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EXPLORING THE POSSIBILITIES OF USING BIO-ADDITIVES IN MILITARY AVIATION FUELS

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Abstract. Analyzing the research directions of leading aviation companies, it is evident that biocomponents will soon become a very important addition to the fuel used in turbine aircraft engines. Similarly, intensive efforts are underway to implement this type of solution in the armed forces. Here, the situation is more complex. All military fuels are intended for long-term storage, and bio-additives significantly alter the properties of fuels during this specific storage process. These changes invariably result in the deterioration of fuel quality parameters. The article presents an analysis and conclusions related to biocomponents as additives to F-35 fuel (NATO code-the military equivalent of Jet A-1 fuel). F-35 aviation fuel mixtures with the addition of biocomponents (HVO-Hydrorefined Vegetable Oil) at concentrations of 0–20% (V/V) were independently composed and stored for extended periods (0–6 months). The disadvantages and potential problems of this solution are discussed. The research has demonstrated that using biocomponents in the mixtures significantly alters the course of the distillation curve and increases the fuel's electrical conductivity. Another adverse effect observed was a significant deterioration in the fuel's low-temperature properties. The research indicates that using a bio-additive like HVO in F-35 fuel will require addressing many challenges. At the level of laboratory tests, it is to determine the limit value of the share of a biocomponent in a mixture at which the normative values are not yet violated and to confirm or rule out whether the mixtures are suitable for long-term storage.

Keywords: F-35 fuel, HVO, laboratory tests, long-term storage, turbine aircraft engines, NATO, army.

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1. Introduction

Aviation is undoubtedly one of the fastest-growing industries. In recent years, there has been a dynamic development of aircraft, propulsion systems, materials and technologies used, as well as the use of fuels. The observed development of aviation fuels results primarily from increasing requirements, the main reason for which is the introduction of restrictions and regulations imposed by the European Community (Böhling, 2023; Dekanozishvili, 2023; Woerdman & Zeben, 2023; Oktay Huseynova, 2021; Gadzicka, 2019). They concern in particular ecological aspects related to excessive emission of harmful compounds contained in exhaust gases (Riebl et al., 2016; You & Wang, 2011). The trend in alternative fuels also results from the need to gradually reduce the consumption of crude oil, whose resources are running out. Aviation fuels must meet a number of requirements to be used in aircraft. In addition to being a source of energy for aircraft propulsion, they are also used as hydraulic fluids and cooling elements of fuel systems (Riebl et al., 2016; Dagaut & Gai¨l, 2007).

Therefore, the process of selecting the appropriate type of fuel for a specific type of engine and aircraft consists of a series of activities, the end result of which should be a compromise in terms of tolerances given to the engine, the fuel used and its intended use plane (Marszałek & Lis, 2022; Murtonen et al., 2009). Taking into account the complex and long process of adapting the appropriate type of fuel to an aircraft, the aviation industry currently faces a new and difficult challenge to take action to introduce new types of fuel (Wijesekara et al., 2015). Currently, the most popular alternative source of power for aircraft, which is still in the research phase, is biocomponents. The results of laboratory tests and test flights, mainly in the USA, show that the use of these fuels in the aviation industry is possible (Dagaut, 2006; Dagaut & Gai¨l, 2007). On the other hand, research results are cited that disqualify the use of biocomponents in aircraft power systems (Mawhood et al., 2016; Kandaramath et al., 2015).

In the case of fuels used in the army, an additional element that negatively affects the quality parameters of the fuels is the fact that these fuels are intended for long-term storage. During such storage, various processes occur, causing quality changes, which in turn affect the efficiency and safety of use. One of the main problems is fuel oxidation, leading to the formation of deposits and acids (Mzé-Ahmed et al., 2014; Wang & Tao, 2016). These byproducts can corrode engine and fuel system components and clog filters. Another issue is the release of water from the fuel, which at low temperatures may result in water freezing in the fuel system. Long-term storage can also lead to changes in the chemical composition of the fuel, which negatively affects its ability to burn efficiently.

In addition, various microorganisms such as bacteria and fungi can grow in the fuel, especially when water is present. This effect is further intensified when biocomponent additives are used. Microorganisms can cause accelerated corrosion and clogging of fuel systems. Additionally, some volatile fuel components may evaporate during long storage, which reduces the fuel's overall performance in terms of its ability to create fuel mixtures. To reduce the described problems, it is crucial to regularly monitor the fuel condition and use appropriate storage methods, which include controlling temperature, humidity and tightness of tanks.

