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Biodiesel from Recycled Sunflower and Palm Oil—A Sustainable Fuel for Microturbo-Engines Used in Airside Applications

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Abstract: An experimental assessment of burning behavior of some aviation fuel and biodiesel obtained from waste oil mixture has been performed within this paper. The biodiesel was obtained from sunflower and palm waste oil (SFP) and the mixtures consisted of 10, 30 and 50% biodiesel in regular aviation fuel. The aviation fuel is a mixture of Jet A fuel + 5% Aeroshell 500 oil (called Ke) with the oil being added for turbo-engine's lubrication. So, the used fuels were: Ke, Ke + 10% SFP, Ke + 30% SFP, Ke + 50% SFP. In first step, SFP was characterized in terms of: density, kinematic viscosity, flash and freezing points and calorific power. Also a deeper analysis was made by using FTIR for all the fuels involved in the experiments. The second step consisted of assessing the chemical reactions that occur during the burning process. Thus starting from the known elemental analysis, the air needed for a stoichiometric reaction has been calculated for each fuel mixtures. Also the resulting CO_2 and water has been calculated from the reactions. The third step consisted of experimental testing the burning behavior of the above mentioned fuels on a micro turbo-engine. The used engine was Jet Cat P80® provided by Gunt Hamburg, Barsbüttel, Germany. The variation of: rpm vs. time, burning temperature vs. time and fuel debit vs. rpm are presented for starting and yield procedures. The tests have been conducted at 8 different working regimes of the engine. For each regime, an 1 min testing period was chose, during which burning temperature vs. rpm, fuel debit vs. rpm and thrust force vs. rpm were monitored. For maximum regime, only calculus for burning, thermal efficiencies and specific consumption have been made. As a main conclusion, the engine working behavior was steady throughout the entire range of rpm and for all the blends fed, thus the studied fuel blends may be considered as sustainable fuel for applications that are using micro turbo-engines with main advantages related to pollution and raw materials allowing the production of this type of fuel.

Keywords: biodiesel; aviation; recycle; sunflower plus palm oil; fuel; sustainability

Citation: Cican, G.; Crunteanu, D.E.; Mirea, R.; Ceatra, L.C.; Leventiu, C. Biodiesel from Recycled Sunflower and Palm Oil—A Sustainable Fuel for Microturbo-Engines Used in Airside Applications. *Sustainability* **2023**, *15*, 2079. https://doi.org/10.3390/su15032079

Academic Editors: T. Hikmet Karakoç, Selcuk Ekici, Ozgur Balli and Alper Dalkiran

Received: 29 November 2022
Revised: 11 January 2023
Accepted: 16 January 2023
Published: 21 January 2023

1. Introduction

21st century is dealing with some extraordinary challenges: increased energy demands and consumption, decreased fuel reserves and climate changes. The latest report on fossil fuels contribution to the global energy consumed in 2021 is declaring this: 29%—crude oil, 27%—coal, 24%—natural gas. So, 80% of consumed energy was assured by means of fossil fuels. On the other hand, from the total of 20% ensured by renewable sources (RES), 10% was biomass [1]. It is well known [2] that the main reason for air quality drop is the use of fossil fuels with its correlated side effects: O_3 layer depletion, global warming and gaseous pollution.

The use of energy obtained from RES may be a sustainable solution to the above mentioned environmental issues since, the very definition of RES means that they can regenerate during or after use unlike fossil fuels. RES can be classified as: biomass, wind, solar, hydroelectric and geothermal and one of the main advantages of using RES is that they do not add pollution while using them [3].

A feasible solution for the use of fossil fuels is the biodiesel. It can represent a competitive alternative for power and consumption demands since it emits fewer gaseous pollutants, it does not affect O_3 layer and is feasible to be used in many types of engines without or slightly modifying them [4,5]. Also biodiesel shows low toxicity, less gaseous emissions and it is biodegradable [6,7].

Some of the main reasons for using biodiesel are as follows:

- Fossil fuel depletion

Need for decreasing greenhouse gasses (GHG) effect since GHG largely comprising H_2O vapours, CO_2, CH_4, NO_x, O_3, CFCs, HCFCs are known to increase the global yearly temperatures means. Moreover, it has been established that human activity has contributed to a 40% increase of CO_2 since 1750 to 2022 [8].

Air pollution by gaseous emission such as SO_x, NO_x and PM, mainly due to the internal combustion engines [9] and the burning within them of fossil fuels. Thus, vegetable oils obtained from biomass may be a sustainable alternative for biodiesel production since as [10,11] are showing biofuels are environmentally friendly and show a great potential of GHG decrease. Also PM emissions from engines that a running on biofuels are estimated to decrease with 30%.

Efforts are being made in the direction of mitigating the negative environmental impact of using fossil fuels both by replacing them partly and/or totally with biofuels and also towards electrification. And, electric vehicles seem to be the better alternative for land transportation (public transport, personal vehicles, etc.), but for heavy transportation (e.g., naval, land, and air) the weight factor–energy density per unit weight plays a crucial role. Therefore, for this kind of heavy transport, biodiesel is needed since it complies with the demands in a similar matter as fossil fuels do [12].

There are 4 so called biofuel generations and they can be briefly described as follows [13]: 1st generation is referring to the biofuels obtained directly from oil rich biomass resources that can also be consumed by humans and/or livestock. Biodiesel, methanol and biogas are the main three fuels obtained directly from oil rich biomass [14]. Biodiesel is produced from the oils extracted from seeds and/or plants such as: soy, corn, sugarcane, etc. The main issue here is the "conflict" fuel vs. food, so the researches turned towards 2nd generation of fuels mainly biodiesel and bioethanol obtained from low cost biomass in order to not interfere with biomass mainly used for food production. So lignocellulosic biomass waste such wood wastes, grass, municipal residues stepped into researcher's attention as feasible raw materials for biofuels production [15,16]. They fulfill the main imposed condition non-edible and non-feedstock. One of the main challenges brought by 2nd generation of biofuels is the advanced technology for biomass-to-fuel conversion.

3rd generation of biofuels are involving microbes and advanced microbial growth in order to obtain large quantities of cellulose and lipids suitable to be transformed in fuels [15]. Algae are the ideal solution since they sow some advantages: rapid growth rate, low environmental impact, high lipids production [17]. Moreover, the main product of algae can be transformed in a wide range of biofuels such as methanol, biodiesel, gasoline, ethanol, aviation fuels, etc. [18].

The increased needs for fuels have turned researcher's attention towards hybrid RES, namely photosynthetic microorganisms able to produce photo-biological solar fuels a combination of photovoltaics and electro biofuels or tailored production of synthetic fine [19].

According to [20], between 2020 and 2021, about 206,410 tons of vegetable oil were processed in the world. Vegetal oils can be used for cooking or as raw material for fuel production. They are extracted from different oil rich plants such as: palm, canola, sunflower seeds, soybean, etc. In particular, palm oil is specific to tropical areas and is obtained from fresh palm fruits being an excellent oil used in food industry. It is estimated that 90% of produced palm oil is used in this industry. Sunflower seed oil consumption amounted to over 18 million metric tons worldwide and palm oil over 73 million metric tons worldwide [21].

