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Article

Lab Scale Investigation of Gaseous Emissions, Performance and Stability of An Aviation Turbo-Engine while Running on Biodiesel Based SAF

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Abstract: The research experimentally examines the viability of biodiesel obtained from pork fat (BP) as a sustainable aviation fuel (SAF) when mixed with kerosene (Ke) - Jet-A aviation fuel + 5% Aeroshell 500 oil. Various blends of biodiesel and kerosene (10, 20 and 30% vol. of BP added in Ke) were subjected to testing in an aviation micro turbo-engine under different operational states: idle, cruise, and maximum power. During the tests, monitoring of engine parameters such as burning temperature, fuel consumption, and thrust force was conducted. The study also encompassed the calculation of crucial performance indicators like burning efficiency, thermal efficiency, and specific consumption for all fuel blends under maximum power conditions. Physical-chemical properties of the blends, encompassing density, viscosity, flash point, and calorific power, were determined. Furthermore, elemental analysis and FTIR were used for chemical composition determination. The research delved into analysing the air requirements for stoichiometric combustion and computed resulting emissions of CO_2 and H_2O. Experimental assessments were performed on the Jet Cat P80® micro-turbo-engine, covering aspects such as starting procedures, sudden acceleration, sudden deceleration, and emissions of pollutants (NO_x, CO and SO_2) during several engine operational phases. The outcomes reveal that the examined fuel blends exhibited stable engine performance across all tested conditions. This indicates that these blends hold promise as sustainable aviation fuels for micro turbo-engines, presenting benefits in terms of diminished pollution and a more ecologically sound raw material base for fuel production.

Keywords: sustainable aviation fuel; engine efficiency; gaseous pollutants; kerosene blends; aviation turbo-engine

1. Introduction

Air quality degradation has several aspects such as: gaseous pollution, global warming, O_3 layer depletion and the main reason is the burning of fossil fuels [1]. Therefore, the use of renewable energy may be a solution for slowing if not stopping the processes involved in air quality degradation.

In terms of aviation fuels, several alternatives have been pointed out by the researchers: the use of alcohols, hydrogen (both liquid and gaseous), synthetic fuels, etc. [2] Nowadays, in the field of aviation fuels the main research is focused on the production and use of bio-fuels which are prove to be more environmentally friendly, have the potential to reduce the greenhouse gasses and CO_2 emissions. [3]

The most promising bio-fuel in aviation applications seems to be the biodiesel because it shows the highest potential to meet the needed energy requirements [4, 5]. It appears to be the most feasible solution to O_3 depletion and environment degradation by successfully replacing classical fuels. It is well established that biodiesel emit fewer gaseous pollutants during burning and its most important advantage is that it can be used in diesel engines without retrofitting them. It also shows lower toxicity, biodegradation and being a renewable fuel can successfully replace classic diesel. [6, 7]

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On the other hand, alcohols seem to be an equally good solution, especially during use in piston engines. [8-10] Ethanol is one of the most important alcohols used in piston engines and studies have been conducted on its use. By covering aspects from ethanol production to engine performances while using gasoline/bioethanol blends (E3, E6 and E10) to gaseous emissions [11], researches have pushed the boundary towards on-board hydrogen production and mixtures made out of alcohol and diesel [12], alcohol and di-methyl carbonate [13]. Also, classes of alcohols (methanol, ethanol, butanol, etc.) have been tested in different mixtures with gasoline and their effect on engine's performances and emissions have been assessed. [14]

It has been studied the improvements brought in terms of engine performances when alcohols have been mixed with gasoline. Thus, the adding of small amounts of alcohol not influence the engine's delivered properties (thrust, fuel consumption, etc.) [15]. CO_2 and total emitted hydrocarbons (THC) increase with the increase of alcohol percentage within the blend [16]. Thus, de adding of the alcohol contribute to the improvement of thermal efficiency and anti-detonation properties of the fuel [17], therefore, larger concentrations ranging from 10 to 85% and even 100% of ethanol in gasoline have been tested. [18-20]

In terms of the use of alcohols in different mixtures for feeding aviation turbo-engines, there have been conducted several studies depending on the type of engine and its required performances. Few of them have been finalized also with demonstrative flights. [21-23]

Besides engines' performances assessing, researches have been focused also on the evaluation of the combustion and gaseous pollutant emissions. [24-29].

Mixtures of ethanol and Jet-A aviation fuel have been used to fed different types of engines starting from GTM-140 micro-turbine, full-size DGEN380 turbofan to four-stroke direct injection diesel engine. [30, 31].

Nevertheless, first tests and certifications on the use of biodiesel/airplane fuel (AVGAS) blends have been made for aviation piston engines [32] but also ethanol/Jet-A mixtures have been tested on piston aviation engines [33]. It has been determined that by using a new type of controller, the engine could overcome some drawbacks it terms of functioning characteristics.

Biodiesel/Jet-A mixtures have been fed to a piston aviation engine and several advantages occurred over the use of ethanol both in terms of physical-chemical properties and delivered performances. Moreover, gaseous pollutants concentrations decreased compared with the ones obtained from the use of classical aviation fuel. [34,35]

Other research papers examined the use of biodiesel as a sustainable fuel for small turbojet engines in laboratory conditions. The studies explore different types of biodiesels and JET-A-1 mixtures and assess their impact on the fundamental parameters of these engines. [36]

The use of bio-ethanol as fuel for aviation turbine engines was also studied. Different compositions, specifically 5%, 10%, and 15% concentrations of bio-ethanol blended with Jet-A fuel, were subjected to testing using the JET CAT P80 micro-turbo-engine. Throughout the testing process, various parameters were meticulously monitored, including engine speed, thrust generated, temperature preceding the turbine, fuel volumetric flow rate, and vibration levels assessed in both axial and radial directions. The micro-turbo-engine was sustained at three distinct operational states: idle, cruise, and maximum speed, each lasting approximately 1 minute. Furthermore, a comparative evaluation was conducted between fuels, scrutinizing the micro-turbo-engine's performance from the idle to maximum positions.

Upon completion of the tests, a comprehensive jet engine cycle analysis was carried out at the maximum operational state. This analysis involved the calculation of fuel-specific consumption, combustion chamber efficiency, and thermal efficiency of the engine for each fuel blend. It is pertinent to note that these assessments were executed without any alterations made to the engine components or the automation system. [37]

In the field of power engineering, investigations into the impact of biofuels and alcohol-derived blends on gas turbines have been conducted. Elevated ethanol concentrations resulted in heightened carbon monoxide (CO) emissions. Conversely, nitrogen oxides (NOx) witnessed a substantial

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decrease of up to 70% in the presence of biofuels, and there was a concurrent reduction in particulate matter (PM10) [38].

An analysis of the possibility of using recycled pork fat-based biodiesel as fuel for aviation turbo-engines is presented in [39]. The analysis consists of the assessment of four blends of Jet-A kerosene with 10%, 30%, 50%, and 100% biodiesel. Current paper is basically a continuation of paper [39].

The research conducted in this study provides an examination of the impacts associated with the utilization of biodiesel in a compact turbojet engine. The primary objective is to investigate the viability of a Jet-A and biodiesel blends as a potential fuel source for small turbojet engines, drawing upon insights from earlier research endeavours. The present study aims to evaluate the operational parameters of a micro turbo-engine commonly deployed in drones and aero-models. This assessment involves varying the composition of kerosene and biodiesel blends. Specifically, a comparative analysis was carried out, comparing fuel mixtures comprising Jet-A and 5% Aeroshell 500 Oil (Ke) against blends featuring 10%, 20%, and 30% biodiesel, with Ke serving as the benchmark reference point.

After determining the physical-chemical properties of the mixtures, a measurement campaign has followed where burning tests were made on the Jet Cat P80 micro-turbo-engine. The novelty of the paper compared with reference [39] is that now the transitory regimes are taken into account and gaseous pollutants resulted from the combustion of the above-mentioned blends and regimes were assessed.