2. Selected methods of producing bio-additives

Biofuels, derived from renewable biological sources, are categorized into primary and processed types. Primary biofuels are unaltered, natural biomass used directly for heating and energy, such as firewood. Processed biofuels, on the other hand, are created by applying various technologies to biomass. The processed category encompasses three generations. The first generation includes fuels made through alcoholic fermentation and esterification, utilizing food-based raw materials like vegetable oils, potatoes, grains, and sugar beets (No, 2014). These biofuels typically contain oxygenated compounds like ethyl alcohol, FAME, and ethers derived from biomethanol and bioethanol. Second-generation biofuels are more advanced, including (Olšovský & Hocko, 2011; Van Gerpen & He, 2014):

- Bioethanol produced from lignocellulosic materials;
- Synthetic fuels generated from synthesis gas, a product of biomass gasification – this category includes liquid hydrocarbons from Biomass to Liquids (BtL) processes, dimethyl ether (DME), biomethanol, Synthetic Natural Gas (SNG), and biohydrogen (You & Wang, 2011);
- Hydrocarbon fuels produced through hydroconversion, such as bio-oil from hydro-pyrolysis of waste lignocellulose, and vegetable oils and animal fats in the HVO process.

FAME parameters are similar to diesel oil, so they can be used as biofuel. They are produced in the transesterification reaction of higher fatty acids with low molecular weight alkyl alcohols, most often in the presence of a catalyst. Many different sources of triacylglycerols, such as vegetable oils, animal fats, and algal oils, can be used for transesterification. In industrial conditions, esters alkyl fatty acids are formed by the transesterification reaction of vegetable oils using alcohol (methanol or ethanol) in a homogeneous alkaline or acid catalyst (Mawhood et al., 2016). Conventional heating is also used. This method is characterized by a long separation time of the glycerin phase from the ester phase. Additionally, it is characterized by a high process cost, which results from the technology of heating the substrates during the reaction. Additionally, although these catalysts are cheap and relatively active, their use may hurt the environment. Replacing conventional chemical methods of obtaining biodiesel with more environmentally friendly processes is one of the main trends in scientific research on biodiesel production (Gollakota et al., 2021; Kandaramath et al., 2015).

Biohydrocarbons are much more helpful for use as biocomponents of aviation fuels. These types of biocomponents can be obtained using various technologies. These technologies remain at an experimental level, and some of them have already been implemented on a pilot industrial scale. The most advanced technologies include:

- HVO (Hydrorefined Vegetable Oil);
- BtL (Biomass to Liquid).

Of these, only HVO technology is implemented on an industrial scale. This technology has become competitive with FAME. Hydrotreated Vegetable Oil is a form of synthetic, alternative, renewable fuel for compression-ignition engines, made from vegetable fats and oils. It is obtained by hydrocracking or hydrogenation of vegetable oil (Aatola et al., 2008). Hydrocracking breaks large molecules into smaller ones using hydrogen (Dimitriadis et al., 2008) while hydrogenation adds hydrogen to the molecules (Kuronen et al., 2007). These methods can be used to create substitutes for gasoline, diesel oil, propane, kerosene and other chemical raw materials. In the production of HVO, hydrogen is the substrate of the process, whereas, similarly, in the production of FAME biodiesel, methanol is used; the catalyst for both processes is KOH. Thanks to this, HVO is characterized by much greater chemical stability compared to typical biofuels (Qiao et al., 2016).

In turn, the technology of second-generation synthetic biocomponents Biomass to Liquid (BtL) allows the use of almost all plant materials (Mueller-Langer & Jungbluth, 2013; Mzé-Ahmed et al., 2014). These technologies are based on biomass gasification. Raw materials that can be used include wood, energy plants and organic waste. Details regarding the production technology of biofuels/bio-additives and the division according to the type of generation they belong to, are presented in Figure 1.

