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EXPERIMENTAL STUDY OF PHYSICAL-CHEMICAL PROPERTIES OF ADVANCED ALCOHOL-TO-JET FUELS

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Abstract. The paper presents an analytical review of technological processes of alternative jet fuel production from alcohols and experimental results on the study of its physical-chemical properties. State-of-the-art in the sphere of civil aviation development within the framework of sustainable development and minimization of transport's negative impact on the environment is presented. The development and implementation of sustainable aviation fuels are considered the main measure for reaching carbon-neutral growth. Two technologies of alcohol-to-jet fuel production are considered, and possible feedstock and processing pathways are presented. Physical-chemical properties of two kinds of alcohol-to-jet fuels are studied experimentally, as well as the properties of conventional jet fuels blended with alternative ones. It is shown that the physical-chemical properties of jet fuels blended with alcohol-to-jet component containing aromatics are very close to conventional jet fuels. All of the studied fuel blends with alcohol-to-jet components completely satisfy the requirements of specifications. Basing on the received results it is expected that alcohol-to-jet component containing aromatics may be successfully used for blending with conventional jet fuel and used as a drop-in fuel.

Keywords: jet fuel, sustainable aviation fuel, alcohol-to-jet, synthesized paraffinic kerosene, synthesized kerosene with aromatics, technological process, physical-chemical properties.

Introduction

Today energy management and energy saving became important issues in modern society and industry. According to the forecasts (Dessens et al., 2014; Lee et al., 2009), the share of conventional energy sources in the total volume of energy use by 2050 will be not less than 70%. The transport sector is even more dependent on conventional energy sources (up to 95%) (Yakovlieva et al., 2019b). The most widespread energy sources for transport are gasoline, jet fuel (JF), diesel fuel and petroleum gas, which are produced from crude oil and other fossil fuels. However, the shortening of the world crude oil deposits and products of its processing, worsening of the state of the environment and the (Kurdel et al., 2022) need to ensure air transport safety determine the need for the development and use of alternative motor fuels and aviation fuels in particular. At the same time, technological processes of alternative aviation fuel (AAF) production from renewable sources and its use have to be environmentally safe and shouldn't compete with other spheres of industry, mainly food production (Ratner et al., 2019).

Today commercial aviation is a source of about 2% of global CO_2 emissions. At the same time, it produces about 12% of all CO_2 emissions from the transportation sector (Brooks et al., 2016). According to forecasts, emissions of CO_2 from civil aviation will increase by about three times by 2050 (Yakovlieva et al., 2019b). The reason for this is the quick development of passenger and cargo air transportation Moreover, road transport becomes more energy-efficient and, thus, the share of aviation in transportation emissions rises. CO_2 emissions are not the only environmental hazard caused by a growing aviation sector. Nitrogen oxides, unburned hydrocarbons, sulfur oxides, particulates, noise, and other pollutants also negatively impact the natural environment (Boichenko et al., 2020).

There is an opinion that today decarbonization of air transport is one of the most complicated compared to other

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*Corresponding author. E-mail: *anna.yakovlieva@tuke.sk* means of transport. One of the possible ways to reduce CO_2 emissions within the aviation sector is to use low-carbon sustainable aviation fuel (SAF) (Wang et al., 2016).

SAF can reduce particulates, nitrogen oxides, sulfur oxides, and critical greenhouse gases. Even more, SAF can deliver real environmental and public health benefits. Today many studies (Boichenko et al., 2020; Han et al., 2019) inform about the possibilities of commercial aircraft electrification. However, developments in this direction are still far from the near- or middle-term perspective, so it can not be considered a possible and real solution to aviation decarbonization. Similarly, there are reports (Lei & Khandelwal, 2021) on developments in the sphere of hydrogen use to power aircraft; however, they are also at the early stages of design (Cecere et al., 2014). Moreover, the use of hydrogen requires the development of new infrastructure for its transportation and storage (Petrescu et al., 2020). Still, SAFs are considered the only accessible alternative to substitute conventional JFs and contribute to the carbon-neutral development of air transport. In this regard, the International Civil Aviation Organization (ICAO) forecasts that today's aviation sector requires fast development of AAFs production facilities (Wang et al., 2016; Boichenko & Yakovlieva, 2020).

Today we observe a significant advance in the sphere of AAFs development and use (Konovalov et al., 2021). However, huge challenges remain in commercializing advanced fuel conversion processes: setting up the AAF production chain (from feedstock supply to fuel conversion), blending, and delivering new fuels, carrying out a complex of lab, bench and fly tests, certification and approval for commercial use.

The set of policy initiatives European Green Deal (Panchuk et al., 2020) aims to reach 2050 with no net emissions of greenhouse gases and achieve economic growth with efficient resource usage. Along with, the Clean Aviation trajectory has defined two aims toward climate neutrality by 2050:

1. Demonstration and introduction of low-emissions aircraft research results, acceleration of the use of SAFs and optimization of "green" operations, so that these innovations will be commercially used by airlines in 2030–2035;
2. Climate-neutral aviation, by introducing future technologies and full deployment of SAFs and alternative energy carriers until 2050.

The overall pathway to developing and introducing SAFs to the market on an industrial scale is complicated and requires a long time. Using new SAFs on commercial flights requires passing long and complicated procedures of fuel testing, certification, and approval (Iakovlieva et al., 2016, Yakovlieva et al., 2019a). All these procedures and requirements for the quality of new fuels are determined in the following specification (Zschocke et al., 2012):

1. ASTM D1655 Standard Specification for Aviation Turbine Fuels (American Society for Testing and Materials, 2011b);
2. ASTM D7566 Standard Specification for Aviation Turbine Fuel Containing Synthesized Hydrocarbons (American Society for Testing and Materials, 2011c);
3. ASTM D4054 Standard Practice for Qualification and Approval of New Aviation Turbine Fuels and Fuel Additives (American Society for Testing and Materials, 2011a).