Having in mind the above mentioned aspects, it is clearly difficult to estimate the real quantity of waste cooking oils (WCO) obtained after the use of sunflower and palm oil in food industry. According to [22], roughly 3.95 million liters of WCO are annually recovered by EU (representing all 28 countries). Moreover, China, USA, India and Japan are contributing to this quantity by 5.6 mil, 1.2 mil, 1.1 mil and 0.57 mil liters [23]. A concerning aspect is that Brazil is producing almost 9 mil liters of WCO but only a quarter is reused [24].

Due to its increasing role in fuel production industry, WCO is nowadays the subject of large projects focused on WCO collection, recycling and reusing WCO as raw material for biofuels production. It is to be mentioned projects as Olly, Recoil, Ekogras, Ecobus, Oilprodiesel, etc. [25].

It is well known that the use of WCO for producing biofuels has a series of advantages: environmental (lower GHG), social (increased quality of life), cheap, can be used locally, etc. Moreover, by using the WCO, the improper use and return to human population is prevented, as well as decreases the costs for sewage maintenance due to improper discard [26].

Transesterification is the most used way to transform WCO into biodiesel and the end product is high quality. The transesterification reaction has mainly two end products: fatty acid alkyl esters and glycerol as described in [27,28]. Of course, the reaction can and it is improved by using catalysts and/or other specific reaction conditions in order to increase the production and to maximize the yield [29].

Each vegetable oil is affected by the conditions in which it was used (cooking conditions), therefore the quality of the biofuel obtained may differ. In this aspect, the literature is scarce in studies regarding the influences of cooking conditions on the obtained biodiesel [30].

The biodiesel produced by WCO can be used in internal combustion engines as many research studies highlights. In [31] the performance, combustion, and emission characteristics of a single cylinder diesel engine fueled with ternary blends of diesel were evaluated.

Advanced researches were carried out in terms of different mixture used as fuels for diesel engines. An important one, ref. [32] is dealing with the use of ethanol as additive for biodiesel based blends. The biodiesel was obtained from sunflower and palm WCO and the main focus is on engine's performances. Also [33] is dealing with high-end mixtures between biodiesel obtained from WCO and Hydrogen and is studying the engine's behavior during ignition period.

Also, there are several studies regarding the use of bio-fuels in turbine engines and aviation application engines. Boeing had studied the use of biodiesel on its planes: Boeing 787, Boeing 737–800, Boeing 747–400, Bombardier Q400, Airbus had tested also on A321, and Falcon 20. All the tests have involved blends between JetA aviation fuel and different biofuels [34–36]. An A380 Airbus flew for three hours with one engine powered entirely by biofuel made from used cooking oil and other fats in year 2022 [37].

Other studies carried out by airplane manufacturers are dealing with the gaseous emissions from burning such blends within turbo engines. [38–40]. Moreover, the use of biofuels mixtures has been studied also for industrial turbines that are also working on JetA, as shown in [40–42] which are studying the gaseous emissions of blends used in GTM + 140 turbine and DGEN380 turbofan.

Paper [43] is studying the use of biodiesel obtained from sunflower and palm WCO in aviation turbo-engines in different blends percentages with Kerosene. Ref. [44] is presenting an analysis of the possibility of using recycled pork fat-based biodiesel as fuel for aviation turbo-engines. The analysis consists of the assessment of four blends of Jet A kerosene with 10%, 30%, 50%, and 100% biodiesel. The [45] investigates the results of the Influence of Biofuel on the Operational Characteristics of Small Experimental Jet Engine. Another paper present a Study on Bio-Diesel and Jet Fuel Blending for the Production of Renewable Aviation Fuel [46] Current paper's aim is to assess the working parameters of an aviation micro turbo-engine usually used for drones and/or aero-models while fed with different blends of kerosene and biodiesel from recycled sunflower and palm oil.

2. Materials and Methods

In order to establish the sustainability of fuel blends based on biodiesel obtained from used sunflower and palm oil, several investigations were performed within this paper. Thus, blends consisting of Jet A fuel + 5% Aeroshall 500 oil (Ke), blends of Ke + 10% SFP, Ke + 30% SFP and Ke + 50% SFP were used.

The biodiesel was purchased from the market, thus the information about related to esterification reaction, resulting methyl and/or ethyl esters, catalysts used are not available for consumers.

Within this chapter, experimental assessment of physical-chemical properties of the above mentioned fuels and fuel blends will be performed. Also, functional testing will be made by feeding a micro turbo-engine with the above mentioned fuels and fuel blends.

2.1. Determination of Physical-Chemical Properties for Fuel Blends

Density-SR EN ISO 3675/2002 [47], flash point-ASTM D92 [48], kinematic viscosity-SR EN ISO 3104/2002 [49], calorific power-ASTM D240-17 [50], freezing point-SR 13552:2012 [51], FTIR and elemental analysis ASTM D 5291–16 [52] of all the fuels used in this paper were determined within the lab and are largely described within papers [43,44].

2.2. Fuel Blends Combustion

Based on physical-chemical properties experimentally determined, the elemental composition of the blends is known, therefore the minimum air quantity needed for stoichiometric combustion for each fuel blend and resulting CO_2 and water can be accurately calculated.

2.3. Micro Turb-Engine Experimental Procedure

The micro turbo engine test bench, the methods, the equipment and the testing procedure are presented.

A Jet CAT P80® turbo engine was used for performing the burning experiments and experimental display is shown in Figure 1. It consists of an axial turbine with a radial compressor and an annular combustion chamber. The intake air is sucked by the fast-rotating rotor compressor (1) (35,000–115,000 rpm) into the aluminum diffuser housing (2). Here the speed of the air is converted into pressure. At the combustion chamber (3) inlet part of the air is branched off and fed to the front face of the flame tube (4). The liquid fuel is passed from the rear into so-called evaporator tubes (5). The fuel is gasified there, and in the front part of the combustion chamber it is mixed with the primary air and combusted. The flame tube is cooled from the outside by the secondary air. It is routed to the flame tube by way of bores (6) in order to cool the very hot combustion gases (approximately 2000 °C) down to the permissible turbine inlet temperature of 600–800 °C. A glow plug (7) ignites the air/fuel mixture during starting. From the combustion chamber, the combustion gases flow into the diffuser (8) of the turbine and are accelerated before entering the axial turbine (9) and the gases discharge their energy in order to drive the rotor compressor. They are emitted into the thrust nozzle (10) at approximately 600 °C. The rotor turbine and the rotor compressor are fitted to a common shaft (11). The shaft is guided on ball bearings (12) in the bearing housing. The bearings are cooled by the compressor air and the electronics (13) for the starter motor (15), temperature monitoring, and speed measurement (14) are located under the front hood [53].