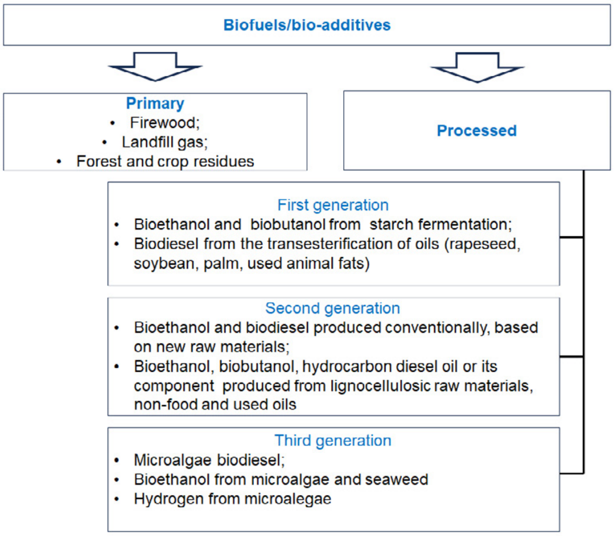

Figure 1. Division of biofuels/bio-additives (own study based on Böhling, 2023)

3. Research methodology

The laboratory samples tested included pure F-35 fuel, pure biocomponent (HVO), and fuel mixtures containing 2%, 5%, 10%, and 20% (V/V) of the biocomponent. These model mixtures were prepared in 5-liter glass vessels and securely sealed with tight stoppers for storage. The preparation was conducted under conditions designed to minimize evaporation losses (ambient temperature of 10 °C), thereby eliminating the possibility of changes in density and potential alterations in the distillation curve due to the evaporation of the lightest fractions. In the initial phase, a comprehensive set of tests (including normal distillation) was performed on the pure components (F-35 and HVO) to determine their selected physicochemical parameters, which directly influence the engine's storage and combustion process. This testing followed the research methodology outlined in Table 1.

In the subsequent step, mixtures were prepared, and their fractional composition was analyzed to assess the impact of the biocomponent on the distillation curve profiles. These tests were conducted in triplicate at three different intervals: immediately after the mixtures were prepared, then after three months of storage, and finally after six months of storage. Throughout the storage period, the containers were placed on a shelf in a brick building, where they were subject to normal temperature fluctuations associated with the changing seasons and external weather conditions, as detailed in Figure 2.

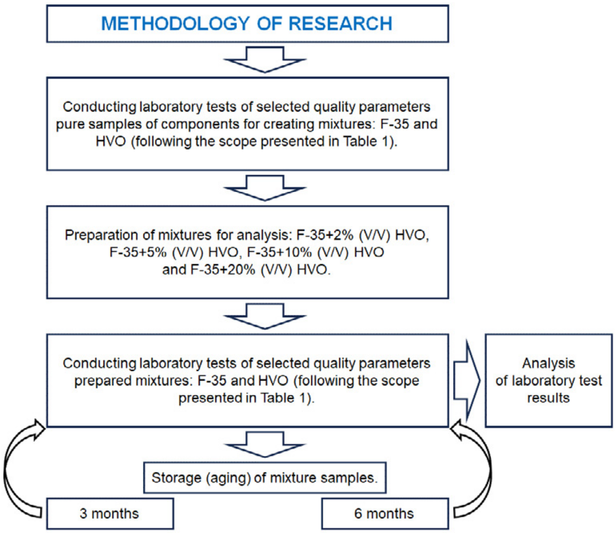

Figure 2. Methodology of research

Table 1. The scope of laboratory tests, along with the normative documents according to which the tests were conducted (source: based on STANAG-3747)

No.	Tested parameter	Test method
1.	Fractional distillation	IP 123/ASTM D86. Standard Test Method for Distillation of Petroleum Products at Atmospheric Pressure.
2.	Density	IP 365/ASTM D4052. Standard Test Method for Density, Relative Density, and API Gravity of Liquids by Digital Density Meter.
3.	Flash point	ASTM D56. Standard Test Method for Flash Point by Tag Closed Cup Tester.
4.	Electrical conductivity	IP 274/ASTM D2624. Standard Test Methods for Electrical Conductivity of Aviation and Distillate Fuels.
5.	Smoke point	IP 598/ASTM D1322. Standard Test Method for Smoke Point of Kerosene and Aviation Turbine Fuel.
6.	Freezing point	IP 16/ASTM D2386. Standard Test Method for Freezing Point of Aviation Fuels.
7.	Oxidation stability	ASTM D7545-13. Standard Test Method for Oxidation Stability of Middle Distillate Fuels – Rapid Small Scale Oxidation Test (RSSOT).

4. Results

The research conducted by the authors was a three-stage study-tests of quality parameters were performed immediately after the preparation of the mixtures and after storage periods of three and six months, according to the model presented in Figure 2.