Traditionally commercial aircraft use conventional JF of grade Jet-A1. Due to several reasons, there is a need to develop "drop-in" SAFs, which will be compatible with conventional oil-derived JFs in terms of composition, materials, and safety (Rahmes et al., 2009, Lew & Biddle, 2014; Wang et al., 2016; Geleynse et al., 2018). Thus, industry and scientists look for the development of sustainable alternative JFs, which will be produced from renewable feedstock and will be used in existing jet engines interchangeably and without a need to make changes in jet engine construction (De Klerk, 2016; Neuling & Kaltschmitt, 2018; Stephen & Periyasamy, 2018). Today, several SAFs are allowed to be mixed with conventional JFs for up to 50% (Seber et al., 2014; Pires et al., 2018; Li et al., 2010). At the same time, some AAFs are still at the stage of developing and testing. The following Table 1 provides a review of existing today technologies for SAFs production.

It may be seen from the Table 1 that some technologies are already approved by the ASTM and included in the ASTM D7566 specification. However, several other technologies are at the testing stage, and some are still being developed.

Among the comparatively new technologies of SAF production is the processing of alcohols into kerosene-type hydrocarbons, known as Alcohol-to-Jet technology (AtJ). From one side, it is considered highly complicated (at first biomass transformation into alcohols and then alcohols to JF), expensive and not mature (Yao et al., 2017). But from the other side, the properties and quality of new JFs seem to be high enough to satisfy the specification requirements. Fuel producers declare that alcohol-derived fuels can be used for conventional JF substitution (Han et al., 2019).

Today there are two technological processes, which are used for AtJ technology. They are known as *Alcohol To Jet Synthesized Paraffinic Kerosene (AtJ-SPK)* and *Synthesized Kerosene with Aromatics (AtJ-SKA)*. As we see in Table 1, ATJ-SPK fuel is already certified and approved by the ASTM for commercial use since it was included in the ASTM D7566 in 2016 (Geleynse et al., 2018). The overall idea of both AtJ-SPK and AtJ-SKA technological processes is the same. The difference between the technological processes is the aromatization stage, which will be discussed below (Wang et al., 2016; Geleyns et al., 2018). According to Achinas et al. (2021), Han et al. (2019) AtJ-SPK and AtJ-SKA fuels are of very high quality and there is a high level of feedstock availability for these fuel production (Seber et al., 2014).

Table 1. Overview of technologies of SAFs production (source: Commercial Aviation Alternative Fuels Initiative, 2022)

Technological process	Feedstock	Description of the production process	Year of the approval by ASTM	Limit for blending with JF
Fischer-Tropsch (FT) fuel	Coal, natural gas, biomass	Conversion of feedstock into synthetic gas ($CO+H_2$) with further transformation into hydrocarbons, typical to conventional JF	2009	50% (vol.)
Hydrotreated Esters and Fatty Acids (HEFA)	Oily feedstock (oils, fats, used cooking oil, fatty acids esters)	Hydrotreatment of feedstock with further break-down of large hydrocarbons into n-paraffins and iso-paraffins, typical for conventional JF	2011	50% (vol.)
Synthesized Iso-Paraffins (SIP) fuel	Sugar feedstock, cellulosic materials	Fermentation of sugars by microorganisms into farnesene with further catalytic hydrogenation and conversion into saturated farnesane	2014	10% (vol.)
Alcohol to Jet Synthesized Paraffinic Kerosene (AtJ-SPK)	Alcohols (ethanol, butanol, iso-butanol)	Dehydration of alcohols to olefins, its oligomerization, then hydrogenation of olefin to saturated hydrocarbons and distillation as conventional JF fraction	2016	50% (vol.)
Catalytic Hydrothermolysis (CH) fuel	Oily feedstock (triglycerides, fatty acids, fatty acids esters)	Conversion of feedstock into hydrocarbons: n-paraffins, iso-paraffins, cycloparaffins, and aromatics, hydrotreatment and distillation as conventional JF fraction	2020	50% (vol.)
Hydroprocessed Hydrocarbons, Esters and Fatty Acids Synthetic Paraffinic Kerosene (HHC-SPK)	Bio-derived hydrocarbons, fatty acid esters, free fatty acids	Hydrotreatment of feedstock to remove oxygen with next cracking and isomerization of hydrocarbons to receive JF components	2020	10% (vol.)
Hydrodeoxygenated Synthesized Kerosene (HDO-SK)	Sugar products: cellulosic materials, commercial sugars	Hydrodeoxygenation of feedstock into intermediate products, dehydration, oligomerization, and hydrogenation into hydrocarbons. Hydrotreatment and distillation as conventional JF fraction	Under testing	–
Hydroprocessed Depolymerized Cellulosic Jet (HDCJ) fuel	Lignocellulosic biomass (lignin, cellulose, hemicellulose)	Depolymerization of biomass, then hydroprocessement of smaller molecules, transformation into hydrocarbons, and distillation as conventional JF fraction	Under testing	–
Synthesized Kerosene with Aromatics (AtJ-SKA)	Alcohols (ethanol, butanol, iso-butanol)	Dehydration of alcohols to olefins, its oligomerization, then hydrogenation of olefin to saturated hydrocarbons, aromatization and distillation as conventional JF fraction	Under testing	–

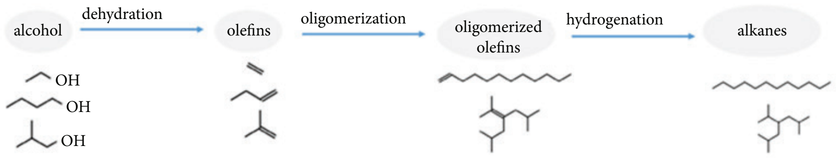

Figure 1. The main stages of the AtJ technological process (Geleynse et al., 2018)

The main stages of producing AtJ fuels from alcohols include three main stages (Figure 1) (Geleynse et al., 2018):

1. dehydration of alcohol to the corresponding olefin;
2. oligomerization of olefins to a new oligomerized olefin;
3. hydrogenation of oligomerized olefin to saturated hydrocarbon product.

These chemical processes are well known and widely used in the petrochemical industry. Processes of alcohol production and alcohol processing into JF are completely independent of each other and can be organized at separate production facilities.