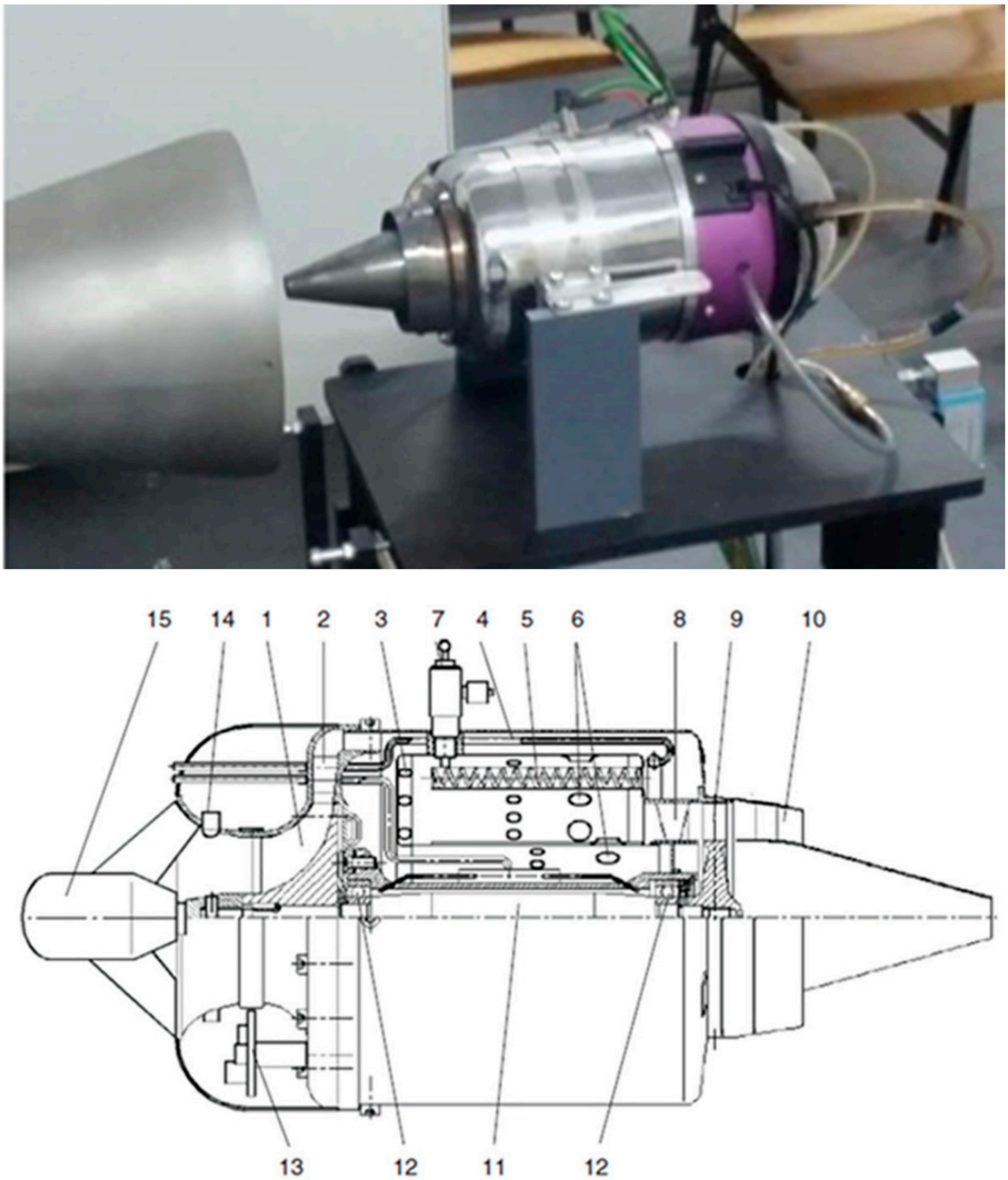

Figure 1. Test bench instrumentation.

The studied fuel blends are: Ke, Ke + 10% SFP, Ke + 30% SFP and Ke + 50% SFP.

The testing procedure comprise 8 different regimes: R1-idle at 35,000 rpm, R2 at 45,000 rom, R3-cruise at 55,000 rpm R4 at 65,000 rpm, R5 at 75,000 rpm, R6 at 87,500 rpm, R7 at 100,000 rpm and R8-maximum at 112,000 rpm (94% of the throttle gas for the safety functioning condition) and other 5 different regimes. For each fuel blends at the same regime the rpm engine was kept constant. For each regime, a testing period was 1 min and the engine parameters have been monitored: T_2 after compressor and $T_{\_comb}$ before turbine, consumption fuel flow Qc, air flow, pressure in the combustion chamber and the force F. The T_2 after compressor and $T_{\_comb}$ before turbine have been measured in a single point.

The engine is set to follow the law in which the shaft speed must be kept constant. So, in order to submit to this law, the fuel is variously injected in the burning chamber. This is necessary for one to be able to monitor parameters as: consumed fuel flow (Qc), temperature in front of the turbine ($T_{\_comb}$), and thrust (F).

3. Results and Discussion

3.1. Physical-Chemical Properties for Fuel Blends Experimental Results

Reference [54] allowed to calculate low calorific power (LCP) of the blends after experimentally determined LCP for Ke and SFP. Commercial specification of aviation turbine fule (Jet A) in accorded by ASTM D1655 are: Flesh point is 42 °C, viscosity at −20 °C is 8 cSt, density at 15 °C is 0.775 to 0.840, freezing point is −40 °C, low calorific power is 42,800 kJ/kg.

Physical-Chemical Properties for Fuel Blends experimental results is presented in Table 1.

Table 1. Physical-chemical properties of blends.

Sample	Flash Point [°C]	Kinematic Viscosity at 40 °C [cSt]	Density at 22 °C [g/cm^3]	Freezing Point [°C]	Low Calorific Power [kJ/kg]	Elemental Analysis %
Ke + 5% Aeroshell 500 Oil	42.3	1.39	0.817	<−35 °C	42,399	C: 85.17 H: 13.31 N: 0.07 O: 1.45
Ke + 10% SFP	45.6	1.75	0.832	<−35 °C	41,989	C: 84.52 H: 13.24 N: 0.07 O: 2.17
Ke + 30% SFP	53.5	2.54	0.854	−29 °C	41,169	C: 83.21 H: 13.1 N: 0.07 O: 3.62
Ke + 50% SFP	71	3.37	0.863	−23 °C	40,350	C: 81.91 H: 12.96 N: 0.07 O: 5.06

After analyzing Table 1:

- It can be observed that Flash point, Kinematic viscosity and density are increasing while biodiesel concentration is increasing too.
- Freezing point increases while the concentration of biodiesel increases, and at 100% SFP, the freezing point is −6 °C, thus making it unusable for aviation applications.
- Low calorific power decreases while biodiesel concentration increases making it a non-desirable property. As for elemental analysis, it can be observed that while the biodiesel concentration increases, carbon and hydrogen content decreases and oxygen concentration increases, leading to the conclusion that the resulting CO_2 concentration resulting from combustion process will decrease.

Figure 2 is showing the FTIR spectra for Ke, Ke + 10% SFP, Ke + 30% SFP, Ke + 50% SFP and 100% SFP.

The FTIR spectra inspected for the blends show variations at 1745.83 cm^{-1} (C=O stretching), 1030.98 cm^{-1}, 1117.54 cm^{-1}, and 1170.23 cm^{-1} (C–O alkoxyl stretching), they are visible in these blends but their intensities vary according to the concentration of the biodiesel. These peaks increase with the concentration of biodiesel present in each of the blend and this shows that the fatty acid methyl esters (FAME) is an indication of the amount of the biodiesel present in each of the biodiesel blend with kerosene since FAME exhibits its appearance at 1745.83 cm^{-1} and 1170.23–1030.98 cm^{-1}.