2. Materials and Methods

In order to establish the sustainability of fuel blends based on biodiesel, several investigations were performed within this paper. Thus, blends consisting of Jet-A aviation fuel (Ke), blends of Ke+10%BP, Ke+20%BP, Ke+30%BP.

Thus, 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. Blends Characterization

In this chapter are presented the equipment and the testing methods used to perform the determinations of the physical-chemical properties for the Jet-A fuel and Ethanol respectively all the fuel blends used for testing.

Density of the Fuel Blends Determination

Densities of: Jet-A fuel, BP and all tested fuel blends respectively, were measured as described in SR EN ISO 3675/2002 [39]. The testing equipment is shown in Figure 1.

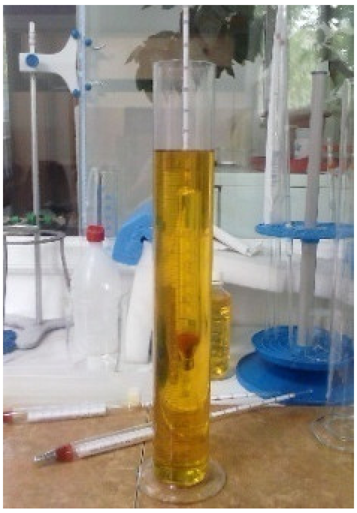

Figure 1. Fuels density measurement.

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Flash Point Measurements

Jet-A fuel, Ethanol and all tested fuel blends, had their flash point (the lowest temperature of which the substances' vapours ignite in the presence of a flame) measured as described in ASTM D92 [40]. Figure 2 is showing the Automatic flash point tester Cleveland, provided by Scavini, Italy used for this measurement.

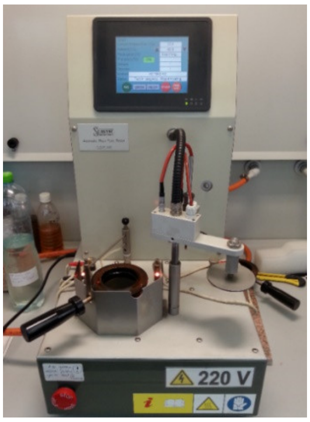

Figure 2. Automatic Flash Point Tester Cleveland.

Kinematic Viscosity Measurements

The measurements were made at 40°C, for the Jet-A fuel, Ethanol, respectively all tested fuel blends, was experimentally determined as described in SR EN ISO 3104/2002 [41]. The equipment is shown in Figure 3 and it's provided by Scavini, Italy.

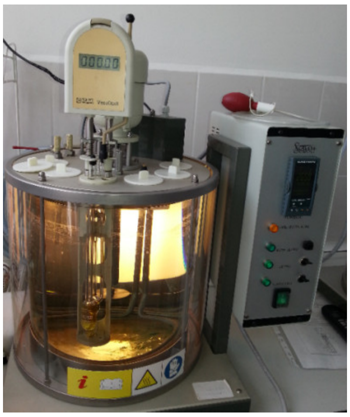

Figure 3. Kinematic viscosity determination equipment.

Low Calorific Power Determination

Low calorific power for the Jet-A fuel, Ethanol, respectively all tested fuel blends was experimentally determined accordance with ASTM D240-17 [42]. IKA WERKE C 2000 Calorimeter provided by Cole-Parmer and shown in Figure 4 was used to determine the low calorific power.

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Figure 4. IKA WERKE C 2000 Calorimeter.

FTIR Analysis (Fourier Transform Infrared Spectroscopy)

The FTIR for all samples was experimentally determined using a (FTIR) Spectrum Oil Express Series 100, v 3.0 spectrometer provided by Perkin Elmer (Figure 5) and having dedicated software for all fuels blends.

Figure 5. FTIR Spectrum OilExpress Series 100, v 3.0 spectrometer.

Elemental Analysis

An elemental analysis for the Jet-A fuel, Ethanol, respectively all tested fuel blends was made in order to assess the main elements of the fuels (C, N, H and O).

Percentage of carbon, hydrogen, nitrogen respectively oxygen content for the above-mentioned fuels have been determined as described in ASTM D 5291–16 [43].

2.2. Theoretical Calculation of the Combustion Process

After the elemental composition of fuel blends was determined, their corresponding minimum air quantities required for stoichiometric combustion were calculated. The accurate calculation of resulting CO_2 and water emissions allows a complete assessment of gaseous pollutant production during combustion. It was thus determined that the examined fuel blends generate lower levels of gaseous pollutants compared to conventional combustion processes.

2.3. Engine Experimental Procedure

The test bench, methods, equipment and testing procedure are presented in the following chapter. The experiments were performed on a Jet CAT P80® turbo-engine [44], as shown in Figure 6.

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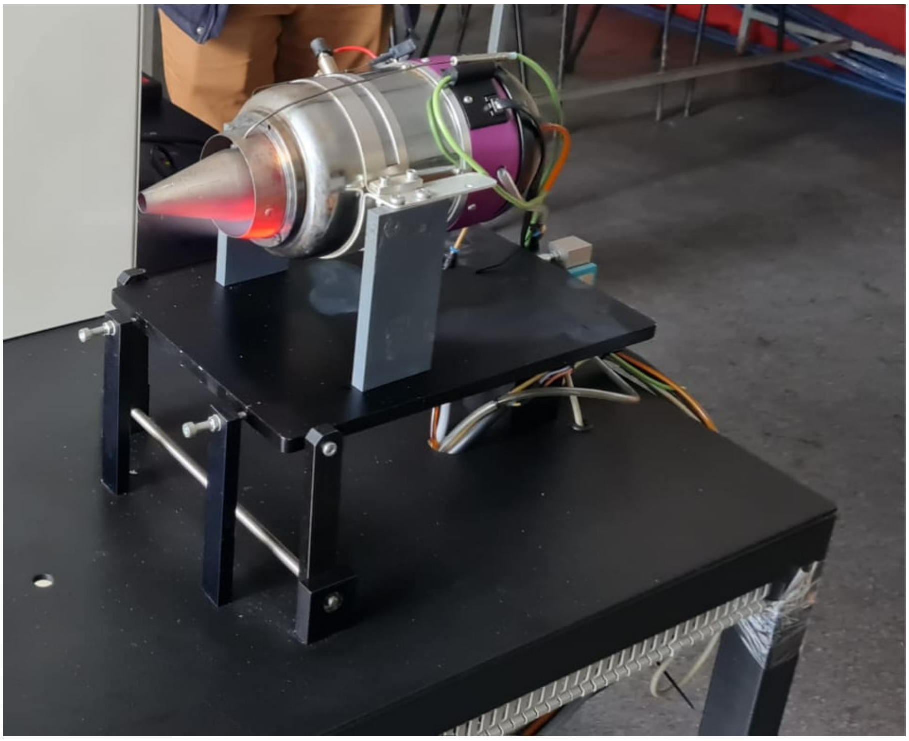
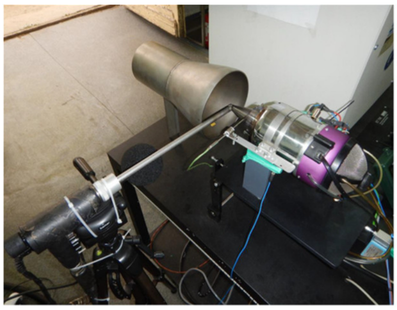


Figure 6. Engine setup for combustion experiments.

