Проведено переестерифікацію нерафінованої рижієвої олії на лужному каталізаторі із застосуванням товарного безводного етилового спирту паливного призначення. Показано, що зростання вмісту вологи в спирті до 1 % призводить до низького виходу етилових естерів. Запропоновано технологічну схему виробництва дослідної партії етилових естерів рижієвої олії у лабораторних умовах. Схема включає: приготування розчину каталізатора, переестерифікацію олії етиловим спиртом, відстоювання, відпарку спирту, розділення, промивку, осушування та фільтрацію. Це дозволяє одержати продукти з вмістом естерів 92–93,5 %. Проведено хроматографічний аналіз продуктів переестерифікації рижієвої олії. Одержані продукти містять переважно ненасичені естери жирних кислот з довжиною вуглецевого ланцюга у 18 атомів.

Виконано порівняльний аналіз жирнокислотного складу одержаних етилових естерів рижієвої олії та етилових естерів ріпакової олії, досліджених у попередніх працях авторів. Жирнокислотний склад дозволяє спрогнозувати нижчу в'язкість, температури помутніння та замерзання етилових естерів з рижієвої олії порівняно з етиловими естерами з олії ріпаку. Висловлене припущення підтверджено експериментальними даними досліджень основних фізико-хімічних характеристик метилових та етилових естерів ріпакової та рижієвої олій. Одержані експериментальні дані свідчать про перспективність застосування продуктів переестерифікації олії рижію як компонентів палив для повітряно-реактивних двигунів. У подальшому компаундування синтезованих етилових естерів жирних кислот рижієвої олії з паливом для повітряно-реактивних двигунів дозволить одержати біопалива з покращеними якісними показниками у порівнянні з біопаливами з використанням естерів ріпакової олії

Ключові слова: рижієва олія, переестерифікація, естери етилові, біокомпонент палива для повітряно-реактивних двигунів

UDC 66.08:665.753.004.12:662.756.3(043.5)
DOI: 10.15587/1729-4061.2020.196947

SYNTHESIS OF CAMELINA OIL ETHYL ESTERS AS COMPONENTS OF JET FUELS

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Received date 08.01.2020
Accepted date 14.02.2020
Published date 28.02.2020

1. Introduction

Today, one of the most promising research directions in the spheres of transport and fuel supply is the design of alternative environmentally safe motor fuels of renewable plant origin. The use of such fuels will contribute to decreasing the anthropogenic impact on the environment, reduction of CO_2 emissions [1] into the atmosphere (during both production and use of fuels). Moreover, this will reduce the dependence of a number of countries on the import of oil products and other energy resources.

Oily agricultural crops are characterized by high energy content being among the most attractive sources of bio-renewable feedstock that can partially replace conventional crude oil, including in the processes of aviation fuel production.

However, the use of conventional oils for technical purposes, for fuel production, in particular, is significantly restricted. This is explained by the fact that such crops as sunflower, soybean, corn, etc. are grown primarily to meet the needs of the food industry. For the same reasons, the cultivation of technical crops, such as rapeseed, is limited by the areas available for cultivation. Today, one of the most promising alternative oil crops that is characterized by low requirements for cultivation conditions is *Camelina sativa L.* [2, 3]. Camelina culture is very unpretentious to soil quality and climatic conditions, resistant to pests, diseases and cold, does not require large amounts of mineral fertilizers. Characterized by a shorter vegetation period, this crop gives a yield of oil per unit area of the crop that is commensurable with rapeseed. The short vegetation period also contributes to the cultivation of Camelina as an intermediate crop in post-harvest crops. In addition, Camelina cultivation does not lead to intensive depletion of fertile land.

Taking into account the abovementioned, it is quite obvious that growing Camelina as a feedstock for biofuel production will have a number of advantages over other agricultural crops used nowadays. The application of biofuels based on Camelina oil will contribute to the reduction of CO_2 emissions throughout the lifecycle of such fuels, decreasing anthropogenic impact on the environment and expansion of feedstock for motor fuel production. This will reduce the dependence on non-renewable energy sources. Thus, the study of the possibility of using Camelina oil for producing components of alternative fuels, in particular aviation, is a relevant scientific and applied issue.