Tables 2, 3, and 4 present the average values of the test results for the prepared mixtures and compare them with the values that the reference samples of F-35 and HVO should have, based on the standards' requirements. The values of the tested quality parameters that did not meet the standard requirements are highlighted in bold font. Measurements for each parameter were conducted at

Table 2. Values of the tested quality parameters of base components (F-35 and HVO) and mixtures immediately after their preparation-ageing time: 0 months (source: own study)

Tested Parameter	Normative requirement*	F-35 (pure)	HVO (pure)	F-35 +2% HVO	F-35 +5% HVO	F-35 +10% HVO	F-35 +20% HVO
Fractional distillation							
Initial Boiling Point	report	149	207	153	154	157	161
10% of the volume distils to the temperature [°C]	205	172	258	173	176	181	183
50% of the volume distils to the temperature [°C]	report	182	279	183	187	194	199
90% of the volume distils to the temperature [°C]	report	219	287	221	226	227	229
Final boiling point [°C]	max. 300	278	302	279	298	313	315
The distillation residue [% of volume]	max. 1.5	1.1	1.2	1.3	1.3	1.5	1.5
The losses [% of volume]	max. 1.5	0.8	0.6	0.9	0.9	0.8	0.9
Density [kg/cm^3]	min. 775–840	792	781	790	789	787	785
Flash point [°C]	min. 38	42.1	77	45.2	46.1	51.2	55.2
Electrical conductivity [pS/m]	50–600	103	101	113	134	148	156
Smoke point [mm]	min. 25	25.1	33	26.3	26.9	29.4	31.3
Freezing point [°C]	max. –47	–55	–41	–53	–53	–47	–46
Oxidation stability [min].	–	1720	1465	1681	1667	1582	1533

Note: *According to ASTM D1655-08 Specification for Aviation Turbine Fuels (ASTM International, n.d.-h).

Table 3. Values of the tested quality parameters of the base ingredients (F-35 and HVO) and mixtures during storage-ageing time: 3 months (source: own study)

Tested Parameter	Normative requirement*	F-35 (pure)	HVO (pure)	F-35 +2% HVO	F-35 +5% HVO	F-35 +10% HVO	F-35 +20% HVO
Fractional distillation							
Initial Boiling Point	report	151	208	153	156	163	171
10% of the volume distils to the temperature [°C]	205	178	261	178	181	188	191
50% of the volume distils to the temperature [°C]	report	182	281	185	189	197	201
90% of the volume distils to the temperature [°C]	report	222	287	225	233	257	262
Final boiling point [°C]	max. 300	281	305	282	301	313	315
The distillation residue [% of volume]	max. 1.5	1.2	1.2	1.2	1.3	1.6	1.8
The losses [% of volume]	max. 1.5	0.8	0.6	0.9	0.9	1.1	1.3
Density [kg/cm^3]	min. 775–840	792	781	790	789	787	785
Flash point [°C]	min. 38	42.5	77	45.1	46.4	51.2	56.2
Electrical conductivity [pS/m]	50–600	106	104	121	136	155	189
Smoke point [mm]	min. 25	26.4	33	27.1	27.9	33.4	34.3
Freezing point [°C]	max. –47	–52	–40	–52	–51	–45	–43
Oxidation stability [min].	–	1687	1401	1633	1604	1571	1522

Table 4. Values of the tested quality parameters of the base ingredients (F-35 and HVO) and mixtures during storage-ageing time: 6 months (source: own study)

Tested Parameter	Normative requirement*	F-35 (pure)	HVO (pure)	F-35 +2% HVO	F-35 +5% HVO	F-35 +10% HVO	F-35 +20% HVO
Fractional distillation							
Initial Boiling Point	report	151	208	153	156	163	171
10% of the volume distils to the temperature [°C]	205	189	277	189	191	193	195
50% of the volume distils to the temperature [°C]	report	182	281	185	197	197	201
90% of the volume distils to the temperature [°C]	report	222	287	225	233	257	262
Final boiling point [°C]	max. 300	285	311	295	306	317	322
The distillation residue [% of volume]	max. 1.5	1.3	1.7	1.3	1.5	1.7	1.8
The losses [% of volume]	max. 1.5	0.8	0.6	0.9	0.9	1.1	1.3
Density [kg/cm^3]	min. 775–840	796	833	798	799	801	808
Flash point [°C]	min. 38	42.5	79.1	46.1	47.3	52.2	57.7
Electrical conductivity [pS/m]	50–600	155	122	158	163	267	313
Smoke point [mm]	min. 25	26.4	33	27.1	27.9	33.4	34.3
Freezing point [°C]	max. –47	–49	–38	–49	–47	–41	–41
Oxidation stability [min].	–	1687	1401	1633	1604	1571	1522

least three times, after which a statistical test for critical errors was performed. These errors were discarded, and the obtained values were averaged. By comparing the results between the fuel samples, normative guidelines regarding the measurement of reproducibility ranges and uncertainty values were obtained.