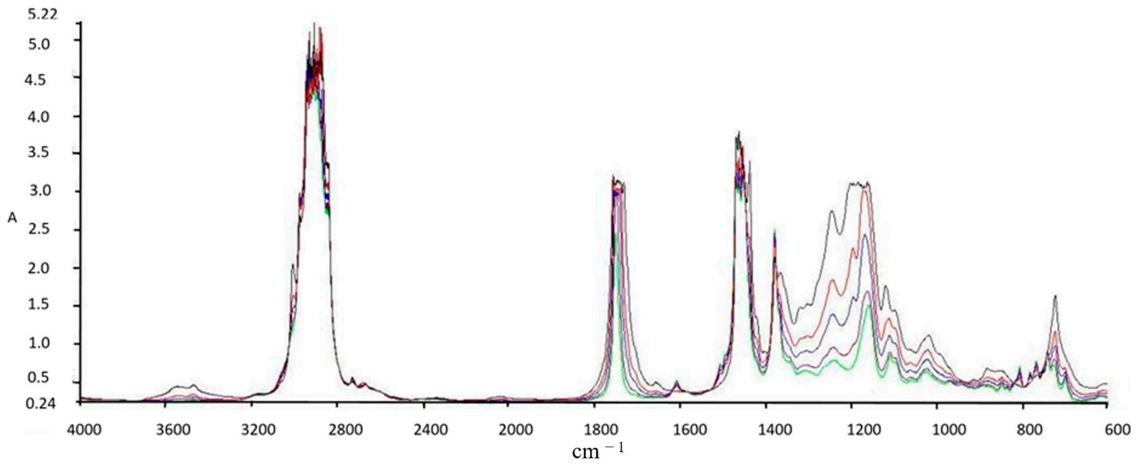

Figure 2. FTIR spectra of green-Ke, purple-Ke + 10% SFP, blue-Ke + 30% SFP, red-Ke + 50% SFP and blak-100% SFP.

Methyl esters also show their absorptions characteristics in the peak around 1820–1680 cm^{-1} which is typical for carbonyl absorption. Also discovered are variations in the intensities within the region of 678.55–721.41 cm^{-1} (=C–H bending; cis–di-substituted alkenes and aromatic). Their intensities were also found to increase with biodiesel concentration in each of the spectrum obtained [55].

3.2. Combustion Reaction Analysis

Knowing the elemental analysis of the fuel blends, the needed air quantity for stoichiometric combustion reaction has been calculated for each one of them. Thus, it is to be considered the hydrocarbon having the general formula $C_cH_hO_oN_n$ [56], and from Table 1, g_C, g_H, g_O, g_N fractions are known.

Needed oxygen quantity for stoichiometric combustion is:

$$M_o = \frac{32}{12gC} + \frac{32}{4gH} - \frac{32}{32gO} = 2.667gC + 8gH - gO \quad (1)$$

$$M_{air} = 4.35M_o \quad (2)$$

Resulting CO_2 and water from the stoichiometric combustion reaction is:

$$CO_2 = 44\frac{gC}{12} \quad (3)$$

$$H_2O = 9gH \quad (4)$$

In accord with Equations (2)–(4). In Table 2 is presented the results of the stoichiometric theoretical combustion reaction for 1 kg of fuel blend.

Table 2. Results of the stoichiometric theoretical combustion reaction for 1 kg of fuel blend.

Blend	M_O [kg]	M_{air} [kg]	CO_2 [kg]	H_2O [kg]
Ke	3.32	14.45	3.12	1.20
Ke + 10% SFP	3.29	14.32	3.10	1.19
Ke + 30% SFP	3.23	14.05	3.05	1.18
Ke + 50% SFP	3.17	13.79	3.00	1.17
SFP	3.02	13.14	2.88	1.13

It can be observed that needed air quantity for the stoichiometric reaction decreases while the biodiesel concentration increases due to the fact that the oxygen content of the sample increases too. CO_2 concentration decreases while biodiesel concentration increases.

3.3. Micro Turbo-Engine Test Bench Experiments

In this chapter, the variation of the measured values during the experimental work for all the working regimes is assessed.

Experimental Results

The results obtained during the starting procedure of the micro turbo-engine are shown within this section. By starting regime one must understand the period between the first movements of the starter until the engine reached a stabile yield regime. The aim is to assess the stability of the starting procedure for each of the fuel blends. Thus, Figures 3–8 are showing the variation of engine's characteristics: rpm vs. time, $T_{\_comb}$ vs. rpm for starting sequence, fuel consumption (Q_c) vs. rpm for starting sequence, $T_{\_fuel}$ vs. rpm, fuel consumption vs. rpm, thrust vs. rpm.

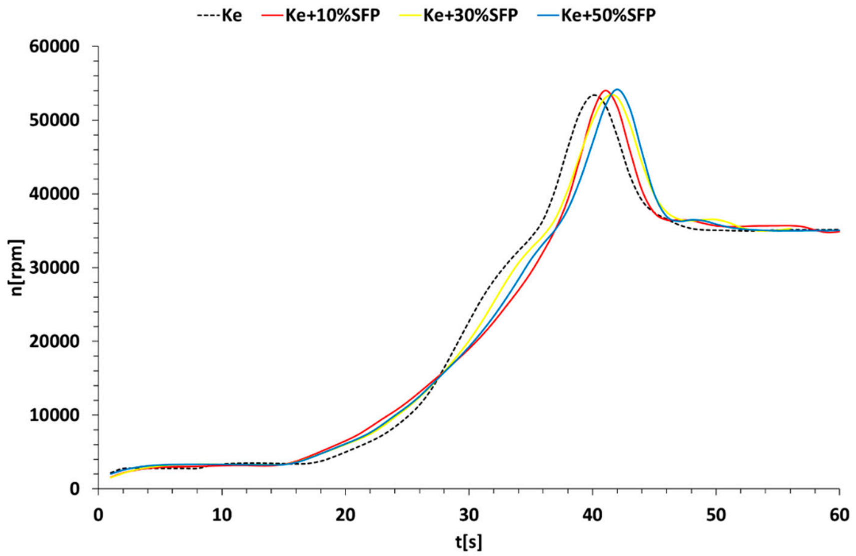

Figure 3. Rpm vs. time variation for starting procedure (until stable yield).

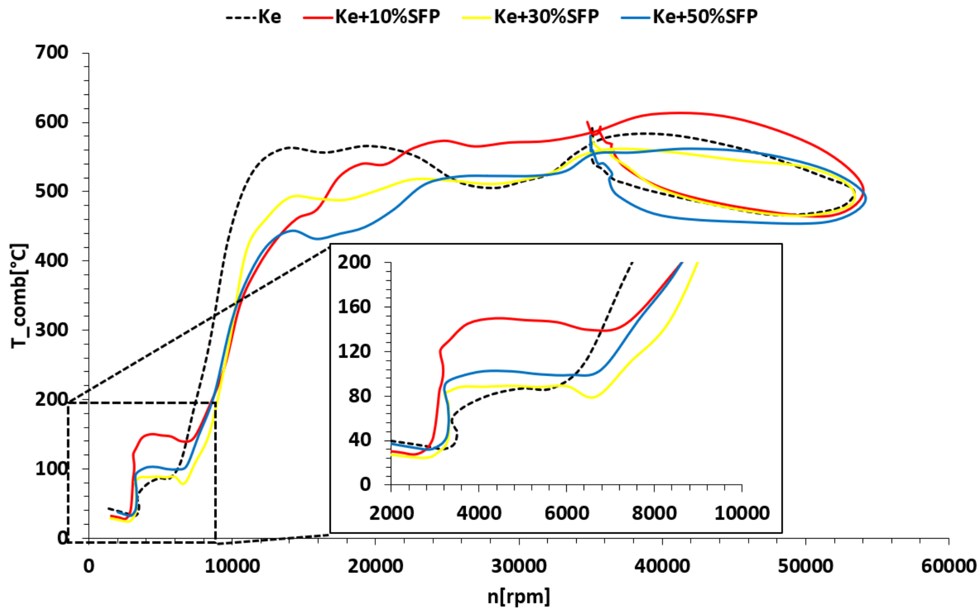

Figure 4. T_comb vs. rpm and blends for starting procedure.