2. Literature review and problem statement

From the studies [2, 3], it is known that in Ukraine, nowadays, the area of Camelina occupies about 5–6 thousand hectares (3 % of all oil crops), mainly in the northern part of the left-bank of the forest-steppe. It is also noted that these areas can be increased by 3–4 times. However, today, there is no certain strategy in Ukraine aimed at the development of Camelina cultivation.

On the contrary, the authors of researches [1, 4] note that in the USA, Canada and a number of EU countries, Camelina is considered to be one of the most promising oil crops for biofuels production. It is shown that until recent times, rapeseed was the main feedstock for alternative motor fuels production (the so-called «first generation» biofuels). However, due to a number of difficulties and ambiguous issues related to rapeseed cultivation, the situation has changed significantly over the last 5 years. The reason for this is the considerable resource and energy costs of the rapeseed cultivation process. This is explained by the fact that obtaining high rapeseed yields requires intensive cultivation of fertile land, which quickly depletes it, introduction of large amounts of fertilizers and pesticides. Rapeseed is very demanding on climatic and soil conditions. In addition, the problem is that the cultivation of rapeseed on fertile lands creates competition for the food industry [5–8]. In this regard, further research into the use of rapeseed for biofuels production, including aviation, is not appropriate.

An alternative solution to the problem is using renewable plant feedstock that does not compete with the food industry and does not present a short or long-term threat to the environment, i. e. which manufacturing and use are sustainable. This view is expressed by the scientists in [9, 10], calling alternative fuels based on renewable feedstock as «second generation» biofuels. One of such types of feedstock is Camelina oil, in particular.

In [10–12], a successful experience of using Camelina oil for the production of aviation biofuels is described. Thus, flight tests were successfully carried out on various types of aircrafts using mixtures of conventional jet fuel of petroleum origin and products of Camelina oil processing [13–15]. The latter were a mixture of aromatic hydrocarbons and C7–C9 isoalkanes, which were obtained via hydrodeoxygenation of oil, followed by selective cracking of the obtained straight alkanes, isomerization and aromatization of cracking products [15, 16]. However, the main disadvantage of such biofuels is that their chemical composition is a mixture of hydrocarbons similar to petroleum jet fuels.

Another solution of the problem mentioned above is the possibility of introducing fatty acid alkyl esters into jet fuels. From the studies [17, 18], it is known that their production is based on the simplest from the chemical and technological point of view process of triglycerides transformation – alcoholysis (transesterification) with simple alcohols. Traditionally [5, 7, 18], methanol is used for transesterification that is explained by its technological advantages during this process and also lower price compared to other simple alcohols. It is known from a number of studies [5, 9, 18, 19] that fatty acid methyl esters (FAME) are widespread as an alternative fuel for diesel engines. However, one of the main unsolved issues regarding the use of FAME as components of jet fuel is their unsatisfactory low-temperature properties [18–20]. Thus, it was shown that due to the high freezing point, the use of jet fuels containing only 10 % vol. of soybean oil FAME is limited by the flight altitude of 7,000 m. The main reason of this problem is the chemical structure of oil FAME molecules. Also, the structure and fatty acid composition of plant oils used as a feedstock for biocomponents production have a significant impact. To increase the content of biocomponents in jet fuel, some researchers [10, 17] propose the isolation of a certain FAME fraction that is characterized by the best low-temperature properties, and use of additives. However, such process is not economically profitable because of the low output of the required fuel components. At the same time, due to the content of Oxygen in FAME molecules, their use in aviation fuels can reduce the formation of soot, and therefore emissions of particulate matter. In addition, fuel mixtures containing FAME demonstrate satisfactory compatibility with aircraft construction materials. However, the disadvantage of Oxygen content [16, 20] in the FAME composition (about 11 %) is the reduction of their energy content compared to fuel of hydrocarbon origin.

A solution to the problem of improving low-temperature properties of biocomponents is the application of higher molecular weight alcohols for transesterification. From the studies [18, 20, 21], it is known that the nature of alcohol used for transesterification strongly affects the physical-chemical properties of the obtained esters. From the studies devoted to the development of biodiesel fuels based on fatty acid ethyl esters (FAEE) of plant oils, it is known [13, 17] that increasing the hydrocarbon chain length of alcohol causes reduction of esters' freezing point [16, 20]. In previous works of the authors [16, 20, 21], it was shown that the use of rapeseed oil FAEE, compared to the FAME, has a positive effect on the performance of fuel mixtures used in jet engines [16, 19, 20]. This suggests that studying the feasibility of Camelina oil FAEE use as a component of jet fuels is seemed to be promising and appropriate. On the one hand, the use of Camelina oil will solve problematic issues with feedstock, and on the other hand, the use of ethanol for transesterification will improve some of the operational properties of jet biofuels.