Usually, small alcohols with carbon atoms C2 – C4, such as ethanol and butanol (n-butanol and iso-butanol) are used for AtJ technologies. Ethanol can be obtained from sugar-containing biomass (sugar cane or corn) using microbial fermentation technologies similar to those used in beer and winemaking (Seber et al., 2014). In the case of non-edible biomass (eg lignocellulose), ethanol production is more problematic (and sometimes expensive) and requires additional pre-treatment to weaken the lignin structure surrounding the cellulose and hemicellulose polymers. These technologies are discussed in detail in studies by Silveira et al. (2018), Yamada et al. (2011). Butanol and isobutanol are also used for the AtJ process and are usually produced by fermentation with modified microorganisms (Fu et al., 2021; Lakshmi et al., 2021).

Today companies-producers of AtJ fuel usually specialize in a certain type of alcohol (Achinas et al., 2021; Geleynse et al., 2018). Company Gevo uses isobutanol fermentation, while company LanzaTech specializes in the fermentation of gas feedstock, including steel mill fuel gas streams and gasified materials. Other companies including Butamax and Cobalt Technologies use renewable butanol. The company Byogy has adapted to existed sugarcane ethanol industry in Brazil (Van Dyk & Saddler, 2021).

The AtJ-SPK process involves only the processing of alcohols into hydrocarbons (Gnansounou & Dauriat, 2010). Production of alcohol is an independent process and is not included in the procedure of fuel certification. However, the source of feedstock and its accessibility may be crucial in terms of fuel sustainability (Seber et al., 2014). The overall scheme of the AtJ-SPK production route is shown in Figure 2.

To convert alcohols to jet fuel, they are first dehydrated to a suitable alkene product containing the same number of carbon atoms. This process takes place with the help of various heterogeneous catalysts: zeolites, silicoaluminumphosphates, acids, aluminium etc (Geleynse et al., 2018). As a result of the dehydration the water is formed and it is separated from the process by a combination of distillation, liquid-liquid separation and molecular sieves. At the next stage of the process alkenes and short-chain olefins are oligomerized into unsaturated compounds with higher molecular weight approximately compatible with petroleum JF. Oligomerization is realized over various heterogenic or homogenous catalysts. Feedstock and reaction conditions may influence the carbon length distribution in products. Certain catalysts may cause isomerization and cracking during oligomerization and create some amount of cyclic olefins, or even aromatics (Han et al., 2019). At the next stage, hydrogen gas is fed into the process and olefins are hydrogenated over solid catalysts to normal, iso-, and cyclic paraffin. In the final stage, the received hydrocarbons are distilled to obtain the final products, among which is the kerosene fraction (Bann et al., 2017).

AtJ-SPK is of high quality, however, it has some disadvantages, which limit its use in blends with

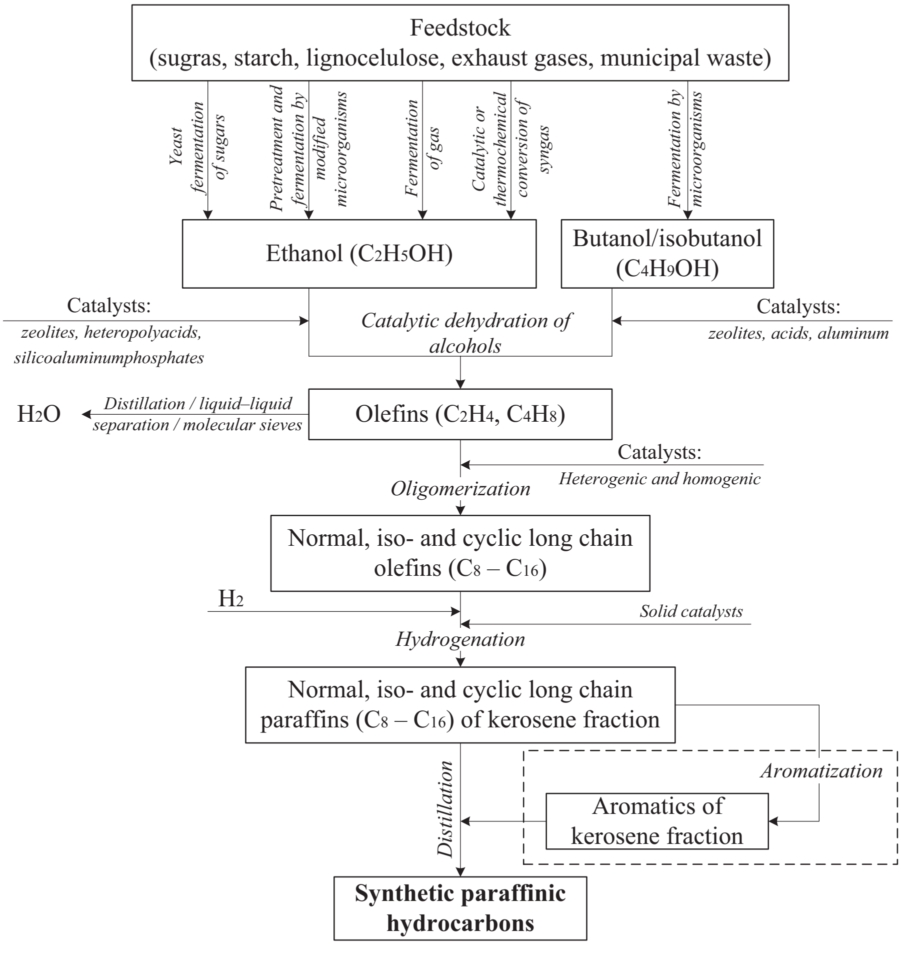

Figure 2. The overall scheme of the AtJ fuel production process (source: author development)

conventional JF. This kind of SAF doesn't contain aromatic hydrocarbons. This leads to a lowering of fuel density (sometimes below the limit) and a change in fractional composition. Despite the high content of aromatics in JF being undesirable (Van Dyk & Saddler, 2021), still, its absence is not allowed. The absence of aromatics in the fuels causes the shrinking of the seal, which can cause seal failures, thus damaging the system. The minimum content of aromatics is suggested to be about 8% (vol.) (Anuar et al., 2021).

Taking into account these issues, they start developing the AtJ-SKA technology (Han et al., 2019). The principle difference between AtJ-SKA and AtJ-SPK is the certain content of aromatic hydrocarbons in the composition of the fuel. The technological process of AtJ-SKA manufacturing is the same as the technological process of AtJ-SPK, except for the presence of an additional stage of hydrocarbon aromatization (this stage is highlighted in Figure 2). Depending on the technological capabilities of the fuel manufacturing enterprise, the production of aromatic substances can be performed as an integrated flow in the overall production process (Seber et al., 2014). The content of aromatics in the final product may be regulated according to the required amount.