This chapter explores the impact of different fuel blends on the performance of a turbocharged engine. The investigated fuel blends consist of kerosene with varying percentages of biodiesel (10%BP, 20%BP, and 30%BP) and with 5% of Aeroshell 500 oil added to each blend for engine lubrication due to the fact that such a small engine does not have its own lubrication system. The tests were conducted under three distinct operating regimes: idle (18.7% throttle gas), cruise (30% throttle gas), and maximum (94% throttle gas for safety functioning). Each regime was subjected to a testing period of approximately 2 minutes, during which engine parameters were closely monitored. The measured parameters included temperature (T_{comp}) after the compressor, temperature (T_{comb}) before the turbine, fuel flow Q_f, air flow, pressure in the combustion chamber, and thrust (F). The turbocharged engine maintained a constant shaft speed throughout the experiments, unaffected by the different fuel blends. However, to sustain this constant shaft speed, the fuel blends were introduced into the combustion chamber in varying proportions. Despite the variations in fuel blends, the compressor operated at a consistent speed, resulting in uniform pressure after the compressor and consistent air flow. Comparative assessments were made for parameters such as consumed fuel flow (Q_f), temperature in front of the turbine (T_{comb}), and thrust (F) under conditions of constant shaft speed.

2.4. Gaseous Emissions Measurements

The gaseous emission measurements were made by using the MRU Vario Plus analyser, which is presented in Figure 7. Simultaneously, measurements of gas components (e.g., O_2, CO, NO, NO_2, NO_x, SO_2, and CH_4) are carried out.


(a)

(b)

Figure 7. MRU Analyzer.

3. Results and Discussions

3.1. Physical-Chemical Properties for Fuel Blends Experimental Results

Table 1 is showing the obtained results of the physical-chemical determinations

It should be mentioned that Low Calorific Power and Elemental analysis were determined only for Jet-A fuel, while for the tested fuel blends, they were computed according to reference [45].

Table 1. Obtained results of the physical-chemical determinations.

Sample	Flash Point [°C]	Viscosity at 40°C, [cSt]	Density at 22°C, [g/cm³]	Low Calorific Value, [kJ/kg]	Elemental analysis, [%]
Ke	42.3	1.39	0.817	45.292	C% = 85.17 H% = 13.31 N% = 0.07 O% = 1.45
Ke+10%BP	44.2	1.51	0.823	44.403	C% = 84.40 H% = 13.22 N% = 0.07 O% =2.32
Ke+20%BP	50.2	1.82	0.830	43.67	C% = 83.21 H% = 13.1 N% = 0.07 O% =3.62
Ke +30%BP	54.7	2.06	0.836	41.99	C% = 82.85 H% = 13.03 N% = 0.07 O% =4.05
100% BP	161	5.08	0.875	39.323	C% = 77,43 H% = 12,38 N% = 0,06 O% = 10,13

A detailed analysis of data presented in Table 1, is leading to several noteworthy conclusions:

- Flash point, kinematic viscosity, and density exhibit an increasing trend with the rise in biodiesel concentration. This correlation suggests a notable impact of biodiesel content on these physical properties.
- A decrease in low calorific power is observed with an increasing biodiesel concentration, indicating an undesirable property. This observation prompts further investigation into the implications for combustion efficiency which may result in a much larger amount of fuel to be required than in the case of a Jet-A fuel.

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- Elemental analysis reveals that as biodiesel concentration increases, carbon and hydrogen content decrease, while oxygen content increases. This suggests a potential decrease in resulting CO_2 concentration during the combustion process, attributed to a reduced need for oxygen.
- Analysis across all studied fuel blends indicates consistent trends. The kinematic viscosity at 40°C, flash point, and low calorific power exhibit a proportional increase with the increase in biodiesel percentage. This uniformity emphasizes the predictable influence of biodiesel concentration on these properties.
- Elemental analysis further establishes that the rise in biodiesel percentage corresponds to an increase in oxygen content and a decrease in carbon content. These findings contribute to a comprehensive understanding of the elemental composition changes induced by varying alcohol concentrations in fuel blends.

FT-IR spectroscopy is a very useful tool in assessing the chemical modifications within a substance. By adding biodiesel within regular aviation fuel its chemical composition modifies. Figure 3 is showing the FTIR spectra for Kerosene, Ke+10%B, Ke+20%Bl, Ke+30%B and 100%B.

When the FTIR spectra are compared, variation appear 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), but their intensity vary according to the concentration of biodiesel, as shown in Figure 8. These peaks increase as biodiesel concentration increases. Fatty acid methyl esters (FAME) is an indication of the amount of the biodiesel present in each of the blends since FAME appear at 1745.83 cm^{-1} and 1170.23 cm^{-1} - 1030.98 cm^{-1}. Methyl esters also show their absorptions characteristics (A=absorbance) in the peak around 1820 – 1680 cm^{-1} [41].

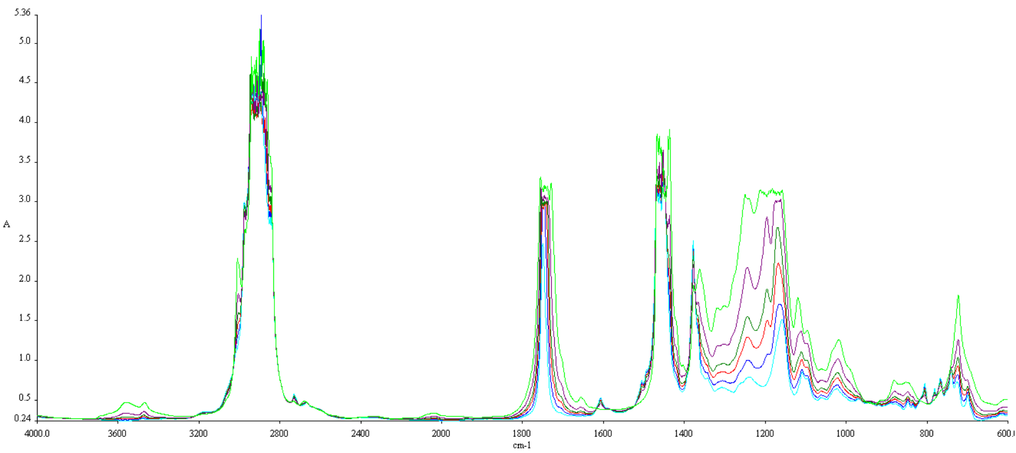

Figure 8. FTIR Spectra of the blends (Spectra of 100%BP - light green, spectra of 30%BP – dark green, spectra of 20%BP – red, spectra of 10% BP – blue, spectra of Ke – light blue).

3.2. Combustion Reaction Analysis

In order to understand the stoichiometric combustion characteristics of various fuel blends, knowledge of their elemental composition is essential. This study considers hydrocarbons with the general formula $C_cH_hO_oN_n$ [47], with specific fractions of g_C, g_H, g_O, and g_N elucidated in Table 1.

The calculation of the needed oxygen quantity for stoichiometric combustion is crucial in providing insights into the combustion process and facilitating a comprehensive understanding of the chemical reactions involved and can be calculated by using Equation (1).

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

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

CO_2 and H_2O from the combustion process can be calculated by using the following:

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

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

Table 2. Obtained values for 1 kg of fuel blend.

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Blend	M_O [kg]	M_{air} [kg]	CO_2 [kg]	H_2O [kg]
Ke	3.32	14.45	3.12	1.20
Ke+10%BP	3.29	14.29	3.09	1.19
Ke+20%BP	3.23	14.05	3.05	1.18
Ke+30%BP	3.21	13.97	3.04	1.17
BP	2.95	12.85	2.84	1.11

An inverse relationship is noted between the required air quantity and biodiesel concentration. This phenomenon is attributed to an increase in oxygen content accompanying higher biodiesel concentrations. Additionally, a proportional decrease in CO2 concentration is observed with increasing biodiesel concentration. These findings underscore the intricate interplay between biodiesel content, oxygen levels, and resultant carbon dioxide concentrations in the stoichiometric combustion process.