3. The aim and objectives of the study

The aim of the study is the evaluation of the possibility of obtaining and using Camelina oil fatty acid ethyl esters as components of jet fuel.

To achieve this aim, the following objectives were set:

– to determine the influence of moisture content in ethanol on the process of transesterification of Camelina oil and yield of fatty acid esters;

– to carry out a comparative analysis of the fatty acid composition of synthesized fatty acid ethyl esters of Camelina and rapeseed oils;

– to investigate the effect of the fatty acid composition of fatty acid ethyl esters of Camelina and rapeseed oils on their physical-chemical properties as components of jet fuel.

4. Experiment methodology

For the transesterification, unrefined Camelina oil produced by VEDALAN LLC (Ukraine) was used (TU U 10.4-38771490-011: 2013).

Samples of commercial ethanol intended for fuelling were used as a transesterification agent – alternative motor fuel component (AMFC) (TU 24.6-30219014-009:2007) of the same origin. The latter, when stored in different containers, due to the high hygroscopicity of ethanol, have accumulated different content of moisture. Thus, the sample of AMFC that was stored in a hermetically sealed container had density at a temperature of 20 °C that equals 0.7890 g/cm^3 (sample AMFC-1), and the sample with improper storage conditions had a density of 0.7924 g/cm^3 (sample AMFC-2), which corresponds to the moisture content of 0.1 % and 1.0 %, respectively.

Potassium hydroxide of AR grade (Czech Republic) was used as a catalyst.

Sodium sulfate anhydrous Pure grade (Germany) was used as the desiccant.

It is necessary to use ethanol with a moisture content of not more than 0.5 % in order to carry out the process of esterification of triglycerides with ethanol using KOH as a catalyst effectively [21].

The most common ethanol-containing product produced by the industry is technical ethanol and rectified ethanol. However, these products contain more than 4.4 % of moisture. Today, Ukraine also produces ethanol-containing products with a low moisture content (up to 0.2 wt%), which are used as additives for gasoline. Such products are «Alternative Motor Fuel Component (AMFC)» and «Universal Alternative Motor Fuel Component (UAMFC)» manufactured according to TU U 24.6-30219014-009:2007 and TU U 20.5-00372536-001:2013 respectively. Such products contain a denaturing additive that makes them unsuitable for food use, but from a chemical point of view, it is neutral with respect to the alkaline transesterification process.

Such products have several advantages: absence of moisture, low price and availability on the market, no problems with excise duty on ethanol. Therefore, it was proposed to use AMFC for the process of oil transesterification to obtain FAEE. Due to the high hygroscopicity of ethyl alcohol, the storage of the abovementioned products increases the moisture content, which can greatly affect the process of transesterification of triglycerides of oils.

Obtaining of Camelina oil ethyl esters (CamEE) included the following steps (Fig. 1):

– preparation of alcohol solution of the catalyst;

– transesterification of oil with ethanol;

– sedimentation and separation of products into ester and glycerol layers;

– evaporation of ethanol from the ester layer;

– reseparation of the glycerol layer 2 formed after ethanol stripping from the esters;

– washing the ester layer 2 with hot water;

– drying the washed esters using a neutral Na_2SO_4 anhydrous desiccant;

– filtering of dried esters on a paper filter.

The synthesis was carried out in a 2 l conical flask with stirring using a magnetic stirrer at room temperature, adding a prepared solution of alkali in AMFC into the oil. 25 g of KOH was dissolved in 493 g of ethanol (AMFC) in a conical 2 l flask. Subsequently, 1,200 g of Camelina oil was added to the resulting alkaline solution and stirred with a magnetic stirrer for 30 min at a speed of 500 rpm at room temperature (17±1 °C). Thus, the estimated molar ratio of alcohol to oil was 6/1, and quantity of KOH was 2.1 % relative to oil. The resulting mixture was transferred into a separating funnel for 2 dm^3 and maintained for 24 hours at room temperature. Thereafter, the lower glycerol layer and the upper ester layer were separated. The ester layer ready for separation was directed to the separation of ethanol by evaporation in a container with a large surface area. After evaporation of the ethanol (for 5–6 days), the resulting product was separated into the lower glycerol layer 2 and the upper ester layer 2. Ester layer 2 was washed with hot water with the ester/water ratio 1/1 7 times with separation in the separating funnel of the lower aqueous layer. The washed ester layer was dried with anhydrous sodium sulfate taken in an amount of 10 % of the loaded ester. After drying, the obtained esters were filtered on a paper filter.