The AtJ-SKA technology is at an early stage of commercialization: it is realized by companies Byogy and Swedish Biofuels, but production volumes are still extremely limited (Geleynse et al., 2018). Now AtJ-SKA technology passes the stage of testing under the ASTM D4054. According to some reports, AtJ-SKA fuel possesses better compatibility with construction materials, and it may improve the quality of emissions (reduce sulfur and particulate matter emissions). Still, more advanced research should be done to estimate AtJ-SKA fuel composition and properties, and its influence on aircraft operation and emissions (Van Dyk & Saddler, 2021). Therefore, researches aimed at development of AtJ-SKA technology and capacity-building for its production seem to be relevant.

Taking into account the abovementioned, the *aim* of this work is to study the physical-chemical properties of AtJ-SKA fuel compared to AtJ-SPK fuel and access the possibility to use it as a drop-in JF.

To reach the aim the following *tasks* have to be fulfilled:

1. To fulfil experimental study of physical-chemical properties of conventional JF of grade Jet A-1, AtJ-SKA fuel and AtJ-SPK fuel;
2. To study experimentally the influence of AtJ-SKA fuel and AtJ-SPK fuel on physical-chemical properties of conventional JF and analyze it in relation to requirements of standard specifications;
3. To access the possibility of using AtJ-SKA fuel as drop-in JF.

1. Methods and materials of the study

During the study, both theoretical end experimental methods of research were applied. Within the framework of the work samples of blended AAFs with different content of AtJ components were studied experimentally.

Fuel samples were produced at the oil processing plant JSC "Ukrtatnafta" in Kremenchuk city, Ukraine. Conventional JF of grade Jet A-1 is produced from crude oil on an industrial scale, both AtJ fuels are produced from ethyl alcohol and are now at the stage of research production.

A sampling of fuel and components was done using an automatic bottle dispenser. Fuel samples were prepared by simple mechanical blending and stored in closed borosilicate glass bottles at room temperature without access to light. The volume of each fuel sample was 1000 ml. Quality parameters of conventional JF, AtJ-SPK component, AtJ-SKA component and blends of JF with each of the components were studied according to standard research methods. The description of the studied fuel samples is given in Table 2.

Selected physical-chemical and exploitation properties of AAF samples were studied by the following parameters: density at temperature 15 °C, viscosity at temperature –20 °C, freezing point, flash point, and fractional

Table 2. Description of studied fuel samples (source: author development)

Designation	Description of the fuel sample
JF	Conventional oil-derived JF
AtJ-SPK	Synthesized paraffinic kerosene component produced from alcohol
AtJ-SPK 25	Blend of conventional JF that contains SPK component in quantity 25% (vol.)
AtJ-SPK 50	Blend of conventional JF that contains SPK component in quantity 50% (vol.)
AtJ-SPK 70	Blend of conventional JF that contains SPK component in quantity 70% (vol.)
AtJ-SPK 90	Blend of conventional JF contains SPK component in quantity 90% (vol.)
AtJ-SKA	Synthesized kerosene with aromatics component produced from alcohol
AtJ-SKA 25	Blend of conventional JF that contains SKA component in quantity 25% (vol.)
AtJ-SKA 50	Blend of conventional JF that contains SKA component in quantity 50% (vol.)
AtJ-SKA 70	Blend of conventional JF that contains SKA component in quantity 70% (vol.)
AtJ-SKA 90	Blend of conventional JF that contains SKA component in quantity 90% (vol.)

composition. These properties were studied according to standard test methods:

1. The *density* was measured by electronic densimeter at a temperature of 15 °C according to ASTM D4052 Test Method for Density, Relative Density, and API Gravity of Liquids by Digital Density Meter (American Society for Testing and Materials, 2015a);
2. The *kinematic viscosity* was measured by automatic viscometer at temperature –20 °C according to ASTM D445 Standard Test Method for Kinematic Viscosity of Transparent and Opaque Liquids (and Calculation of Dynamic Viscosity) (American Society for Testing and Materials, 2015b);
3. The *freezing point* was measured by the automatic device according to the standard method GOST 5066-2018 (ISO 3013-74) Motor fuels. Methods for measuring could point and freezing point (Governmental Standard, 2018);
4. The *flash point* was measured by the automatic device according to ASTM D93 Test Methods for Flash Point by Pensky-Martens Closed Cup Tester (American Society for Testing and Materials, 2016);
5. The *fractional composition* was measured by the automatic device according to ASTM D86 Test Method for Distillation of Petroleum Products at Atmospheric Pressure (American Society for Testing and Materials, 2015a).

Experimental studies were fulfilled at the Testing Interactive Laboratory "Aviatest" of the Ukrainian scientific-research and educational center of chemmotology and certification of fuels, lubricants and technical liquids, National aviation university. Data about hydrocarbon composition of fuel samples were provided by the producer.

Measurements of each of the parameters was done for three time for each sample. To estimate the accuracy of the measurements and received results the statistical error analysis of data was done.

The arithmetic mean value $\overline{x}$ of data received was calculated as:

$$\overline{x} = \frac{1}{N}\sum x_i , \qquad (1)$$

where N – number of measurements; x_i – measured value.

Standard deviation *S* was calculated as the square root of the variance:

$$S = \sqrt{\frac{\sum (x_i - \overline{x})^2}{N-1}} . \qquad (2)$$

Standard error $S_{\overline{x}}$ was calculated as:

$$S_{\overline{x}} = \frac{S}{\sqrt{N}} . \qquad (3)$$

Variance Var_x was calculated as:

$$Var_x = \frac{1}{N-1}\sum (x_i - \overline{x})^2 . \qquad (4)$$

Relative deviation S_r, % of determination of the degree of influence of AtJ components on fuel properties was calculated as:

$$S_r = \frac{S}{\overline{x}_{\max} - \overline{x}_{\min}} \cdot 100 , \qquad (5)$$

where $\overline{x}_{\max}$ – maximal average value of the studied fuel property; $\overline{x}_{\min}$ – minimal average value of the studied fuel property.