3.3. Micro-Turbojet Engine Experimental Results

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

3.3.1. Experimental Results

This section presents the outcomes of the initial phase of the micro turbo-engine, focusing on the starting procedure. The starting regime is defined as the duration from the initial starter movement to the point where the engine achieves a stable operational state. The primary objective is to evaluate the stability of the starting process for different fuel blends. Figures 9–11 illustrate the variations in engine characteristics during this phase, including rpm vs. time, fuel temperature vs. rpm, and fuel flow rate vs. rpm. These visual representations provide insights into the dynamics and performance of the engine during the critical starting period for each fuel blend.

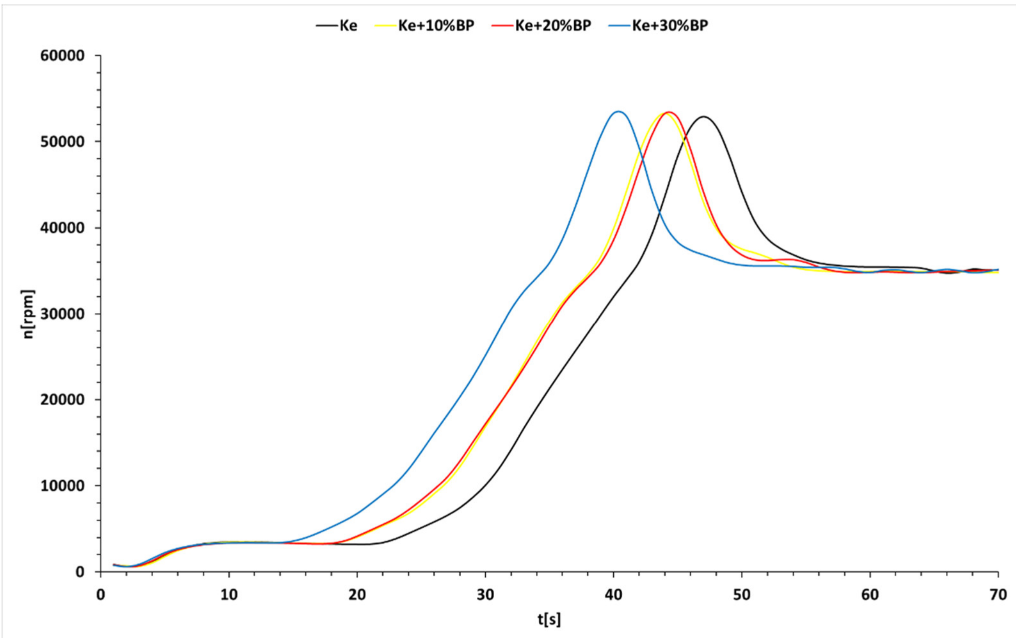

Figure 9. Rpm vs. time variation for starting procedure (until stable yield).

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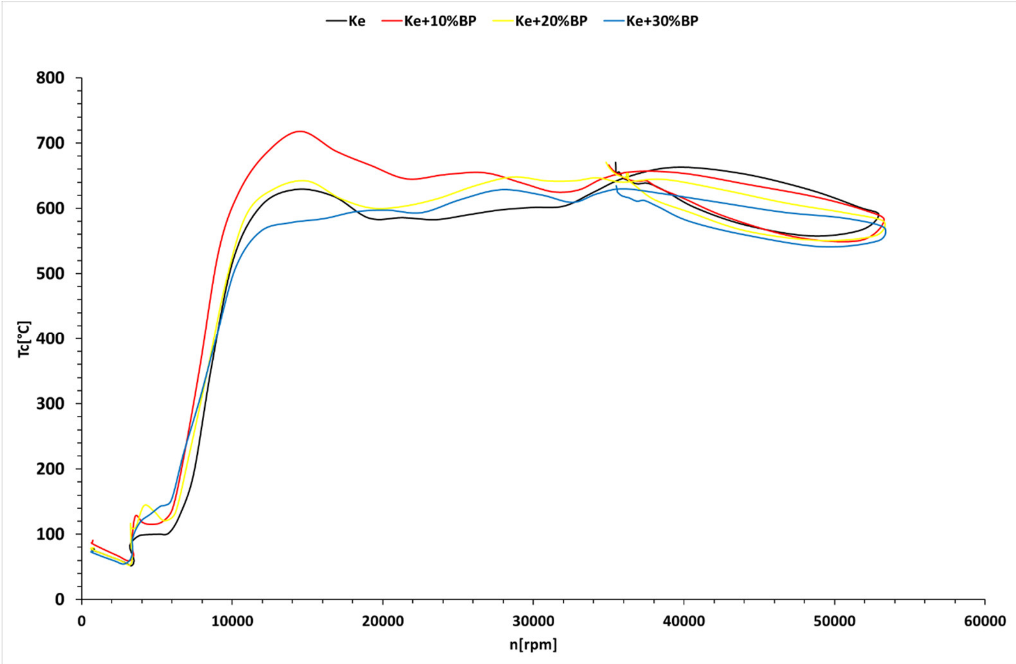

Figure 10. T_{comb} vs. rpm and blends for starting procedure.

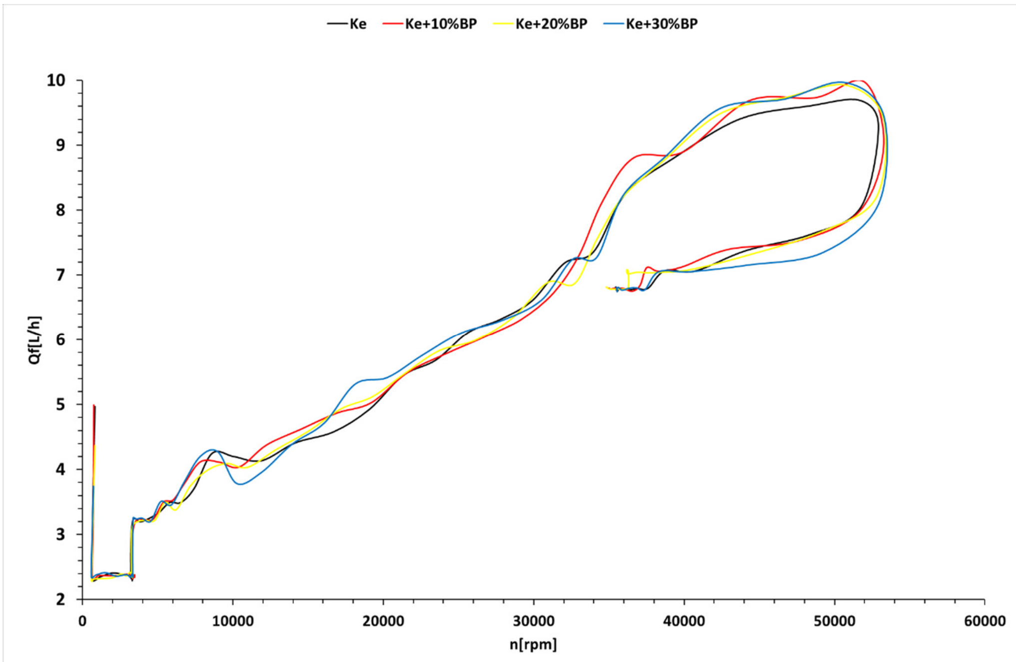

Figure 11. Q_c (L/h) vs. rpm and blends for starting procedure.

It can be observed from Figure 9 that the starting time is decreasing as the biodiesel concentration increases, thus for Ke, the stating time is the lowest. The variations shown in Figure 10 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 10 is showing time frame needed for the spark plug to ignite the fuel blends decreases as the biodiesel concentration increases due to the fact that the temperature inside the combustion chamber increases too, thus leading to a more rapid ignition.

Figure 11 is showing that the fuel debit needed for the starting procedure increases while the biodiesel concentration increases. This is due to the fact that the starting temperature for Ke is higher

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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.

