend leads to a decrease in CI, which is connected with the effect of BioDF on the FC of DF. Altogether, all blends except B20 S_{BioDF} correspond to the requirements [21] with respect to CI (not less than 45 points).

Results of the determination of low-temperature properties (CFPP and PP) of BioDF/PDF blends are presented in Table 6. The symbol Δ stands for the change in low-temperature properties with respect to pure PDF.

One can see that the addition of BioDF has a negative effect on the low-temperature characteristics of DF, though CFPP of the blends is independent of BioDF concentration (increases by 2 and 1 °C for S_{BioDF} and M_{BioDF}, respectively), while PP increases by 2–11 and by 4–8 °C (for S_{BioDF} and M_{BioDF}, respectively) with an increase in BioDF content in the blend from 5 to 20 vol. %. In general, the addition of S_{BioDF} worsens the low-temperature properties of DF to a more substantial

TABLE 6

Low-temperature characteristics of S_{BioDF}/PDF and M_{BioDF}/PDF blends

Parameter	B5 S_{BioDF}	B10 S_{BioDF}	B20 S_{BioDF}	B5 M_{BioDF}	B10 M_{BioDF}	B20 M_{BioDF}
CFPP, °C	−13	−13	−13	−14	−14	−14
ΔCFPP, °C	2	2	2	1	1	1
PP, °C	−26	−24	−17	−24	−23	−20
ΔPP, °C	2	4	11	4	5	8

extent than the addition of M_{BioDF}, which is due to the worst low-temperature properties of BioDF obtained from sunflower oil.

It should also be stressed that the regulated CFPP value [21] for all BioDF/PDF blends corresponds to the requirements for the Summer grade (not more than −5 °C).

Relying on the results obtained, the following BioDF/PDF ratios may be proposed for the production of commercial DF of the Summer grade:

– 90 vol. % PDF and 10 vol. % S_{BioDF} (an increase in S_{BioDF} content is impossible because of the discrepancy from the requirements [21] in CI value);

– 90 vol. % PDF and 10 vol. % M_{BioDF} (an increase in M_{BioDF} is impossible because of the discrepancy from the requirements [21] in viscosity and $FC_{50\%}$).

The production of commercial DF of the Inter-season and Winter grades is possible only in the case if low-temperature additives are used.

Effect of the additive on low-temperature properties of the blends of biodiesel fuel with petroleum diesel fuel

Results of the determination of CFPP (as the major regulated low-temperature parameter) for BioDF/PDF blends and for pure PDF with low-temperature additive are presented in Table 7. The symbol Δ designates the change in CFPP with respect to the blends without the additive.

One can see that the efficiency of the low-temperature additive decreases with an increase in BioDF content in the blend. For example, the introduction of the additive does not change CFPP of blends containing 20 vol. % BioDF.

In addition to the low efficiency of the low-temperature additive with respect to BioDF, polar oxygen-containing compounds appearing in the blends due to BioDF attract the components of the additive preventing them from the interaction with *n*-paraffins that are present in PDF and define the low-temperature characteristics of blends.

A decrease of BioDT content increases the additive effectiveness. Indeed, even with BioDF content in the blend 10 vol. % the preparation of commercial DF of the Inter-season grade (CFPP not more than −15 °C) [21] becomes possible.

TABLE 7

CFPP values for BioDF/PDF/low-temperature additive blends

Blend	CFPP, °C	ΔCFPP, °C
PDF	−30	15
B5 S_{BioDF}	−18	5
B5 M_{BioDF}	−20	6
B10 S_{BioDF}	−17	4
B10 M_{BioDF}	−18	4
B20 S_{BioDF}	−13	0
B20 M_{BioDF}	−14	0

CONCLUSION

It was established on the basis of the results of BioDF synthesis from five kinds of vegetable oil (sunflower, mustard, linseed, corn, and camelina) using ethanol as transesterifying agent and potassium hydroxide as a catalyst that the highest yield of BioDF is observed for sunflower oil (59.12 %), the lowest one – for camelina oil (43.18 %), which is due to differences in composition and reactivity of the fatty acids presented in different vegetable oils.

It was revealed through the determination of the major physicochemical and low-temperature characteristics of the obtained BioDF that the highest viscosity is characteristic of BioDF obtained from camelina oil, and the lowest – from sunflower oil; the highest density is characteristic of BioDF obtained from linseed oil, the lowest – from corn oil; the largest molecular weight is exhibited by BioDF obtained from camelina oil, the lowest – from corn oil. It is also shown that the best low-temperature characteristics are those of BioDF obtained from mustard oil, and the worst ones – from sunflower oil.

It is shown that the low-temperature additive for PDF turned out to be low-efficient for the improvement of the low-temperature properties of BioDF, which is explained by the mechanism of the additives action, through the interaction with *n*-paraffins of oil that are absent in BioDF.