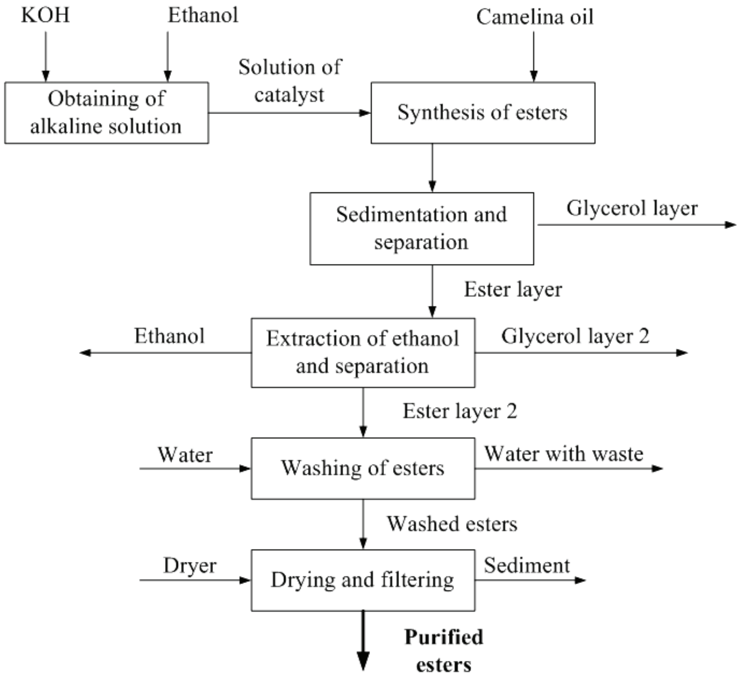

Fig. 1. Schematic diagram of obtaining Camelina oil ethyl esters

Application of this scheme of synthesis and purification of products allows obtaining purified esters with a content of FAEE of more than 95 % without applying vacuum distillation of products.

The content of FAEE in transesterification products, as well as their fatty acid composition, was determined by an adapted method. The methodology is based on the method of quantitative gas chromatography determination of FAME in biodiesel according to the European standard EN14013 [22]. The analysis was performed on an Agilent 7890A gas chromatograph equipped with a splitting/no splitting gas flow injector, a flame ionization detector, and an Agilent HP-88 capillary column. Capillary column characteristics: carrier – (88 % – cyanopropyl) acrylic-polysiloxane, length – 100 m, inner diameter – 0.25 mm, deposited phase thickness – 0.2 μm). High purity helium was used as the carrier gas.

Instead of more expensive methylheptadecanoate, which is recommended for use as an internal standard in the method according to EN14103, more accessible methyl palmitate was used. Samples for analysis were prepared in the form of hexane solutions according to the procedure described in EN 14103.

The content of alkyl esters in the samples was calculated from the known sample masses and internal standard, purity of the standard and the ratio of the peak area of the standard to the sum of ester peak areas determined from the chromatogram.

The density of the samples of FAEE of Camelina and rapeseed oils was determined according to the American standard ASTM D4052 [23] on the Anton Paar DMA 4500M density determination device at a temperature of 15 °C.

The viscosity of the samples of FAEE of Camelina and rapeseed oils was determined according to the American standard ASTM D445 [24] on Walter Herzog HVU 482 automatic viscometer at 20 °C.