In order to assess the engine's stability during transitory regimes, a sudden acceleration and deceleration experiment has been performed for all fuels and blends. After the engine was sudden accelerated from idle until max regime, it was kept there for 30 seconds until stabilized and after that the sudden deceleration took place, back to idle.

Figures 12–14 are showing the variation of the most important parameters: fuel temperature vs. rpm, fuel flow rate vs. rpm and thrust vs. rpm.

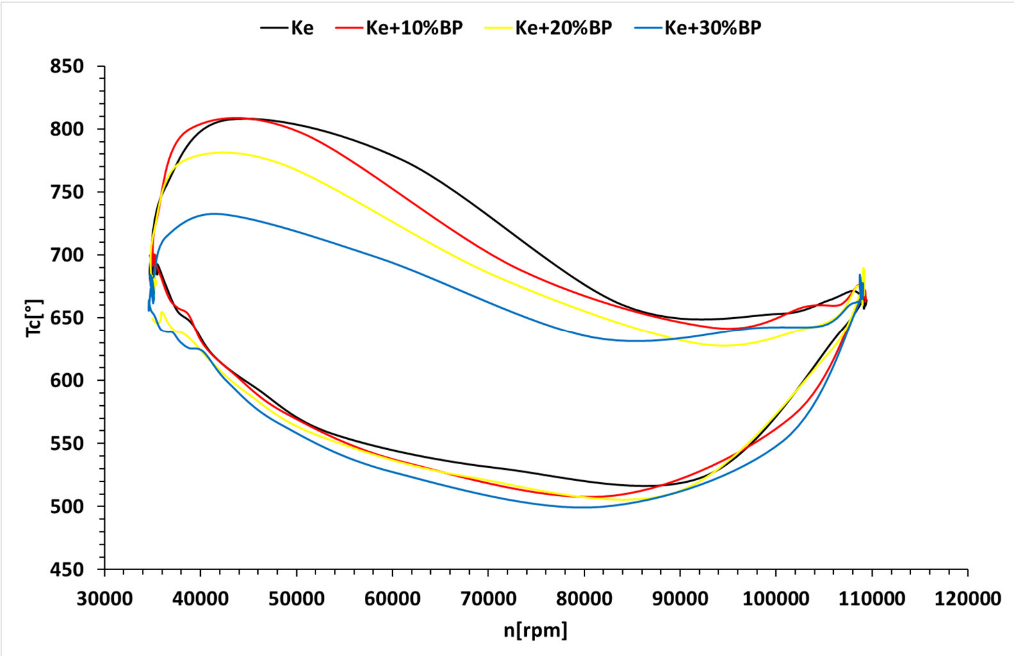

Figure 12. T_{comb} vs. rpm during sudden acceleration and deceleration.

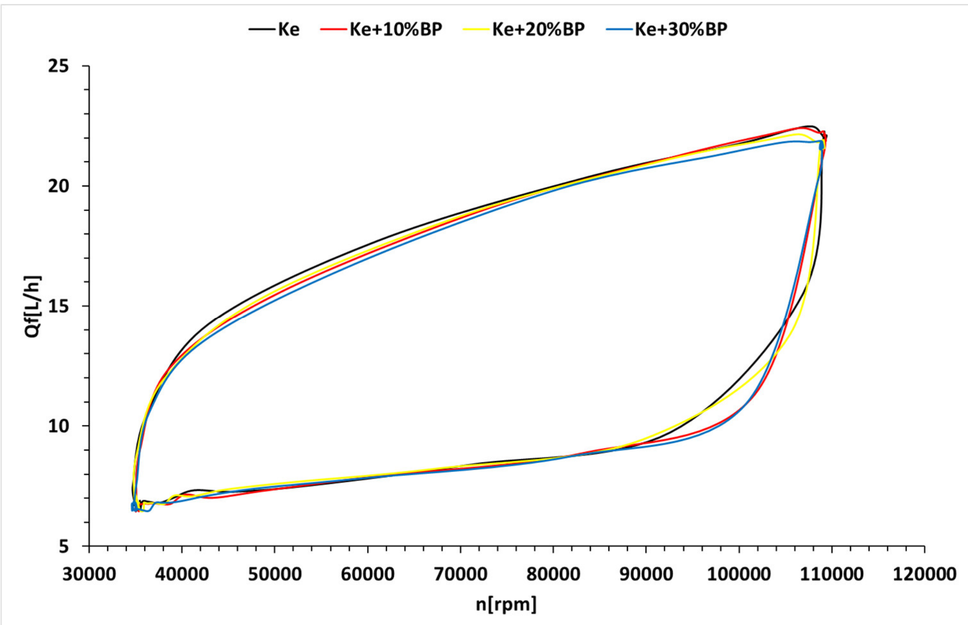

Figure 13. Q_c (L/h) vs. rpm during sudden acceleration and deceleration.

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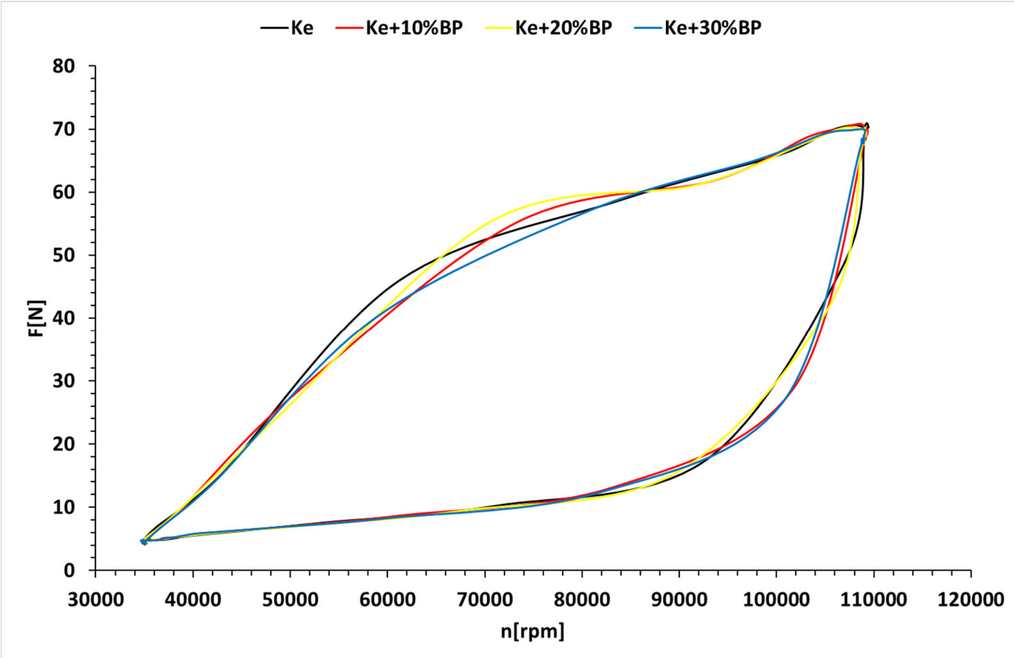

Figure 14. F vs. rpm during sudden acceleration and deceleration.

Out of the 3 figures showed above (12-14) the following aspects are to be assessed: while the engine was suddenly accelerated form idle to max, kept until stabilizes and then sudden decelerated it can be observed that the fuel temperature in front of the turbine is lower during the sudden acceleration and deceleration and also decreases as the biodiesel concentration increases. Fuel flow increases during the sudden acceleration period and increases as the biodiesel concentration increases due to the lower calorific power of the biodiesel. The delivered thrust decreases as the biodiesel concentration increases and also is lower during the sudden acceleration period.