2. Results of the study and discussion

It is known that properties of JFs are determined by its chemical and hydrocarbon composition. Presence and content of each group of hydrocarbons affect energy, low-temperature properties, fluidity, combustibility, chemical stability, *etc*. The data about the hydrocarbon composition of studied fuel samples are given in Table 3. It is seen that the hydrocarbon composition of fuel samples differs significantly. Conventional JF contains high amount of n-paraffins and cycloparaffins compared to AtJ-SPK and AtJ-SKA fuels. The reason for this is the natural composition of crude oil which is used for JF production. Depending on the origin of crude oil the ratio of hydrocarbons in JF may vary in some range. At the same time peculiarities of AtJ-SPK and AtJ-SKA production process result in high content of iso-paraffins and low content of n-paraffins and cycloparaffins. Such distribution of hydrocarbons will result in differences in the physical-chemical properties of AtJ fuels and affect the properties of blended JF. Some content of olefins in conventional JF is explained by its crude oil origin. And presence of olefins in AtJ fuels may be explained by the incompleteness of its conversion into paraffins during the production process.

As it was described in the previous section, procedures of qualification and certification of new SAFs start from lab test, which include studying both physical-chemical and operation parameters. According to Yakovlieva et al. (2019a), Kulik et al. (2015) physical-chemical properties of JFs are considered basic; they stipulate the fuel's operation properties and allow to make a general estimation of the fuel's quality. Among these properties, the density, fractional composition, kinematic viscosity, aromatics, heat of combustion, freezing point, and flash point were studied.

Table 3. Hydrocarbon composition of studied fuel samples (source: author development)

Fuel sample	n-paraffins, %	iso-paraffins, %	cycloparaffins, %	aromatics, %	olefins, %
JF	12.4	37.8	34.3	13.9	1.6
AtJ-SPK	3.9	93.7	1.8	<0.01	0.6
AtJ-SKA	1.7	79.8	2.4	15.7	0.4

Table 4. Comparative characteristics of studied fuel samples and standard requirements (source: author development)

Fuel property	Unit of measurement	ASTM D7655	ASTM D1655	JF	AtJ-SPK	AtJ-SKA
Density at temperature 15 °C	kg/m^3	775–840	775–840	795	757	786
Fractional composition:	°C					
initial boiling point, max		registered	registered	155.6	174.6	164.8
10% distilled at temperature, max		205	205	169.8	178	174.8
50% distilled at temperature		registered	registered	195.1	180.9	186.7
90% distilled at temperature		registered	registered	238.9	220.1	205.6
Final boiling point, max		300	300	258.5	249.8	249.6
Kinematic viscosity at temperature –20 °C, max	mm^2/s	8,0	8.0	3.8	4.8	3.4
*Aromatics, max	% (vol.)	25	25	13.9	<0.01	15.7
*Neat heat of combustion, min	MJ/kg	42.8	42.8	43.32	43.85	43.68
Freezing point, max	°C	–47	–47	–49	–80	–80
Flash point, min	°C	38	38	44	47.5	48.5

Note: *values of the parameters were taken from the manufacturer's technical documents for the fuel.

At the first step of the research, these properties were studied for the pure conventional JF Jet A-1, AtJ-SPK component, and AtJ-SKA components produced from ethyl alcohol. The obtained results were compared to the requirements of standard specifications ASTM D7655 and ASTM D1655 and are presented in Table 4.

From the results in Table 4, it is seen that the tested sample of conventional JF completely meets the standard requirements; all the values of the parameters are not marginal. At the same time, some properties of AtJ components slightly differ. Extremely low freezing points of both AtJ components may be observed. Low freezing point may positively affect blended JFs in terms of improvement of low-temperature properties. Except that, the density of the AtJ-SPK component is lower than minimal standard requirements Therefore, density values may limit the maximal content of AtJ-SPK component in JF blends. Both AtJ-SPK and AtJ-SKA components have slightly higher neat heat of combustion that will positively affect energy properties of blended JFs. Lower value of heat of combustion of AtJ-SKA may be explained by the presence of aromatic compounds (Table 3), which are typically characterized by lower heat of combustion compared to respective paraffins. Consequently, the next step of the research was to study the properties of blended fuel samples and analyse the influence of components on the properties of aviation fuels.

From Yakovlieva et al. (2019a) it is known that *density* is one of the most important properties that have a direct effect on the combustibility of the JFs, and their specific consumption during the flight. It also plays an important role in the evaluation of fuel's energy characteristics, i.e., energy content and heat of combustion. Figure 3 presents the results of the study of AtJ components' influence on the density of blended JF samples. It is seen that the AtJ-SPK component has a significantly lower density (757 kg/m^3) compared to the conventional JF (795 kg/m^3). Low density of AtJ-SPK component may be explained by the absence of aromatics (that is proved by the data in Table 3). Moreover, the technological process of AtJ-SPK production is organized in such a way to eliminate the formation of long chain hydrocarbons with high molecular weight. From the graph in Figure 3 it is seen that rising the content of AtJ-SPK in JF leads to a gradual decrease in the density of fuel blends.

A similar tendency is observed for fuel blends with AtJ-SKA component. Taking into account that value of AtJ-SKA density is similar (786 kg/m^3) to conventional JF the reduction of the density of fuel blends is not so intense as for AtJ-SPK components. The horizontal line in the graph in Figure 3 shows the minimal requirement of specifications for JF density. All fuel blends with AtJ-SKA components completely meet standard requirements. And the content of AtJ-SPK component is limited to 50% (vol.)