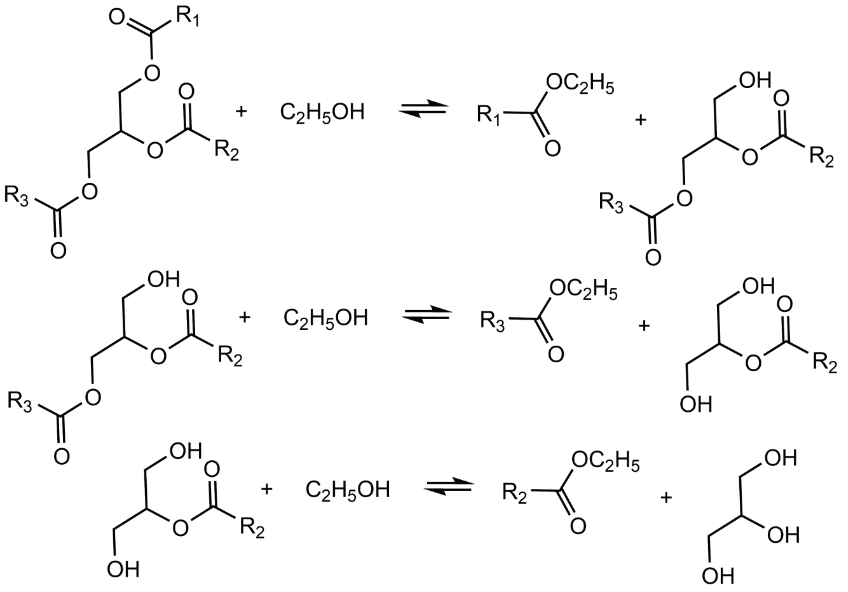

Fig. 2. Scheme of transesterification of triglycerides with ethanol

The pour point of FAEE of Camelina and rapeseed oils was determined according to the American Standard ASTM D97 [25] on the ISL device for determining the low-temperature characteristics of fuels. The heat of combustion of the samples of FAEE of Camelina and rapeseed oils was determined according to the American standard ASTM D4809 [26] in the IKA C 200 automatic calorimetric bomb.

5. Results of determining the influence of moisture content in ethanol on the process of transesterification and fatty acid ethyl esters output

The process of transesterification of triglycerides with ethanol is a catalytic three-stage equilibrium process, which is schematically shown in Fig. 2. To shift the equilibrium toward the reaction products, one of the initial substances must be taken in excess.

Due to the relative ease of isolation from transesterification products, alcohol is usually taken in excess. In addition, separation of one of the reaction products in a separate phase also leads to a shift of equilibrium toward the reaction products, so the spontaneous formation of a separate glycerol layer is an important technological aspect that contributes to the greater yield of esters. Most of the alkaline catalyst also comes into the glycerol layer. The use of ethanol with a high moisture content prevents separation of glycerol into a separate phase, which leads to a decrease in the yield of FAEE and complicates their subsequent separation from the mixture of conversion products.

The use of ethanol with different moisture content significantly influenced the process of alkaline ester synthesis and led to the formation of different amounts of final products. Thus, Tables 1, 2 present the material balance of the process of obtaining ethyl esters from Camelina oil in laboratory conditions with the application of AMFC with a moisture content of 0.1 and 1.0 % respectively.

Table 1

Material balance of the process of CamEE production using alcohol with 0.1 % of moisture

Input			Expense		
Name of component	Mass of component, g	Content of component, %	Name of component	Mass of component, g	Content of component, %
Synthesis of esters					
KOH	104.1	1.45	Ester layer	5877.2	82.14
Ethanol (AMFC-1 sample)	2051.4	28.67	Glycerol layer	1275.2	17.82
Camelina oil	5000.0	69.88	Losses	3.1	0.04
Stripping of alcohol					
Ester layer	5877.2	100.00	Ester layer 2	4003.8	68.12
			Glycerol layer 2	776.5	13.21
			Stripped alcohol and losses	1096.9	18.66
Washing with water					
Ester layer 2	4003.8	12.5	Washed esters	3831.9	11.96
Water	28026.6	87.5	Water for washing	28198.5	88.04
Drying on Na_2SO_4 and filtration					
Washed esters	3831.9	90.91	Purified esters (CamEE-1 sample)	3554.9	84.34
Na_2SO_4	383.2	9.09	Sediment	660.2	15.66

Table 2

Material balance of the process of CamEE production using alcohol with 1.0 % of moisture