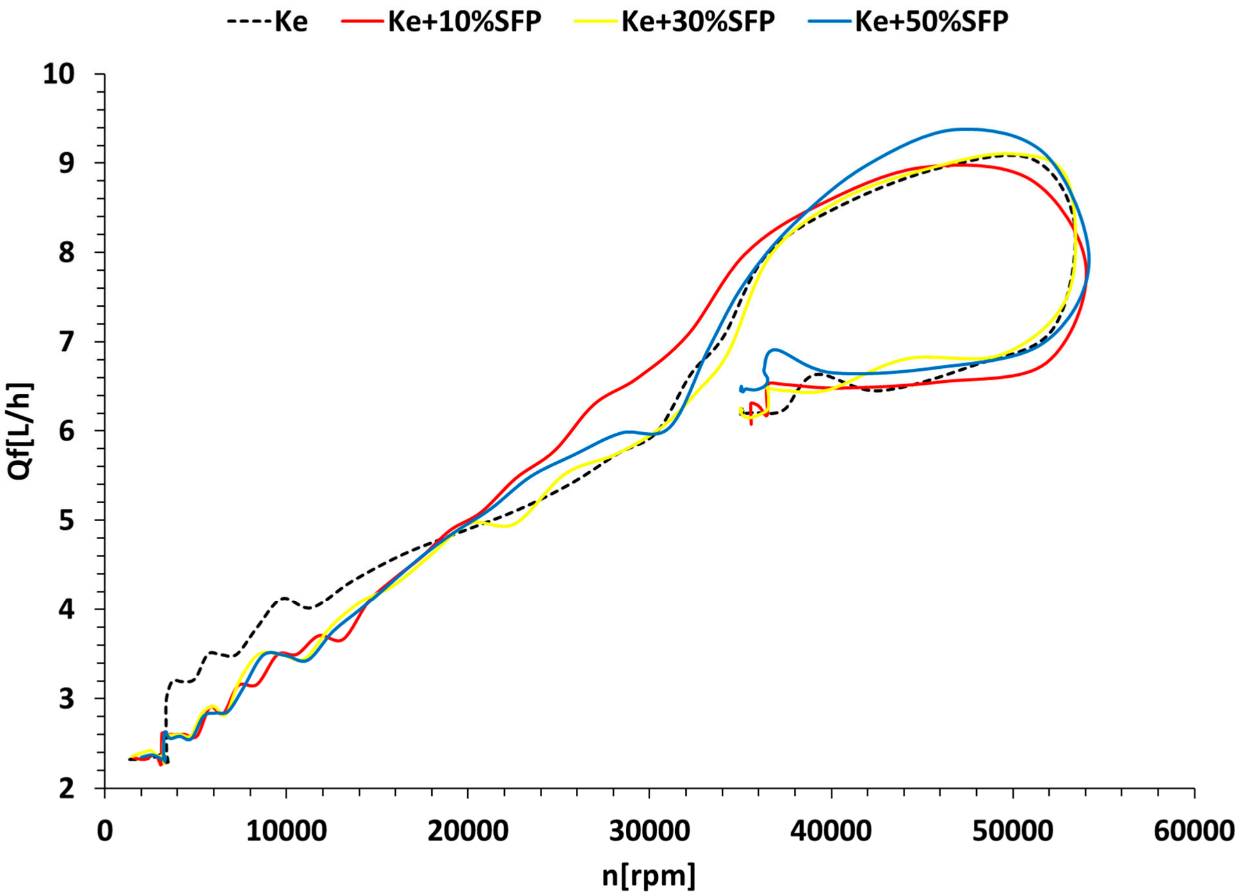

Figure 5. Qc (L/h) vs. rpm and blends for starting procedure.

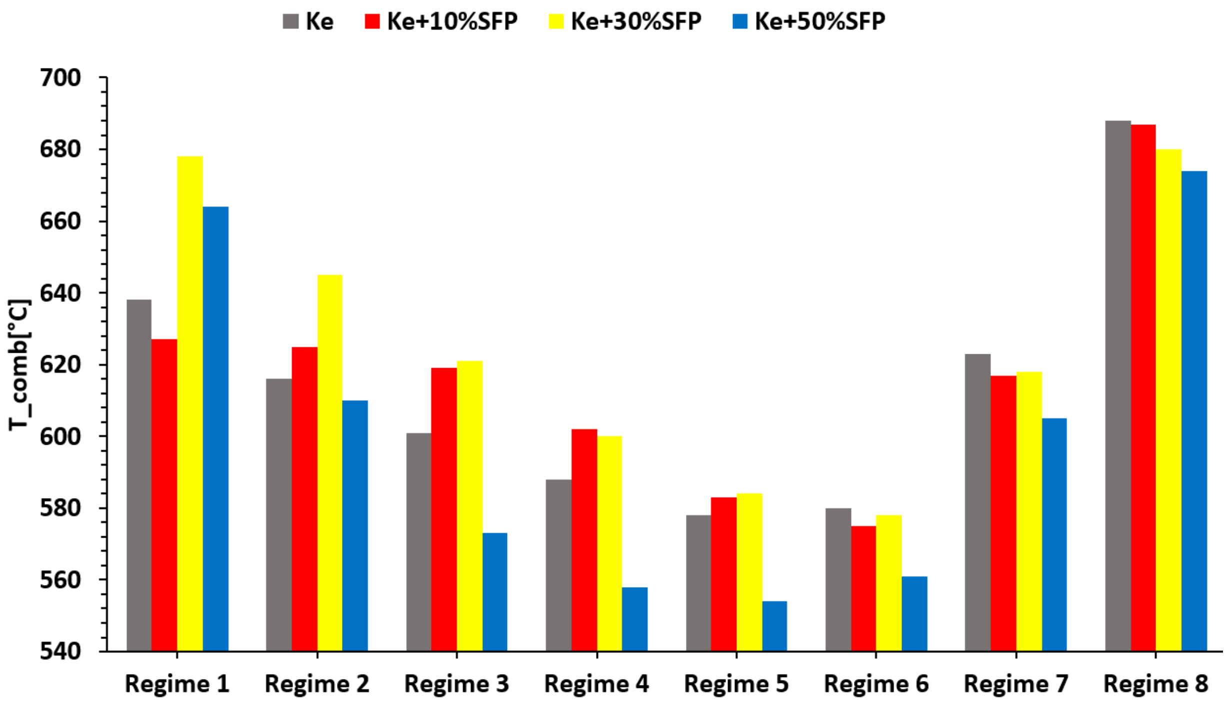

Figure 6. T_fuel vs. regimes and blends.