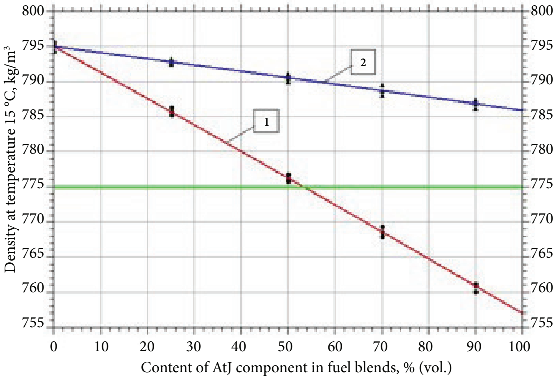

Figure 3. Dependence of the density of JF blends on the content of AtJ components produced from alcohols: 1 – AtJ-SPK component, 2 – AtJ-SKA component

Table 5. Fractional composition of JF blends with AtJ-SPK and AtJ-SKA components (source: author development)

	JF	AtJ-SPK 25	AtJ- SKA 25	AtJ-SPK 50	AtJ- SKA 50	AtJ-SPK 70	AtJ-SKA 70	AtJ-SPK 90	AtJ-SKA 90	AtJ-SPK	AtJ-SKA
Initial boiling point	155.6	158.2	156.4	162.6	159.1	166.3	160.4	171.7	163.3	174.6	164.8
10% distilled at temperature	169.8	172.5	170.8	173.4	172.1	173.8	173.2	177.2	174.5	178.0	174.8
50% distilled at temperature	195.1	189.8	191.8	186.2	189.7	183.8	188.4	181.7	186.9	180.9	186.7
90% distilled at temperature	238.9	236.5	234.2	234.8	226.7	232.7	218.8	225.8	210.4	220.1	205.6
Final boiling point	258.5	254.6	256.7	252.3	256.2	249.5	255.6	248.2	254.9	249.8	249.6

Fuel's *fractional composition* is considered a parameter that characterizes and influences the combustibility of the JF. It directly characterizes evaporation, mixture formation, the degree of combustion of the fuel, its specific consumption, the absence of smoke, and carbonization in the combustion chamber (Yakovlieva et al., 2019a). Having analyzed data in Table 3 it may be seen that the distribution of boiling points of both components slightly differs compared to conventional JF. Thus, in the next step the influence of components on the fractional composition of blended JFs was studied (Table 5).

As is seen from the Table 5, the fractional composition of AtJ-SPK component is more narrow (174.6–249.8 °C), compared to the fractional composition of conventional JF (155.6–258.5 °C). It has a slightly higher initial boiling point and a lower final boiling point. Both values are completely within the requirements of the specification. AtJ-SKA component containing aromatics has similar to AtJ-SPK factional composition, however, it is characterized by lower initial boiling point (164.8–249.6 °C).

Analyzing the data presented in Table 5 it may be concluded that blending the AtJ-SPK component with conventional JF leads to slight raise in the initial boiling point of fuel and decreased content of light fractions. This may affect the startability of the jet engines. Blending AtJ-SKA provides less rise in initial boiling points of JF blends. In general, the distribution of fractions is closer to conventional JF. Overall fractional composition of blended JFs with both AtJ-SPK and AtJ-SKA components satisfies standard requirements of specifications.

JFs' viscosity causes an impact on the fuel fluidity and permeability in the aircraft fueling system – it determines the injection and spraying of fuel in the combustion chamber. Viscosity influences fuel filters and nozzles' efficiency at low temperatures, mainly the degree of fuel spraying and droplets diameter. Increased viscosity causes a worsening of fuel atomization and thus vaporability and completeness of combustion (Yakovlieva et al., 2019a). At the same time, the viscosity influences the lubricity and anti-wear properties of JFs (Yakovlieva et al., 2019a). Low viscosity can negatively affect the lubricity of JF. In the next step of the research, the influence of alcohol-derived components on the viscosity of blended was assessed (Figure 4).

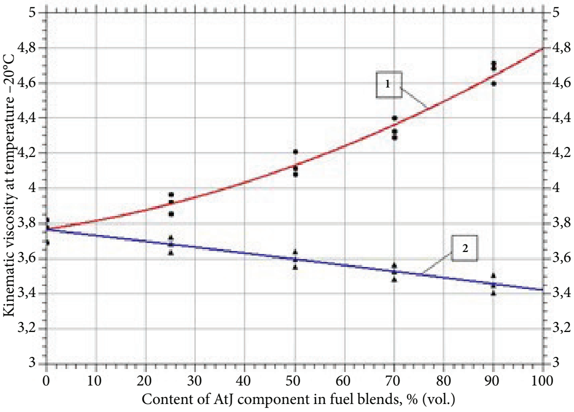

Figure 4. Dependence of the viscosity of JF blends on the content of AtJ components produced from alcohols:
1 – AtJ-SPK component, 2 – AtJ-SKA component

AtJ-SPK component possesses higher viscosity compared to conventional JF (4.8 mm^2/s and 3.8 mm^2/s respectively). This may be explained by the chemical structure of the component, which is composed mostly of isoparaffins. Adding AtJ-SPK biocomponent to the JF leads to some rising in viscosity. The viscosity value of the AtJ-SKA component is very similar to the viscosity of conventional JF (3.4 mm^2/s and 3.8 mm^2/s respectively). Thus, blending JF with AtJ-SKA component results in a slight reduction of viscosity of fuel blends change and satisfies overall fuels' viscosity characteristics. In general, the viscosity values of all the fuel blends with both AtJ-SPK and AtJ-SKA components are within the allowed limits and satisfy the requirements of specifications (max 8.0 mm^2/s).

Such parameter as *freezing point* allows estimating low-temperature properties of JFs, mainly fluidity at low temperatures during high-altitude flights of sub-sonic aircraft. This parameter is considered one of the most important for estimating the quality of modern conventional and alternative JFs for civil aviation. Thus, next, the influence of two kinds of AtJ components on the freezing point of blended JFs was evaluated. As is seen from the graph in Figure 5 both components AtJ-SPK and AtJ-SKA are characterized by extremely low freezing points (–80 °C). Such values may be explained by the chemical composition of components.