Next Figures 15–17 are showing the main monitored parameters of interest in performance analysis that were recorded during the operation of the turbo-engine within stable regimes (idle, cruise and max). The data were averaged for 1 minute of functioning at each regime. The monitored and recorded parameters are: thrust, fuel flow, gas temperature in front of the turbine and gaseous pollutants concentrations, such as CO, SO2 and NOx

Figure 15 provides the charts that describe variation of the temperature in front of the turbine for the 3 stable operating regimes and for the four different types of fuel.

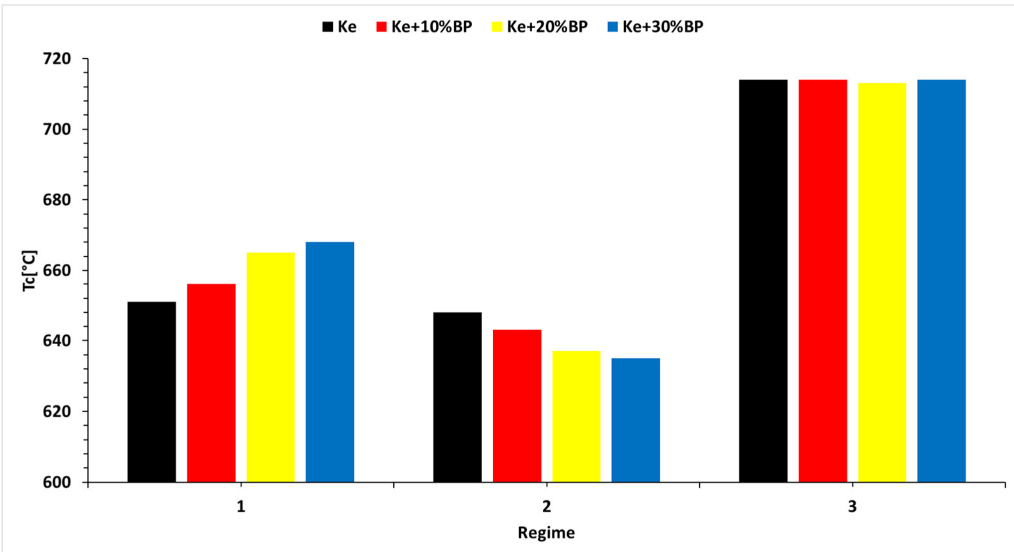

Figure 15. Variation of T3 (°C) depending on regime and blends.

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From Figure 15, it can be noticed that the temperature measured in the combustion chamber is higher when the turbo-engine is powered by each of the four tested biodiesel blends while operating in the idle mode, than in the case of using a Jet-A type fuel without exceeding the upper prescribed limit for engine exploiting that is 800°C. In the cruise operating regimes, the temperature measured in the combustion chamber decreases below the temperature attained in the combustion chamber when using a Jet-A type fuel, considering the reference temperature, when the biodiesel concentration in the four tested combustible blends increases. In the maximum operating regime, the temperature measured in front of the turbine when using the four combustible blends exhibits small fluctuations against the temperature attained in the combustion chamber when using a Jet-A type fuel. These small fluctuations can be attributed to the reading errors of the used thermocouple.

Figure 16 provides the charts that show the variation of the fuel flow of the five fuel blends tested for the four operating regimes. As it can be observed, there are no notable fluctuations in the fuel flow when the turbo-engine is operated.

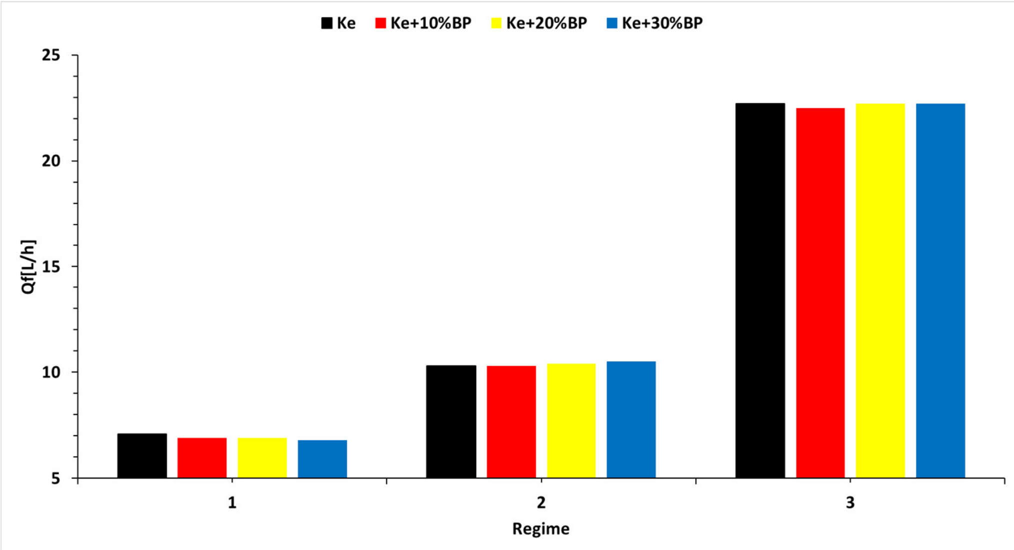

Figure 16. Variation of Qc [L/h] depending on the regime and blend.

Figure 17 provides the charts that display the variation of the thrust when the turbo-engine is powered by the fuel blends while operating in the 3 regimes mentioned above.

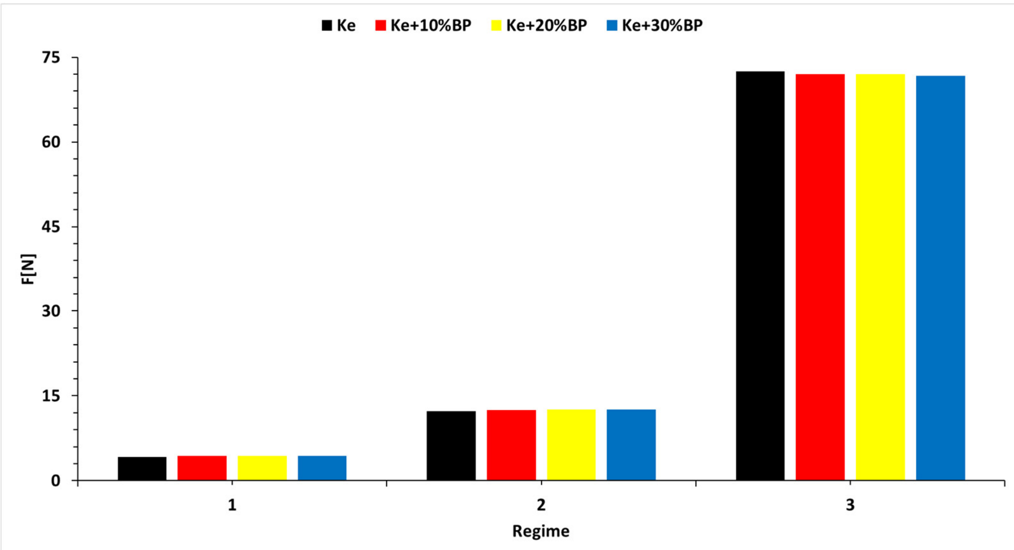

Figure 17. Variation of thrust F[N] depending on the regime and blend.

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In all cases, the thrust of the turbo-engine exhibits an increase when biodiesel concentration increases in the fuel blends tested, for all the four studied operating regimes.

By analysing the data from the Figures 15–17, the first conclusion that can be drawn is that the integrity and functionality of the turbo-engine are not affected when biodiesel is added in fuel.

When the turbo-engine operates at idling regime, the temperature in front of the turbine has greatest fluctuations of all operating regimes. Fuel consumption, has small fluctuations for all operating regimes and for all fuel blends.

Thrust exhibited positive variations of few percentages when the turbo-engine worked at idle and cruise regimes.

Figures 18–20 are showing the variation of the most important gaseous pollutants obtained during the combustion process. Thus, NO_x, SO_2 and CO emissions have been measured as described above.