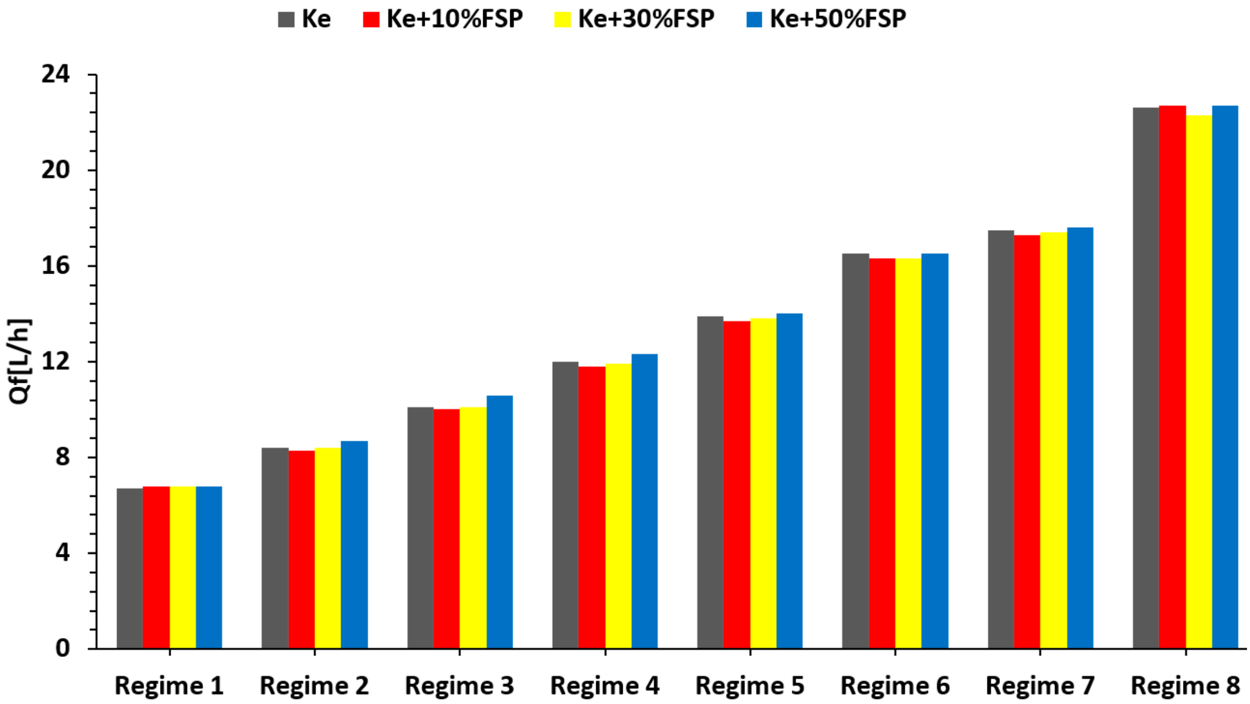

Figure 7. Qc vs. regimes and blends.

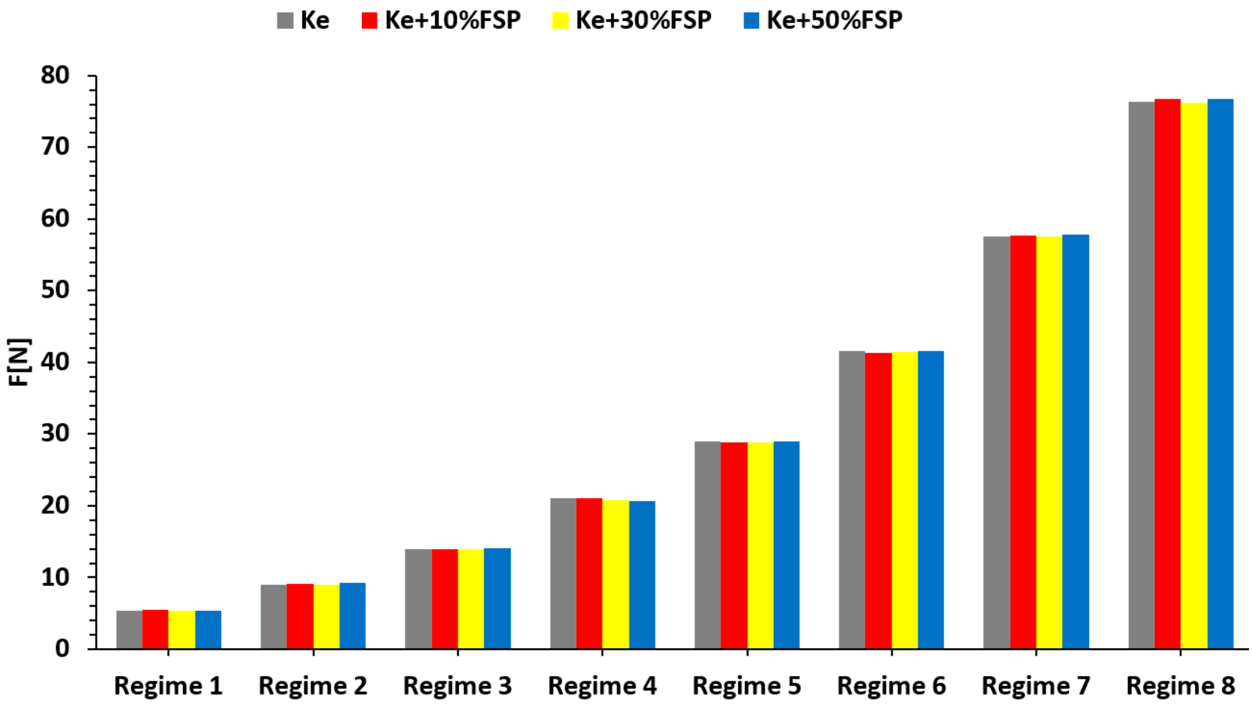

Figure 8. F vs. regimes and blends.

The starting procedure from start to idle engine regimes cannot be controlled by the operator, it is done automatically by the engine, so the loops from Figures 3–5 are specific to the microturboengine type.

It can be observed from Figure 3 that the starting time is increasing as the biodiesel concentration increases, thus for Ke, the stating time is the lowest. The variations shown in Figure 4 indicates that the succession f the starting procedure leads to a slight decrease of the fuel temperature due to the fact that when the engine is initiated by the electric starter, outside air is sucked in the burning chamber. Also, Figure 4 is showing time frame needed for the spark plug to ignite the fuel blends which increases as the biodiesel concentration increases.

Figure 5 is showing that the fuel debit needed for the starting procedure decreases while the biodiesel concentration increases. This is due to the fact that the starting temperature for Ke is higher than the starting temperatures of the fuel blends, therefore, the engine is forcing a large amount of fuel within the burning chamber in the case of Ke. After the working temperature is reached, the fuel debit variation is switched (lower for Ke and higher for fuel blends). So, during the "cold" period of the starting procedure, Ke debit is higher than fuel blend's ones and after the working temperature is reached, Ke debit is lower than fuel blends' ones.