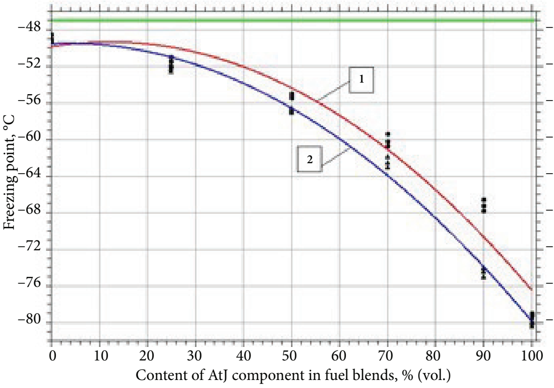

Figure 5. Dependence of the freezing point of JF blends on the content of AtJ components produced from alcohols: 1 – AtJ-SPK component, 2 – AtJ-SKA component

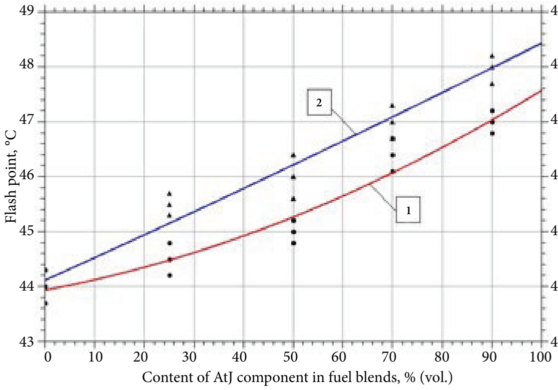

Figure 6. Dependence of the flash point of JF blends on the content of AtJ components produced from alcohols: 1 – AtJ-SPK component, 2 – AtJ-SKA component

Both AtJ-SPK and AtJ-SKA have a high content of iso-paraffins in AtJ components (Table 3). Moreover, the process of AtJ components production eliminates the synthesis of long-chain straight paraffins, which have a high freezing point. It is seen from the graph that blending JFs with components provides a significant decrease in the freezing point of the blended JFs (maximal value of freezing point allowed by specification is shown with a horizontal line). It may be concluded that both AtJ components improve the low-temperature properties of blended JFs.

Jet fuels' *flash point* is one of the most important parameters that characterize its fire safety during various technological processes, such as aircraft fuelling, refuelling from fuel tanks to trucks, *etc*. Standard specifications to conventional and alternative JFs determine a minimally acceptable flash point, which should be not less than 38 °C. The influence of both components AtJ-SPK and AtJ-SKA on flash points of blended JFs was studied (Figure 6).

It is seen from the graphs that AtJ-SPK and AtJ-SKA components have higher flash points compared to the conventional JF (47.5 °C, 48.5 °C and 44 °C respectively). It is possible to conclude that blending JFs with components leads to the increase of fuel flash points and thus to the improvement of fire safety.

The accuracy of the experimental measurements and received results was estimated by fulfilling the statistical error analysis of the received data. Mathematical data processing and statistical error analysis allow concluding about the sufficient accuracy of measurements and sufficient reliability the effect of blending AtJ-SPK and AtJ-SKA components with JF on its physical-chemical properties.

Conclusions

Within the study, the hydrocarbon composition and physical-chemical properties of conventional JF, AtJ-SPK and AtJ-SKA fuels were studied. JF is composed mostly of iso- and cycloparaffins (~38% and 34% correspondingly) with lower content of n-paraffins (~12%) and aromatics (~14%). AtJ-SPK fuel is composed almost completely of iso-paraffins (~94%) which results in differences in its physical-chemical properties. The density of AtJ-SPK fuel is significantly lower than JF and doesn't satisfy the requirements of the specification. At the same due to the additional stage of aromatization during the production process, AtJ-SKA fuel contains fewer iso-paraffins (~80%) and some amount of aromatics (~16%). This makes the composition of AtJ-SKA fuel more similar to conventional JF, the same as its physical-chemical properties.

The influence of AtJ-SPK and AtJ-SKA components on the physical-chemical properties of blended JFs was studied. It was found that the AtJ-SPK component leads to a significant decrease in the density of blended JF. Taking into account the requirements of specifications the AtJ-SPK component may be blended in quantity not more than 50% (vol.). Blending the AtJ-SPK component with JF leads to some change in fractional composition, mainly to the raise of the initial boiling point of blended fuel and decreased content of light fractions. Adding this component to JF also leads to the rise of kinematic viscosity, but the values are within the required limits. However, AtJ-SPK component provides the decrease of freezing point and increase of flash point, which positively affect low-temperature and safety properties of blended JFs. At the same time, the content of AtJ-SPK in JFs blends is also limited by the content of aromatics – at least a minimum recommended value (about 8%) should be maintained.

Taking into account that the properties of the AtJ-SKA component are more similar to conventional JF, the change of properties of blended JFs is not so intense as for the AtJ-SPK component. AtJ-SKA fuel causes a minimal change in the density of blended JFs. A slight reduction of kinematic viscosity is observed. Blending AtJ-SKA provides fewer changes in fractional composition compared to AtJ-SPK and the distillation profile of blended JF is closer to conventional JF. And similarly to AtJ-SPK, AtJ-SKA component positively influences on low-temperature and safety properties of blended JFs.

In general, it may be concluded that the physical-chemical properties of JFs blended with AtJ-SKA component are very close to conventional JFs. All of the studied fuel samples containing AtJ-SKA component completely satisfy the requirements of specifications. Basing on the received results it is expected that AtJ-SKA component may be successfully used for blending with conventional JF and the maximal limit of AtJ-SKA fuel in blends may be increased compared to AtJ-SPK component. At the same time, further researches are required to study the influence of AtJ-SKA fuel on the operation and environmental properties of blended JFs.

Therefore, the results of this study create the basis for further research aimed at the development and implementation of AAFs containing AtJ components. The next stages of the research will be devoted to studies of the operation of blended JFs, fulfilment of bench tests on model jet engines, and assessment of its emission characteristics.

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Disclosure statement

The authors do not have any competing financial, professional, or personal interests from other parties.

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Appendix

Statistical error analysis of the experimental results

Analysis of statistical errors of experimental studies of the density of blended JFs is given in Table A1. It shows that the maximum values of standard deviations and standard errors do not exceed the units of measurement in the range of the studied parameter. The standard deviation of density measurement is in the range of 0.5–0.65 for fuel blends with AtJ-SPK component and 0.45–0.75 for fuel blends with AtJ-SKA component. The relative deviation of the determination of the degree of influence of AtJ-SPK component on JF density is in the range of 1.3–1.7%, and the relative deviation of the determination of the degree of influence of AtJ-SKA component is 4.9–8.2%. Therefore, the deviations allow us to estimate with sufficient reliability the effect of blending AtJ-SPK and AtJ-SKA components with JF on its density.