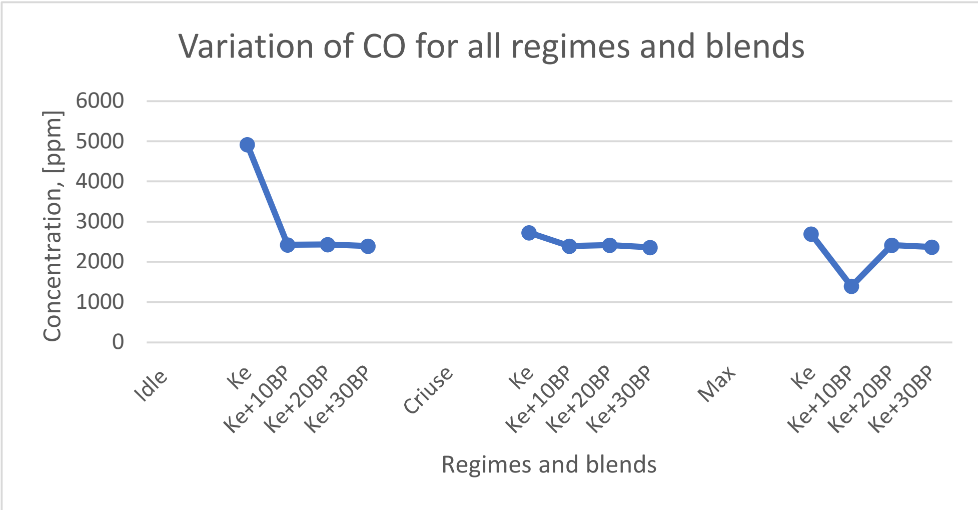

Figure 18. CO concentration vs. regimes and blends.

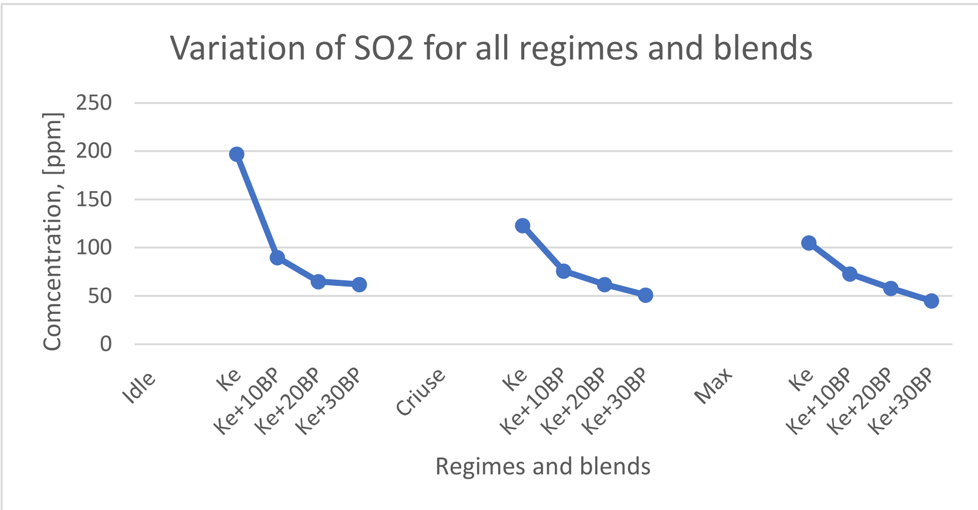

Figure 19. SO_2 concentration vs. regimes and blends.

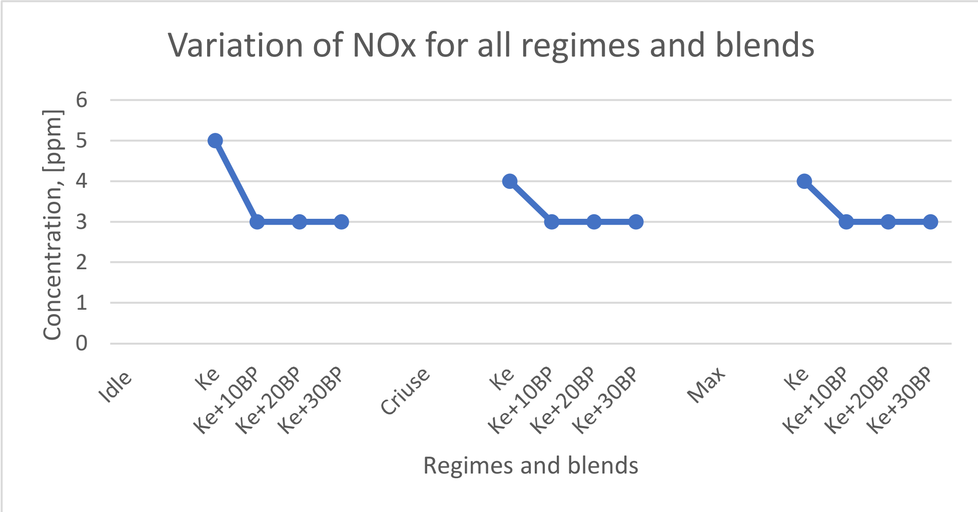

Figure 20. NO_x concentration vs. regimes and blends.

Figure 18 is showing a drastic decrease of the CO production when the blends are used compared to Jet-A especially during idle and maximum regimes. This aspect can be correlated with the data from Table 1 where is clearly shown that the amount of oxygen brought by the biodiesel into the blend increases, thus the need for outside air decreases, leading to an improved burning process and less CO production. Also, according to Table 1, carbon content decreases as the biodiesel concertation increases which may lead to a lower Coproduction during combustion process.

Figures 19 and 20 are also showing decreases of the gaseous pollutants while the concentration of biodiesel increases, although in the case of NO_x this decrease is slim. Nevertheless, the adding of biodiesel in the blend improves the combustion process, therefore less pollutants are formed. Even though the content of nitrogen (N) within the blends remains constant, the nitrogen from the outside air decreases as the need for outside air decreases. The same theory can be applied to sulphur.

3.3.2. Jet Engine Cycle Analysis

Performance parameters are computed based on the methodology outlined in reference [48]. Density determination for each examined fuel blend enables the conversion of measured fuel flow, as recorded by the engine instrumentation, from l/h to kg/s. The specific consumption (S) is defined by Equation (5):

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

where: Mf represents the fuel flow in kg/s. In the context of both comprehending combustion development within the combustion chamber and estimating combustion completeness, the calculation of combustion efficiency (ηb) is crucial. This efficiency is expressed by Equation (6), offering a quantitative measure of the effectiveness of the combustion process, serving as a valuable indicator in the analysis of engine performance and combustion dynamics:

$$\eta_b = \frac{(\dot{M}f + \dot{M}a)cp_{3\_comb} \cdot T_{\_comb} - \dot{M}a \cdot cp_{\_comp} \cdot T_{\_comp}}{\dot{M}f \cdot LCP} \quad (6)$$

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

The thermal efficiency of an engine, a crucial performance metric, is defined as the ratio of the net rate of organized work output to the rate of thermal energy available from the fuel within the engine. This parameter, denoted by Equation (7), provides a quantitative measure of the engine's effectiveness in converting the thermal energy from fuel combustion into useful work output. Thermal efficiency is a key indicator in assessing the overall performance and energy conversion capabilities of the engine under consideration:

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

Figures 21–23 are showing the variations of the specific fuel consumption, burning efficiency and thermal efficiency for the maximum regime for all 4 fuels.