Figure 6 is showing the temperature in front of the turbine variation which is oscillating while the blends are fed in the engine. The largest variation can be observed during yield regime since this one is often considered a quasi-stable one. Another conclusion that can be drafted from Figure 6 is that the combustion temperatures are decreasing while the concentration of SFP in increasing, especially at higher regimes.

Physical-chemical properties of the blends are the main factor influencing the variation of the combustion temperature.

Figure 7 is showing the consumed fuel flow which shows no or little variation while the blends are fed into the engine. However, the general tendency is that consumed fuel increases as the SFP concentration increases.

Figure 8 is showing the variation of thrust (F) while blends are fed into the engine which increases as the concentration of SFP increases. This aspect can be correlated with the variation of the fuel flow shown in Figure 4 and also with density measurements since all blends have their densities higher than Ke.

The first conclusion that occurs after scrolling through the above figures is that the functionality and integrity of the engine were neither compromised nor endangered.

3.4. Jet Engine Performance Analysis

Engine's performance parameters are calculated according to [57].

Equation (5) allows to calculate the specific consumption S:

$$S = 3600 \cdot \frac{\dot{M}f}{F}\left[\frac{kg}{N \cdot h}\right] \tag{5}$$

where: Mf is fuel flow in kg/s.

Combustion efficiency ηb, this is calculated by using Equation (6):

$$\eta_b = \frac{\left(\dot{M}f + \dot{M}a\right)cp_{\_comb} \cdot T_{\_comb} - \dot{M}a \cdot cp_{\_comp} \cdot T_{\_comp}}{\dot{M}f \cdot LCP} \tag{6}$$

where: LCP—Lower Calorific Power, cp—specific heat capacity, T_comb—temperature in front of the combustion chamber (that was recorded).

Engine's thermal efficiency is often calculated since it is very helpful in assessing an engine's performance. Thus, Equation (7) is used to calculate this parameter.

$$\eta_T = \frac{\left(\dot{M}a + \dot{M}f\right) \cdot v_e^2}{2 \cdot \dot{M}f \cdot LCP} = \frac{\left(\dot{M}a + \dot{M}f\right) \cdot \left(\frac{F}{\dot{M}a + \dot{M}f}\right)^2}{2 \cdot \dot{M}f \cdot LCP} \tag{7}$$

Figure 9 is showing the specific fuel consumption for all the fuels used within the paper.

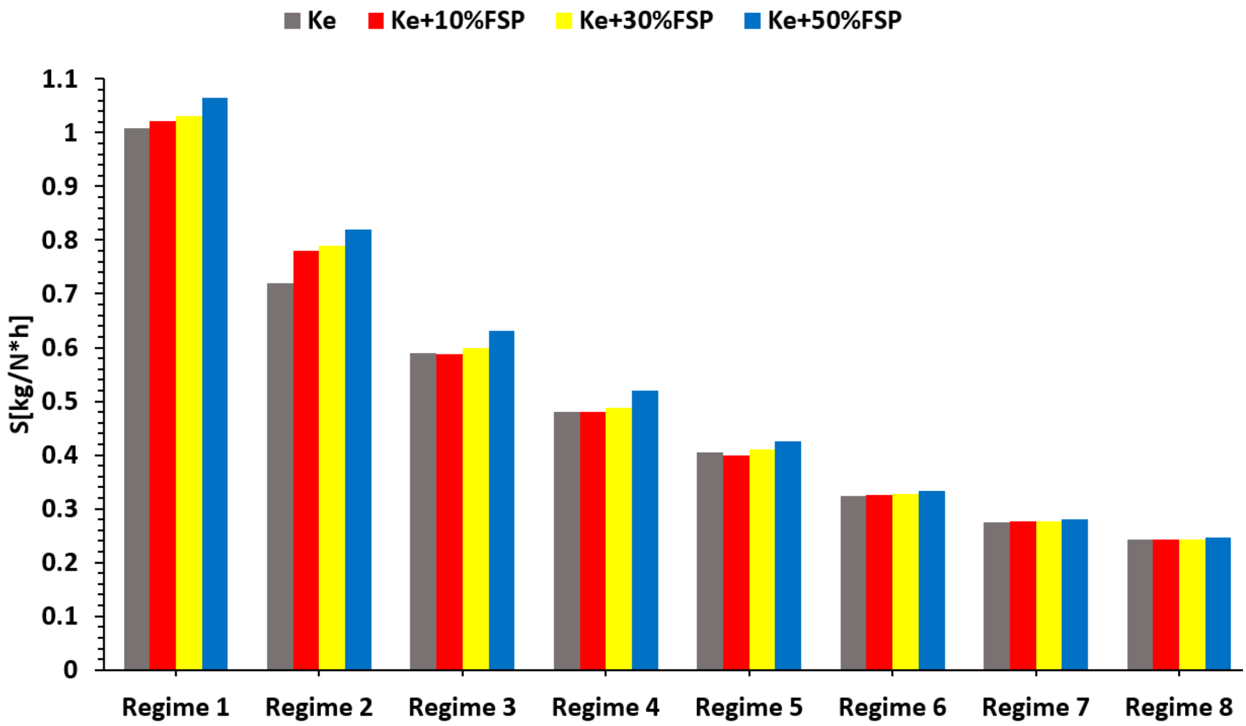

Figure 9. Variation of specific consumption for all regimes and all tested fuel blends.

As it can be observed specific fuel consumption increases while the concentration of SFP increases. This is strongly correlated with LCP. Thus, an obvious conclusion is that in case of biodiesel usage for aviation purposes, larger fuel tanks are needed.

Figure 10 is showing the combustion efficiency vs. rpm and biodiesel concentrations in the blends.