It is established that the efficiency of the low-temperature additive decreases with an increase of BioDF content in blend with PDF, which is likely to be due to the presence of polar oxygen-containing compounds in BioDF.

Recommendations are elaborated for the use of BioDF/PDF/low-temperature additive blends as commercial DF. For the production of the Summer grade fuel, it is recommended to use a blend of 90 vol. % PDF and 10 vol. % BioDF. For the production of the Inter-season grade fuel, it is recommended to apply a blend of 90 vol. % PDF and 10 vol. % BioDF, as well as the low-temperature additive.

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REFERENCES

1 Demirbas A., Biodiesel: a Realistic Fuel Alternative for Diesel Engines, Springer-Verlag London Limited, 2008. 208 p.
2 Markov V. A., Devyanin S. N., Semenov V. G., Shakhov A. V., Bagrov V. V., The Use of Vegetable Oils and Fuels on Their Basis in Diesel Engines, Moscow: LC NITs Inzhener (Soyuz NIO), LC Oniko-M, 2011. 536 p.
3 Erdiwansyah, Mamat R., Sani M. S. M., Sudhakar K., Kadarohman A., Sardjono R. E., An overview of higher alcohol and biodiesel as alternative fuels in engines, *Energy Reports*, 2019, No. 5, P. 467–479.
4 Singh D., Sharma D., Soni S. L., Sharma S., Kumari D., Chemical compositions, properties, and standards for different generation biodiesels: A review, *Fuel*, 2019, No. 253, P. 60–71.
5 Levterov A. M., Savitsliy V. D., Levterova L. I., Experimental investigation of the motor characteristics of the mix biodiesel fuel, *Avtomobilnyi Transport*, 2011, No. 28, P. 81–84.
6 Tsai J. H., Chen S. J., Huang K. L., Lin Y. C., Lee W. J., Lin C. C., Lin W. Y., PM, carbon, and PAH emissions from a diesel generator fuelled with soy-biodiesel blends, *J. Hazard. Mater.*, 2010, Vol. 179, No. 1–3, P. 237–243.
7 Cheruiyot N. K., Hou W. C., Wang L. C., Chen C. Y., The impact of low to high waste cooking oil-based biodiesel blends on toxic organic pollutant emissions from heavy-duty diesel engines, *Chemosphere*, 2019, Vol. 235, P. 726–733.
8 GOST ISO 3405–2013, Oil products, Determination of fraction composition at atmospheric pressure, Moscow: Standartinform, 2014. 30 p.
9 ISO 12185:1996, Crude oil and oil products, Determination of density, Method involving an oscillating U-shaped tube, Moscow: Standartinform, 1996. 12 p.
10 GOST 33–2016, Oil and oil products, Transparent and non-transparent liquids, Determination of kinematic and dynamic viscosity, Moscow: Standartinform, 2017. 34 p.
11 GOST 32139–2013, Oil and oil products, Determination of sulphur content by means of X-ray fluorescence energy-dispersive spectrometry, Moscow: Standartinform, 2014. 18 p.
12 ISO 4264:2018, Petroleum products – Calculation of cetane index of middle-distillate fuels by the four variable equation, ISO, 2018. 9 p.
13 Altynov A. A., Bogdanov I. A., Kirgina M. V., Development of calculation methods to determine the performance characteristics and low-temperautre properties of diesel fuel, *Neftepererabotka I Neftekhimiya*, 2018, No. 2, P. 5–12.
14 ASTM D2224-78, Method of Test for Mean Molecular Weight of Mineral Insulating Oils by the Cryoscopic Method, ASTM, 1983.
15 GOST 066–91 (ISO 3013–74), Motor fuel, Methods to determine cloud point, chilling point and crystallization point, Moscow: Izd-vo Standartov, 1992. 8 p.
16 GOST EN 116–2013, Diesel and furnace fuel for residential use, Method to determine the limiting filterability temperature, Moscow: Standartinform, 2016. 28 p.
17 GOST 20287–91, Oil products, Methods to determine pour point and chilling temperature, Moscow: Standartinform, 2006. 9 p.
18 Rochelle D., Najafi H., A review of the effect of biodiesel on gas turbine emissions and performance, *Renewable & Sustainable Energy Reviews*, 2019, Vol. 105, P. 129–137.
19 Kuznetsov A. V., Fuel and Lubricants, Moscow: KolosS, 2007. 199 p.
20 Graboski M. S., McCormick R. L., Combustion of fat and vegetable oil derived fuels in diesel engines, *Prog. Energy Combust. Sci.*, 1998, Vol. 24, Issue 2, P. 125–164.
21 GOST 305–2013, Diesel fuel, Technical specification, Moscow: Standartinform, 2014. 10 p.
22 Bogdanov I. A., Altynov A. A., Belinskaya N. S., Kirgina M. V., Investigation of the effect of the composition of straight-run diesel fuel on the efficiency of low-temperature additives, *Neftepererabotka I Neftekhimiya*, 2018, No. 11, P. 37–42.