Input			Expense		
Name of component	Mass of component, g	Content of component, %	Name of component	Mass of component, g	Content of component, %
Synthesis of esters					
KOH	104.2	1.50	Ester layer	4841.3	67.62
Ethanol (sample of AMFC-1)	2055.9	28.70	Glycerol layer	2315.7	32.34
Camelina oil	5000.0	69.80	Losses	3.0	0.04
Stripping of alcohol					
Ester layer	4841.3	100.00	Ester layer 2	4129.9	85.31
			Glycerol layer 2	353.2	7.29
			Stripped alcohol and losses	358.2	7.40
Washing with water					
Ester layer 2	4129.9	12.50	Washed esters	3184.9	9.64
Water	28909.3	87.50	Water for washing	29854.3	90.36
Drying on Na_2SO_4 and filtration					
Washed esters	3184.9	90.91	Purified esters (CamEE-2 sample)	2899.9	82.77
Na_2SO_4	318.5	9.09	Sediment	603.5	17.23

From the given data (Tables 1, 2), it is seen that the application of alcohol with a high moisture content leads to an increase in the mass of the formed glycerol layer (32 % vs. 18 % of the total mixture). Also, it leads to the reduction of the amount of the final product – samples of washed ethyl esters of Camelina oil (CamEE-1 and CamEE-2, respectively) from 71 % to 58 wt% of the used oil.

6. Results of studying of the fatty acid composition of fatty acid ethyl esters of Camelina and rapeseed oils

Later, the content of Camelina oil ethyl esters in the transesterification products, as well as their fatty acid composition, was determined by gas chromatography. In addition, the fatty acid composition of the sample of rapeseed oil ethyl esters (RapEE) that was studied by the authors in previous researches [18–20] as a component of jet fuel, has been determined.

The conditions of analysis used provided good separation of the peaks of individual ethyl esters with the same number of carbon atoms (Fig. 3, 4). Methyl palmitate and ethyl palmitate peaks are also clearly separated.

In addition to the concentration and fatty acid composition of CamEE-1, the conditions of analysis also allow identifying and evaluating the residual ethanol content. The peak of the latter on the chromatogram is located immediately after the peak of n-hexane (not shown in Fig. 3). Ethanol was not found in the purified samples of Camelina oil esters.

The concentration of ethyl esters in the CamEE-1 and CamEE-2 samples (obtained using AMFC-1 and AMFC-2 alcohol samples, respectively) was 91.9 and 93.6 %.

The chromatogram of the RapEE sample recorded under the same conditions as CamEE samples is shown in Fig. 4. Esters contain a small amount of saturated fatty acids – 10.6 % in the case of Camelina and 8.6 % in the case of rapeseed. The majority of the samples are C18 esters (18 carbon atoms in the fatty acid molecule). Among them, oleic acid is predominant in the CamEE, whereas the RapEE sample contains predominantly poly-unsaturated fatty acids. It should also be noted that RapEE sample does not actually contain C20 and higher esters, whereas in CamEE-1 and CamEE-2 samples their portion exceeds 10 %.

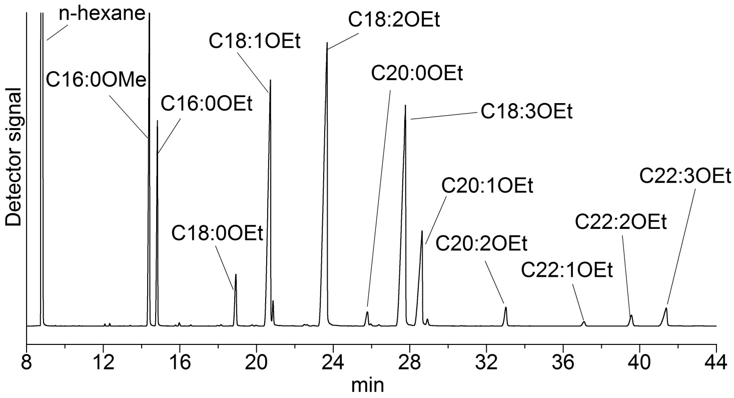

Fig. 3. Chromatogram of CamEE-1

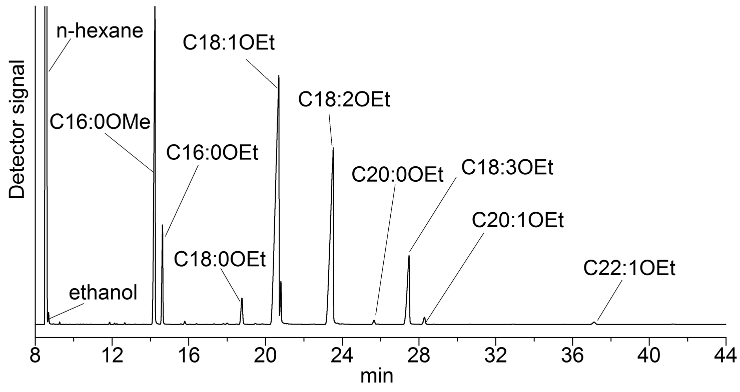

Fig. 4. Chromatogram of RapEE-1

7. Results of studying the influence of fatty acid composition of Camelina and rapeseed oil ethyl esters on their physical-chemical properties