From the analysis of the data contained in Tables 2, 3, and 4, it is evident that mixing F-35 with HVO has a significant impact on three quality parameters: the profile of normal distillation curves compared to pure F-35, the freezing point, and the electrical conductivity. In the case of normal distillation, attention should be paid to two characteristic points: the temperature at which 10% of the mixture's volume has distilled (Figure 3) and the final boiling point (Figure 4). Figure 4 shows that even small additions of HVO cause a fairly significant increase in the tested parameter towards the limit value. Additionally, this effect is amplified during the storage process and quickly approaches the normative value of 205 °C. It should be assumed that in the case of a subsequent test (another 3 months of aging), the normative limit value would be exceeded. This phenomenon has a similar mechanism to the contamination of gasoline with diesel fuel (Ryczyński & Smal, 2017; Ryczyński, 2015).

A slightly different situation can be observed when analyzing Figure 4 – the final boiling point temperature. In this case, the normative values were exceeded during the study conducted immediately after preparing the test mixtures. All values exceeding the norm are marked in red on the figure. In the first test, such an effect was observed for mixtures with 10% and 20% HVO content. It can be concluded that aging processes occurring during storage

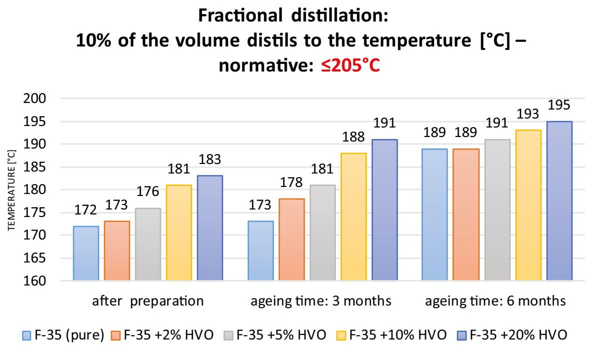

Figure 3. The influence of the HVO bio-additive content and the length of ageing time on the course of the distillation curve at the point of distilling 10% of the volume

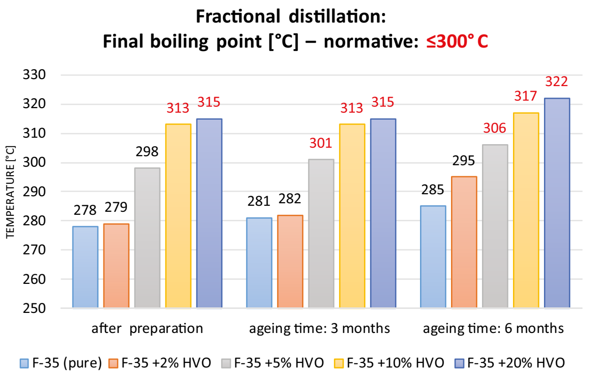

Figure 4. The influence of the HVO bio-additive content and the length of ageing time on the distillation curve: temperature of the end of distillation

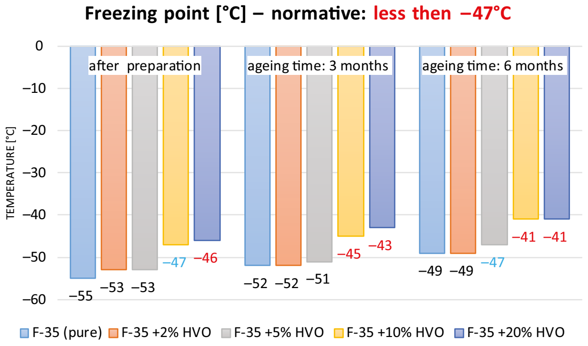

Figure 5. The influence of the HVO bio-additive content and the length of ageing time on the freezing temperature value

contribute to the intensification of this phenomenon. In subsequent tests, the normative value was also exceeded for the mixture with 5% HVO content.

The analysis of the data presented in Figure 5 indicates a very strong influence of HVO on the low-temperature properties of the test mixtures. Any HVO content exceeding 5% by volume disqualifies such a mixture as a fully qualified fuel. Similar to Figure 4, all freezing point temperatures exceeding the norm are marked in red. A detailed discussion of the results obtained and a comprehensive interpretation that considers the mechanisms occurring in the test mixtures are presented in Chapter 5.