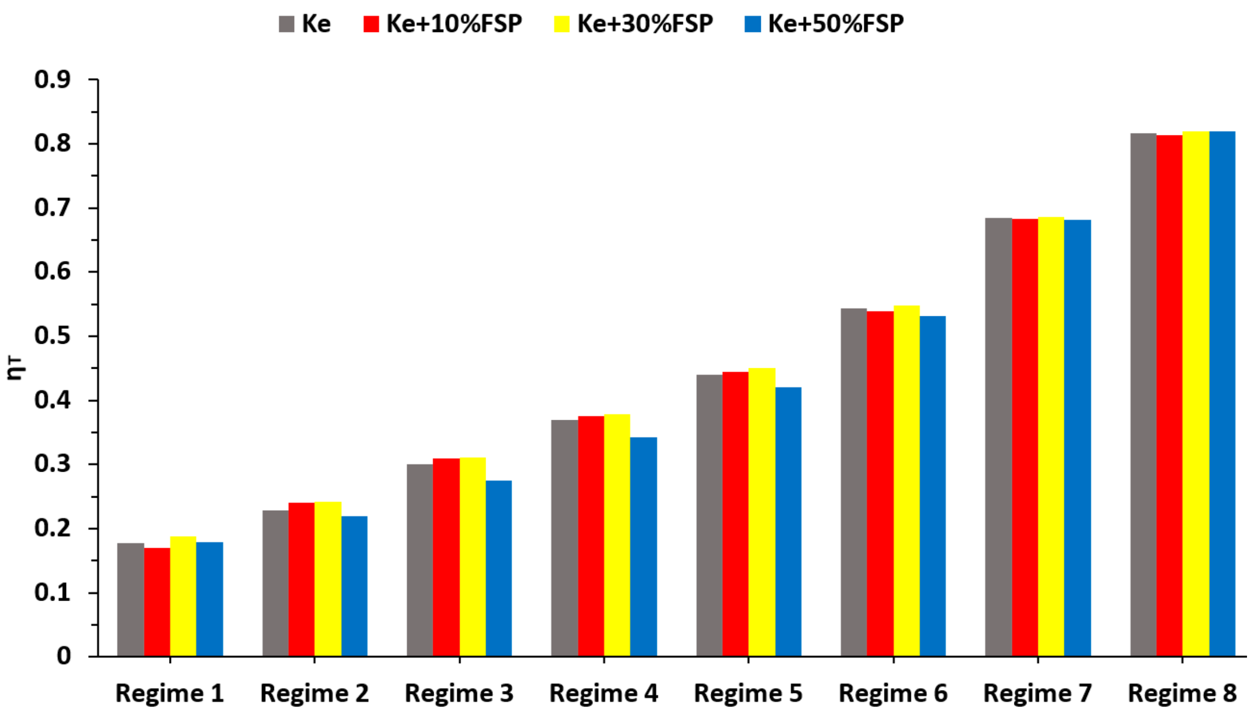

Figure 10. Variation of the combustion efficiency for all the tested fuel regimes and all blends.

Combustion efficiency remains constant during the experiments conducted at higher regimes proving the stability of the combustion regardless the blends fed into the engine. However, for lower working regimes this efficiency slightly varies due to the blends fed.

Figure 11 is showing the variation of air/fuel ration vs. rpm for all the fuel blends used within the experiment and as one can assess, this ratio decreases as the biodiesel concentration increases due to the extra oxygen brought by the biodiesel in the mixture. Thus, lower oxygen quantities from the environment are needed.

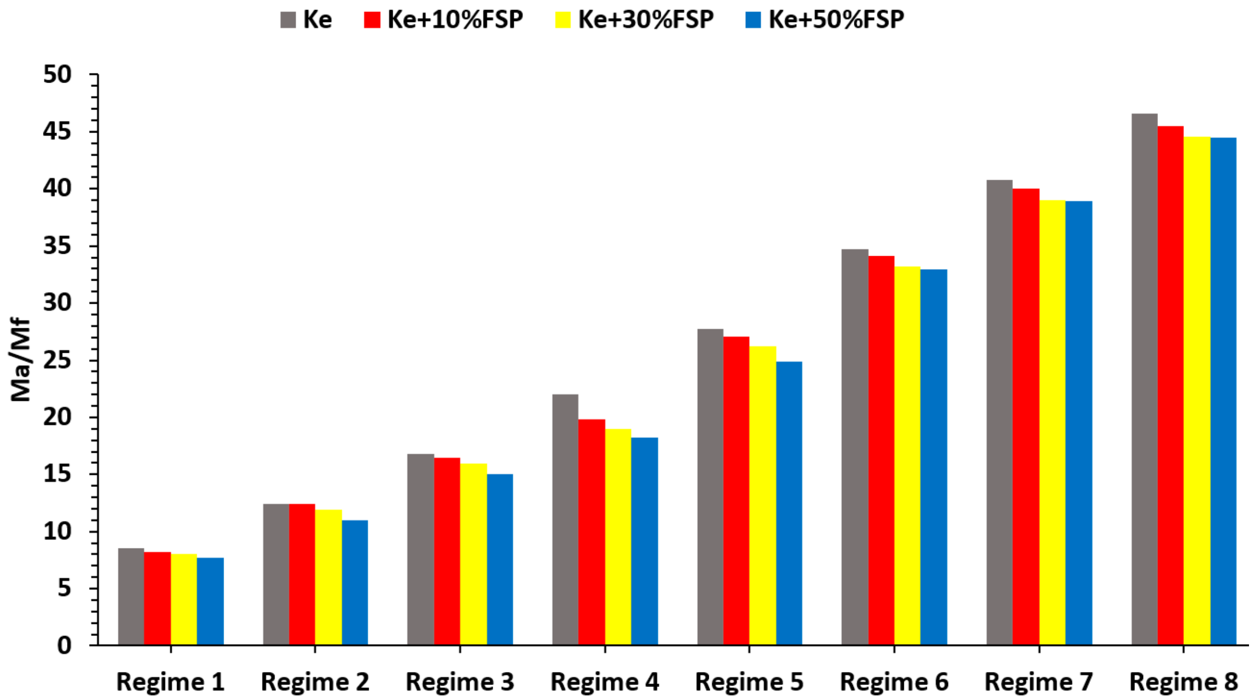

Figure 11. Variation of $\dot{M}a/\dot{M}f$ for all regimes and all tested fuel blends.

Table 3 is showing the thermal efficiency calculated by using Equation (7). It is to be mentioned that thermal efficiency was calculated only for the maximum working regime.

Table 3. Calculated thermal efficiency for max regime.

Fuel	Ke	Ke + 10% SFP	Ke + 30% SFP	Ke + 50% SFP
η_b [%]	5.490	5.501	5.525	5.587

Analysing Table 3, it can be observed that the value of the thermal efficiency is very low, in contrast to the values from the literature, because operating procedures of a turbo engine differs from those of the airplane's turbo engines. It is to be noticed that thermal efficiency is increasing as the biodiesel concentration increases within the blends.

4. Conclusions

- The experiments performed on Jet CAT P80® micro-turbo engine highlights the possibility of using different percentages of biodiesel in fed fuel without putting in danger the engine's integrity.
- Some of the properties of the used blends vary proportionally with the percentage of biodiesel within the blend. Thus, freezing point increases as the biodiesel concentration increases, making these blends unsuitable for high altitude flights.
- On contrast, some characteristics decrease as the biodiesel concentration increases. LCP decreases as the biodiesel concentration increases, leading to increased fuel consumption.

- Biodiesel has lower carbon content than usual Ke so the produced CO_2 while burning biodiesel blends is lower, making it more environmentally friendly.
- Also, SPF has larger amount of O_2 within its molecule, thus the requirements of O_2 from air decreases, leading to lower CO_2 generated during the burning process.
- Low LCP of the biodiesel is leading to increased fuel consumption as the percentages of biodiesel increases.

As a main conclusion, the tested fuel blends, Ke + 10% SFP, Ke + 30% SFP, Ke + 50% can be used in aviation applications that are using micro turbo-engines since during the experiments, the engine's integrity was never at risk. These blends are suitable to be used in applications were the flight is made at lower altitude (e.g., drones and/or aero models) than Ke since the freezing point of the blends is lower than Ke's. Moreover, the raw material used for obtaining the biodiesel is abundant, cheap and partially solve the waste cooking oil disposal.

Author Contributions: G.C.: Conceptualization; R.M. and L.C.C.: Experimental Analysis of Physical-Chemical Properties for Fuel Blends, G.C., D.E.C. and C.L. carried out Micro-Turbojet Engine Experiments. G.C.; R.M. and L.C.C. carried out results about burn chemical reaction for all the fuels studied. All authors have read and agreed to the published version of the manuscript.

Funding: This work has been funding by University POLITEHNICA of Bucharest through the PubArt program.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The datasets used and analyzed during the current study are available from the corresponding author on request.

Acknowledgments: Physical-Chemical analysis has been carried out within INCDT COMOTI's lab.

Conflicts of Interest: The authors declare no conflict of interest.

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