Comparative analysis of the fatty acid composition of ethyl esters of Camelina and rapeseed oils was carried out in order to evaluate the possibility of using Camelina oil esters as components of jet fuel. Since the properties of oils and their esters, respectively, are determined by the qualitative and quantitative composition of individual fatty acids, the data on the fatty acid composition of esters allows predicting their physical and chemical properties. Table 3 gives data about the fatty acid composition of Camelina oil according to the data [2, 12, 27] compared to the fatty acid composition of the synthesized CamEE samples and RapEE sample, which were previously studied as components of jet fuel [19].

Based on the determined fatty acid composition of the samples, it is possible to predict how some properties of CamEE and RapEE will correlate. It is known from the literature [19] that the viscosity of alkyl esters increases with the extension of the hydrocarbon chain of the acid residue and with the decrease of unsaturation of molecules. Therefore, it is expected that CamEE will be characterized by a lower viscosity. The high content of polyunsaturated fatty acids should also ensure lower pour and cloud points of the samples obtained from the Camelina oil. At the same time, differences in the fatty acid composition of the samples should not significantly affect their energy content. It is also known that in case of the same fatty acid composition, ethyl esters are characterized by better low-temperature properties than methyl but also somewhat higher viscosity [19].

The described dependence is confirmed by the obtained results of determining the physical-chemical characteristics (Table 4). Data on the characteristics of methyl esters of rapeseed and Camelina oils were taken from previous studies of the authors [19, 20].

From the results given in Table 4, it is seen that if the same type of alcohol (methyl, ethyl) is used, the viscosity, pour point and density are reduced during replacing rapeseed oil with Camelina oil as feedstock for esters. At the same time, the energy content of the obtained fuel components remains almost constant. In addition, we see that the use of ethanol instead of methanol has a positive effect on the density and pour point of biocomponents, which during application will positively affect the performance of jet fuel.

Table 3

Comparative analysis of fatty acid composition of Camelina oil according to the data [2, 12, 27], and CamEE and RapEE

Name of the acid	Short name	Content of fatty acid, % of the sum of all fatty acids								
		[12]	[12]	[12]	[12]	[27]	[2]	Cam EE-1	Cam EE-2	RapEE
Palmitic	C16:0	5.3	6.8	5.4	5.4	8.3	6.1	6.6	6.7	5.7
Stearic	C18:0	2.5	2.7	2.5	2.6	2.4	2.1	2.6	2.6	2.5
Oleic	C18:1	12.6	18.6	14.9	14.3	20.3	16.3	20.0	20.2	49.4
Linolic	C18:2	15.6	19.6	15.2	14.3	23.9	19.9	29.6	29.8	30.6
α-Linolenic	C18:3	37.5	32.6	36.8	38.4	29.5	36.3	24.5	24.4	9.0
Arachic	C20:0	1.2	1.5	1.3	1.4	–	0.6	1.1	1.0	0.4
Eicosenic	C20:1	15.5	12.4	15.5	16.8	10.7	16.4	9.7	9.6	0.8
Eicosadienic	C20:2	2.0	1.3	1.9	–	1.5	–	1.3	1.3	–
Eicosatrienic	C20:3	1.7	0.8	1.6	–	1.1	–	–	–	–
Behenic	C22:0	0.3	0.2	0.3	0.2	–	–	–	–	–
Erucic	C22:1	2.9	2.3	2.8	2.9	1.8	2.2	0.9	0.9	0.4
others	–	2.9	1.2	1.8	3.7	0.5	0.1	3.7	3.5	1.2

Table 4

Comparison of physical-chemical characteristics of ethyl and methyl esters of Camelina and rapeseed oils