Analysis of statistical errors of experimental studies of kinematic viscosity of blended JFs is presented in the Table A2. It is seen that the maximum values of standard deviations and standard errors do not exceed the units of measurement in the range of the studied parameter. The standard deviation of kinematic viscosity measurement is in the range of 0.55–0.657 for fuel blends with AtJ-SPK component and 0.042–0.064 for fuel blends with AtJ-SKA component. The relative deviation of the determination of the degree of influence of AtJ-SPK component on JF viscosity is in the range of 5.3–6.6%, and the relative deviation of the determination of the degree of influence of AtJ-SKA component is 13.9–21.2%. Therefore, the deviations allow us to estimate with sufficient reliability the effect of blending AtJ-SPK and AtJ-SKA components with JF on its density.

Analysis of statistical errors of experimental studies of the freezing point of blended JFs is presented in the Table A3. It is seen that the maximum values of standard deviations and standard errors do not exceed the units of measurement in the range of studied parameter. The standard deviation of the freezing point measurement is in the range of 0.25–0.66 for fuel blends with AtJ-SPK component and 0.25–0.6 for fuel blends with AtJ-SKA component. The relative deviation of the determination of the degree of influence of AtJ-SPK component on the JF freezing point is in the range of 0.8–2.15%, and the relative deviation of the determination of the degree of influence of AtJ-SKA component is 0.8–1.94%. Therefore, the deviations allow us to estimate with sufficient reliability of the effect of blending AtJ-SPK and AtJ-SKA components with JF on its freezing point.

Analysis of statistical errors of experimental studies of the flash point of blended JFs is given in the Table A4. It shows that the maximum values of standard deviations and standard errors do not exceed the units of measurement in the range of the studied parameter.

Table A1. Statistical error analysis of density measurements (source: author development)

Fuel sample	N	$\bar{x}$	S	$S_{\bar{x}}$	Var$_x$	S_r, %
JF	3	794.967	0.651	0.376	0.423	1.718
AtJ-SPK 25	3	785.767	0.551	0.318	0.303	1.453
AtJ-SPK 50	3	776.267	0.503	0.291	0.253	1.321
AtJ-SPK 70	3	768.633	0.651	0.376	0.423	1.718
AtJ-SPK 90	3	760.733	0.569	0.328	0.323	1.479
AtJ-SPK	3	757.133	0.651	0.376	0.423	1.718
AtJ-SKA 25	3	792.767	0.451	0.26	0.203	4.945
AtJ-SKA 50	3	790.6	0.458	0.265	0.21	5.055
AtJ-SKA 70	3	788.733	0.751	0.433	0.563	8.242
AtJ-SKA 90	3	786.8	0.6	0.346	0.36	6.593
AtJ-SKA	3	785.867	0.451	0.26	0.203	4.945

Table A2. Statistical error analysis of kinematic viscosity measurements (source: author development)

Fuel sample	N	$\bar{x}$	S	$S_{\bar{x}}$	Var$_x$	S_r, %
JF	3	3.765	0.064	0.037	0.00416	6.066
AtJ-SPK 25	3	3.916	0.056	0.033	0.00318	5.501
AtJ-SPK 50	3	4.135	0.067	0.0388	0.00453	6.582
AtJ-SPK 70	3	4.34	0.055	0.0316	0.00299	5.305
AtJ-SPK 90	3	4.665	0.0613	0.0354	0.00376	5.992
AtJ-SPK	3	4.784	0.0618	0.0357	0.00382	6.0903
AtJ-SKA 25	3	3.765	0.0645	0.0372	0.00416	21.192
AtJ-SKA 50	3	3.682	0.0431	0.0249	0.00186	14.238
AtJ-SKA 70	3	3.599	0.043	0.0248	0.00185	14.238
AtJ-SKA 90	3	3.524	0.042	0.0243	0.00177	13.907
AtJ-SKA	3	3.454	0.0507	0.0293	0.00257	16.556

Table A3. Statistical error analysis of the freezing point measurements (source: author development)

Fuel sample	N	$\overline{x}$	S	$S_{\overline{x}}$	Var_x	S_r, %
JF	3	–48.9	0.361	0.208	0.13	1.18
AtJ-SPK 25	3	–51.5	0.5	0.289	0.25	1.639
AtJ-SPK 50	3	–55.267	0.252	0.145	0.063	0.823
AtJ-SPK 70	3	–60.1	0.656	0.379	0.43	2.148
AtJ-SPK 90	3	–67.2	0.6	0.346	0.36	1.967
AtJ-SPK	3	–79.4	0.529	0.306	0.28	1.734
AtJ-SKA 25	3	–52.167	0.351	0.203	0.123	1.13
AtJ-SKA 50	3	–56.767	0.252	0.145	0.063	0.808
AtJ-SKA 70	3	–62.433	0.603	0.348	0.363	1.938
AtJ-SKA 90	3	–74.467	0.503	0.291	0.253	1.619
AtJ-SKA	3	–79.967	0.451	0.260	0.203	1.448

Table A4. Statistical error analysis of the flash point measurements (source: author development)

Fuel sample	N	$\overline{x}$	S	$S_{\overline{x}}$	Var_x	S_r, %
JF	3	44	0.3	0.173	0.09	8.571
AtJ-SPK 25	3	44.5	0.3	0.173	0.09	5.714
AtJ-SPK 50	3	45	0.2	0.115	0.04	5.714
AtJ-SPK 70	3	46.4	0.3	0.173	0.09	8.571
AtJ-SPK 90	3	47	0.2	0.115	0.04	5.714
AtJ-SPK	3	47.5	0.3	0.173	0.09	8.571
AtJ-SKA 25	3	45.5	0.2	0.115	0.04	4.444
AtJ-SKA 50	3	46	0.4	0.231	0.16	8.889
AtJ-SKA 70	3	47	0.3	0.173	0.09	6.667
AtJ-SKA 90	3	47.967	0.252	0.145	0.063	5.556
AtJ-SKA	3	48.5	0.1	0.058	0.01	2.222

The standard deviation of the flash point measurement is in the range of 0.2–0.3 for fuel blends with the AtJ-SPK component and 0.1–0.4 for fuel blends with the AtJ-SKA component. The relative deviation of the determination of the degree of influence of the AtJ-SPK component on the JF flash point is in the range of 5.7–8.57 %, and the relative deviation of the determination of the degree of influence of the AtJ-SKA component is 2.2–8.9%. Therefore, the deviations allow us to estimate with sufficient reliability the effect of blending AtJ-SPK and AtJ-SKA components with JF on its flash point.