5. Discussion and interpretation of the results obtained

F-35 is a specialized aviation fuel for jet and turbine engines. It has a low freezing point, crucial to maintaining fuel fluidity in extremely low temperatures at high altitudes. Its ignition point is relatively high, which increases safety compared to aviation gasoline by minimizing the risk of accidental ignition. F-35 also has a high smoke point, translating into clean combustion and a lower tendency to create engine carbon deposits. It is less viscous than other types of aviation fuels, making it easier to pump and filter in various conditions. It has a specific boiling range, which ensures combustion efficiency over a wide temperature range. It is chemically stable, allowing long-term storage without significant loss of quality. A characteristic feature of this fuel is its high hygroscopicity, so storing it in appropriate conditions is essential to avoid contamination.

All the described features show why the research team chose these specific quality parameters for analysis. The selected parameters are the most critical quality parameters-they directly affect the fuel properties related to combustion in the engine and indicate limitations related to the fuel storage process.

Therefore, it is important to precisely explain what characterizes a given parameter and the mechanisms associated with it. This is important because research has shown that mixing F-35 fuel with HVO disturbs the balance, leading to deviations from the normative values. This was evident when determining three characteristic temperatures during normal distillation (initial and final boiling points, temperature at which 10% of the fuel's volume has been distilled), freezing point and electrical conductivity. Although the electrical conductivity standards were not directly exceeded, a small addition of HVO resulted in a relatively rapid increase in this parameter.

The temperature at which 10% of the fuel's volume has been distilled, alongside the initial boiling point (IBP), is the most important indicator providing information about the composition and properties of the fuel. Reaching the temperature at which 10% of the fuel volume has evaporated offers insight into the content of the lightest hydrocarbon fractions. Meanwhile, the IBP is the temperature at which the fuel transitions from a liquid to a gaseous state, marking the onset of the distillation process. These parameters are particularly important because they inform us about the volatility of the initial fractions of the fuel. In the case of the F-35, low values of these parameters indicate a high content of light hydrocarbon fractions, which are essential for creating an efficient air-fuel mixture necessary for ignition in jet engines, thereby facilitating efficient engine starting. The IBP and the temperature at which 10% of the fuel's volume is distilled are key indicators used to characterize the overall composition of the fuel and its performance characteristics, such as storage stability. In practice, fuels with lower values of these temperatures are preferred because they strike an optimal balance between ease of ignition and minimizing the risk associated with excessive volatility.

The Final Boiling Point (FBP), in the case of F-35 aviation fuel, is the indicator that determines the highest temperature at which the last part of the fuel ceases to be in a liquid state and ultimately transitions to a gaseous state. In the case of F-35, the FBP usually falls within the range of about 250 to 300 degrees Celsius, which is considered an optimal range, ensuring a balance between low-temperature fluidity and limiting the risk associated with excessive vaporization. This is crucial information as it indicates the upper limit of the temperature range in which fuel components vaporize. This directly impacts various aspects of fuel usage, including performance, safety, and storage. A high-value FBP in fuel may suggest the presence of heavier hydrocarbon fractions, which affect properties such as the viscosity and density of the fuel. These heavier components are essential for maintaining fuel stability, especially under extreme conditions, such as the very low temperatures encountered at high altitudes in aviation. At the same time, fuel with a suitably high FBP remains liquid and does not vaporize too quickly, which is crucial for safe and efficient combustion in jet engines. On the other hand, fuel with too low an FBP may be more prone to vapour formation at higher temperatures, which can pose a risk, especially during storage and transport.

Among the quality parameters directly related to the conducted distillation, an important aspect is the impact of HVO on the increased value of the so-called distillation residue. The amount of distillation residue provides key information about the heavier components of the fuel. These components have a higher boiling point and are difficult to evaporate. The mechanism underlying this phenomenon involves the molecular structure of these hydrocarbons. Heavier hydrocarbons have longer carbon chains or more complex structures, which require the delivery of higher energy (in the form of heat) to break the intermolecular forces, keeping them in a liquid state. As a result, they remain as a residue after the lighter components have evaporated. The amount of distillation residue is an essential factor for several reasons. Heavier hydrocarbons do not burn as efficiently and cleanly as lighter ones (with shorter chains), which can lead to more residues or deposits in the engine. Finally, a large amount of distillation residue can affect the flow properties of the fuel, especially at lower temperatures, potentially leading to problems in transport and transmission systems (pipelines).