Ester	Molecular mass of alcohol, g/mol	Viscosity at temperature 20 °C, mm^2/s	Density at temperature 15 °C, kg/m^3	Pour point, °C	Energy content (higher), MJ/kg
RapME	32	6.72	884	–15	39.83
RapEE	46	7.27	877	–18	40.27
CamME	32	5.18	882	–16	39.61
CamEE	46	6.42	875	–18.5	39.84

8. Discussion of results of the process of Camelina oil transesterification and properties of obtained biocomponents

Previous studies of the authors were devoted to the production of biocomponents for jet fuels based on methyl and ethyl esters of rapeseed oil fatty acids and studies of characteristics of aviation biofuels blended with these biocomponents [16, 19, 20]. However, the obtained results showed a number of disadvantages of using rapeseed oil esters as jet fuel components as it was described above.

At the same time, the application of Camelina oil can be a solution to problematic issues. On the one hand, the process of growing Camelina crop ensures the sustainability and environmental safety of its biocomponents. This is due to the fact that growing Camelina culture does not deplete fertile soils that is typical for rapeseed crop. In addition, the unpretentiousness of Camelina to geographical and climatic conditions, as well as properties of soils, which is typical for rapeseed, greatly simplifies the cultivation process and amount of material costs. Thus, the use of Camelina oil will expand the feedstock base for alternative motor fuel production.

On the other hand, the properties of Camelina oil and its esters are slightly different from the properties of rapeseed oil and its esters, which is shown in Fig. 3, 4, and also in Table 3. In particular, the presence of a higher proportion of polyunsaturated fatty acids in Camelina oil provides more optimal properties of esters as components of jet fuels, considering the characteristics of conventional jet fuels. As can be seen from Table 4, biocomponents based on Camelina oil esters will be characterized by a lower density, viscosity, pour point, which are more similar to the same properties of jet fuels. In the future, this will increase the content of renewable biocomponents in alternative aviation fuels, thereby improving their environmental safety.

At the same time, it should be noted that the quantitative and qualitative fatty acid composition of fatty acid esters depends on the initial oil and can vary within one kind of oil up to several percents, which is caused by conditions of plant cultivation (climate, soil cover, availability of fertilizers, moisture level, etc.), species and varietal diversity. Therefore, further studies using different batches of Camelina oil are required to obtain the most objective results.

The obtained results are the basis for further researches towards the development of alternative aviation fuels. In particular, the next stage of the work will be comprehensive studies of the physical, chemical, operational and environmental performance of biocomponents based on Camelina oil as a component of aviation fuels. Subsequently, it is planned to work on the compounding of Camelina oil esters with petroleum jet fuels, development of receipts of alternative aviation fuels, their laboratory and bench testing.

9. Conclusions

1. Fatty acid ethyl esters of Camelina oil were obtained by the method of transesterification with ethanol on an alkaline catalyst. It was determined that increasing the moisture content of ethanol used for transesterification from 0.1 % to 1.0 % reduces the yield of esters from 71 % to 58 % and increases the amount of waste in the final reaction products. At the same time, it is found that the use of Camelina oil provides a sufficiently high content of esters in the final reaction products (about 92–93.5 %).

2. Qualitative and quantitative fatty acid composition of Camelina and rapeseed oil ethyl esters was identified by the method of gas chromatography. It was shown that Camelina oil esters have a higher content of polyunsaturated fatty acids (~56 %) compared to rapeseed oil esters (~40 %). There is a higher content of molecules with an extended hydrocarbon chain (13 %) compared to rapeseed oil esters (1.6 %).

3. The influence of fatty acid composition on the physical-chemical properties of Camelina oil esters is substantiated. In particular, a higher content of polyunsaturated fatty acids in esters of Camelina oil will contribute to their better viscosity and low-temperature characteristics compared to rapeseed oil esters. Experimental studies have confirmed that Camelina oil esters have lower viscosity (6.42 mm^2/s), density (875 kg/m^3) and pour point (–18.5 °C) compared to rapeseed oil esters (7.27 mm^2/s, 877 kg/m^3, –18 °C, respectively). The energy content of Camelina and rapeseed oil esters does not differ significantly – 39.84 MJ/kg and 40.27 MJ/kg, respectively. The obtained results indicate that the physical-chemical properties of Camelina oil ethyl esters are more similar to those of jet fuels and can be successfully used to produce alternative aviation fuels.

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