Understanding the freezing mechanism of aviation fuel (Freezing Point) requires an analysis of this process's chemical and physical aspects. The F-35 fuel is a mixture of various hydrocarbon groups, each with its specific freezing temperature. As the fuel temperature lowers, those components with higher freezing temperatures (paraffinic hydrocarbons) begin to crystallize first. In the freezing process, the hydrocarbon molecules in the fuel start organizing into regular crystalline structures. This is a result of the decrease in kinetic energy of the molecules, which limits their movement and leads to the formation of ordered arrangements. Under normal conditions, these molecules are in constant motion, keeping the fuel liquid. However, as the temperature drops, their mobility decreases, ultimately leading to a transition to a solid state and loss of fuel fluidity. Hydrocarbons with longer carbon chains and higher molecular weight usually freeze earlier, which can lead to problems such as clogging of fuel lines. Moreover, the complex chemical composition of F-35 fuel means that the freezing process does not occur simultaneously for the entire fuel volume but spreads gradually, starting from the heaviest fractions. An additional catalyst for these processes, accelerating the freezing, can be the presence of contaminants, such as water or adding another component (HVO in the conducted studies), in the fuel, which can lower its freezing temperature. Contaminant molecules serve as nucleation points for the crystallizing hydrocarbons, accelerating the entire process.

Another quality parameter that changes under the influence of using the HVO bio-additive and during the storage process of prepared mixtures is the electrical conductivity of the fuel. The mechanism of forming electrical charges in fuel is closely related to the manipulative activities carried out in the storage and distribution process. During operations such as pumping through pipelines, filters, and pumps and moving in tankers and aircraft tanks, static electrical charges are generated in the fuel. These charges tend to cluster together, forming electric fields. As the fuel moves, the charge density and the energy of the electric field increase. Under certain conditions, when the removal of charges from the liquid is difficult or impossible, the energy of the electric fields can excessively increase. There is then a danger of electrostatic discharge in the form of a spark, which can ignite flammable fuel vapours with sufficiently high discharge energy. The formation of electrostatic charge during transport is a multi-parameter process and difficult to quantify. The magnitude of the electric charge is often the result of many simultaneous phenomena. The generated electrostatic charges tend to separate into positive and negative and then re-cluster together violently. This process is catalyzed by polar bodies contained in the fuel, such as surfactants, which can be adsorbed on the inner walls of distribution system elements and on the surfaces of separate fuel phases (e.g., water). The conductivity of the fuel is very low in the case of very high purity of the fuel – there, the phenomenon of electrification practically does not occur. This state is difficult to achieve and maintain, as every fuel contains particles of a separate phase in an amount causing its electrification. A way to lower the electrical conductivity of F-35 fuel is to dose it with an antistatic additive. This is the only known way to discharge electrostatic charges in aviation fuel in the air (without contact with the ground). The function of the additive is to increase the specific electrical conductivity of the fuel, facilitating the removal of the charge from its entire volume. Such additives are surfactants with an ambivalent structure, containing both a hydrophilic and a hydrophobic part.

Normative documents in the armed forces regarding the quality of fuels for turbine aircraft engines require maintaining electrical conductivity in the range of 50–500 pS/m. The electrical conductivity of the fuel greater than 50 pS/m ensures proper discharge of charges from the fuel. However, a value above 600 pS/m may disrupt the operation of onboard devices containing semiconductor elements.

Additionally, information obtained as a result of the conducted research is the fact that overdosing on the antistatic additive can rapidly increase the rate of water separation in the fuel.

For a comprehensive analysis, it is essential to emphasize the positive impact of HVO on the flash and smoke points. Both of these parameters are critical in assessing the safety and usability of aviation fuels.

The flash point of a fuel is the lowest temperature at which it can evaporate to form an ignitable mixture with air. A higher flash point means a lower risk of accidental ignition. The smoke point measures a fuel's tendency to produce smoke during combustion. This parameter is directly related to the quality of fuel combustion. A higher smoke point indicates cleaner combustion and the emission of fewer solid particles. This is significant for aircraft engines. Fuel with a high smoke point ensures cleaner combustion, reduces engine wear by limiting the formation of carbon deposits, and minimizes environmental pollution. The smoke point can also indirectly indicate the aromatic content in the fuel; fuels with a higher content of aromatic hydrocarbons typically have a lower smoke point.

Oxidation stability was the last quality parameter tested for F-35 fuel and its mixtures. This parameter refers to the fuel's ability to resist oxidation and degradation processes over time. Oxidation stability affects the "life expectancy" and reliability of the fuel during storage and use. When fuel is exposed to oxygen, especially at the high temperatures typical of the operating environment of jet engines, chemical reactions can occur leading to the formation of deposits and acids. These degradation products can clog fuel filters, damage engine components and reduce overall engine performance. The excellent oxidation properties of F-35 fuel ensure that it remains stable and maintains its properties for a long time, minimizing the risk of harmful contaminants and ensuring the safe and efficient operation of engines. The research observed no drastic changes in the oxidation stability of fresh and aged mixtures.

6. Conclusions

A comprehensive analysis of the impact of hydroprocessed vegetable oil on F-35 aviation fuel reveals several key observations and implications. Firstly, adding HVO significantly changes the key quality parameters of F-35 fuel, particularly affecting the profile of normal distillation curves, freezing point, and electrical conductivity. These changes indicate a fundamental alteration in the fuel properties caused by the presence of HVO. In terms of distillation characteristics, the presence of HVO affects the initial and final boiling temperatures and the temperature at which 10% of the fuel volume has been distilled. This change suggests an increased concentration of heavier hydrocarbon fractions in the fuel, potentially impacting parameters such as volatility and combustion efficiency. These changes could be crucial as they directly affect the fuel's behaviour in the engine and the engine's performance and overall efficiency. The studies have shown significant concerns regarding changes in the fuel's low-temperature properties. With HVO content exceeding 5% by volume, the fuel's freezing temperature significantly decreases. This change practically disqualifies the tested mixtures as fully qualified aviation fuel. Lower freezing temperatures can lead to operational problems, such as clogging of fuel line filters, especially at high altitudes with exceptionally low temperatures.

Another critical finding is increased electrical conductivity after adding HVO, even in small amounts. This change is particularly important from a safety perspective, as it affects the fuel's ability to dissipate electrostatic charges. Increased electrical conductivity could potentially increase the risk of ignition.

The increased distillation residue observed after adding HVO indicates a higher concentration of heavier hydrocarbons in the fuel. This could lead to more residues or deposits in the engine and affect the fuel flow properties, especially at lower temperatures.

A positive aspect is that the study showed that HVO benefits the flash and smoke point temperatures. A higher flash point reduces the risk of accidental ignition, improving safety. At the same time, a higher smoke point means cleaner combustion and less emission, which is beneficial for engine durability and environmental emissions.

Mixing bio-components such as HVO with aviation fuels offers certain benefits but also introduces significant changes in the critical properties of the fuel. These changes require a thorough assessment of the suitability of such fuel mixtures for aviation purposes. For a more detailed analysis, a series of operational tests would be required at a facility equipped with an engine, including endoscopic engine tests and assessment of components after prolonged contact with the tested mixtures.

Based solely on the results of laboratory tests of selected quality parameters, the suitability of the HVO bio-additive as a component of mixtures with F-35 fuel is ambiguous. In the case of small amounts of bio-additive at 2–5% V/V, no adverse effect on the values of normative parameters was found. In the case of the HVO bio-additive content of 10 and 20% V/V, increased values of the boiling point and solidification point were recorded. Particularly disturbing may be reaching the limit values of parameters related to the low-temperature properties of fuels, which directly affect flight safety. Therefore, the most severe challenge at the level of laboratory tests is to precisely determine the permissible value of the share of the biocomponent in the mixture to maintain the normative values of low-temperature parameters-tests carried out indicate the range of 5–15% V/V.

The data presented in the article concerns laboratory tests. The authors are conducting experimental research on mixtures on a test stand equipped with a PZL-10W engine. The first results obtained are auspicious. They indicate a significant improvement in parameters affecting the emission of harmful substances into the atmosphere. The biocomponent used to create the mixtures (20% V/V) reduces the emission of harmful nitrogen oxides (by 25%) despite a slight increase in fuel consumption (not exceeding 5%). The temperature of exhaust gases has also decreased significantly – in the case of an addition of 20% V/V, it is a drop of 55 °C. To more precisely determine the suitability of the biocomponent for turbine aircraft engines, the bench research program was expanded to include emission tests: carbon dioxide (CO_2), carbon monoxide (CO) and large-ring hydrocarbon groups (which have carcinogenic solid properties).

Author contributions

Jacek RYCZYŃSKI and Laurynas ŠIŠOVAS conceived the study and were responsible for the design and development of the data analysis. Artur KIERZKOWSKI and Tomasz KISIEL were responsible for data collection. Laurynas ŠIŠOVAS was responsible for the analysis. Jacek RYCZYŃSKI wrote the manuscript of the paper.

Disclosure statement

The authors declare that they have no conflict of interest.

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