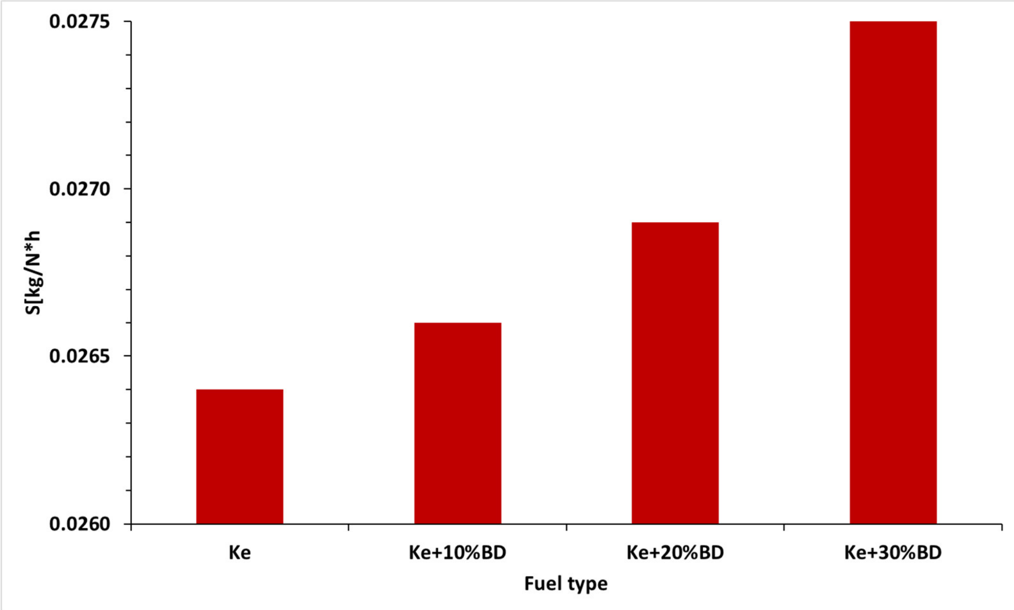

Figure 21. Variation of specific consumption for all the tested fuel blends.

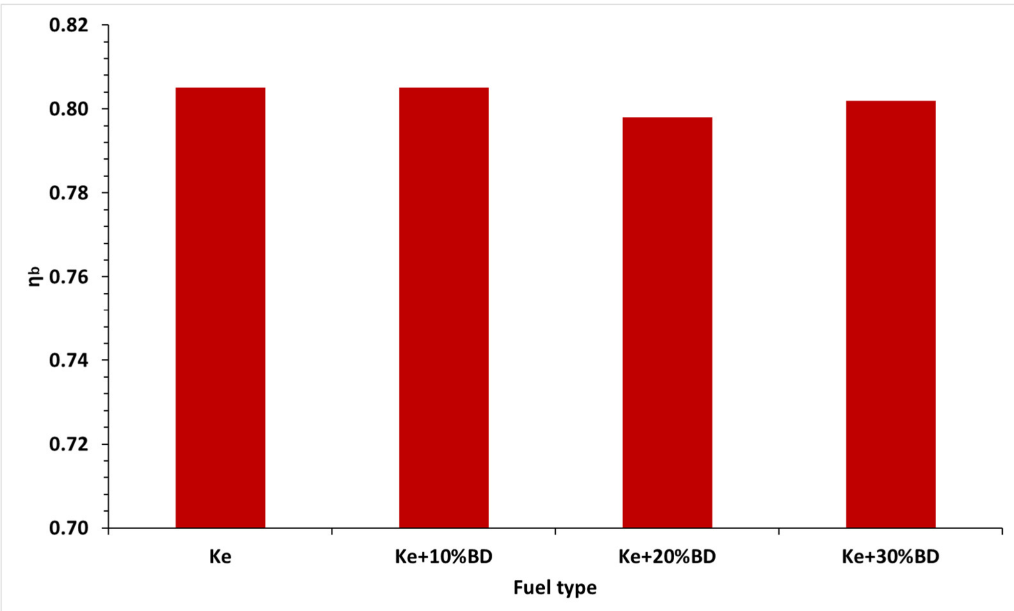

Figure 22. Variation of the combustion efficiency for all the tested fuel blends for 3 regimes.

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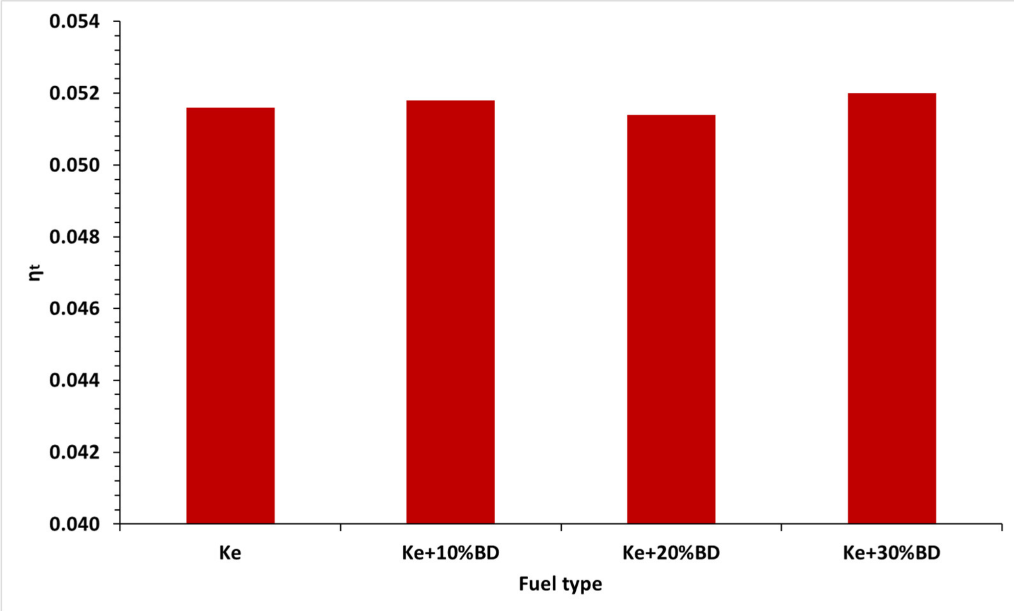

Figure 23. Variation of the thermal efficiency for all the tested fuel blends for maximum regime.

Figure 21 shows an increase of the specific consumption of fuel observed due to the higher concentration of biodiesel in the combustible blends and a lower calorific power of the blend.

It can be noted that specific consumption of the turbo-engine displays a small increase, which is a normal considering that the calorific power of the biodiesel is lower than the one of the Jet-A. Due to the lower LCV and higher specific consumption of the fuel blends comparing with the Jet-A, the introduction of the biodiesel in aviation as fuel will lead to the necessity of bigger fuel tanks.

Analysing Figures 22 and 23, 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 regular turbo-engine differs from those of the turbo-engines used for aviation applications.

The burning efficiency and the thermal efficiency exhibit small variations between the four tested combustible blends due to the increasing concentration of the biodiesel in the fuel blends tested.

4. Conclusions

The measurements made on Jet CAT P80® turbo-engine show that the addition of the biodiesel in fuel does not endanger the functionality of the turbo-engines.

A higher biodiesel concentration in blends will increase the freezing point which leads to the impossibility of using these blends at high altitudes without being heated. The calorific value decreases with the increase of the biodiesel concentration having as consequence the increase of the specific consumption.

Combustion temperatures in front of the turbines increase with the increase of biodiesel concentration without endangering the engine integrity. The combustion efficiency and the thermal efficiency of the engine do not show significant variations between the kerosene and the other mixtures.

The tests results presented in this paper showed that for all the studied cases, other than Jet-A fuel, the vibrations fit the limits of functionality, some regimes having slightly higher vibration levels. On the third regime presented, at a speed of around 80k RPM, the vibration levels are higher for the biodiesel blends that the Jet-A fuel. An explanation would be that the burn of biodiesel is causing a different temperature/pressure distribution on the turbine that produce an apparent unbalance.

The adding of biodiesel within the blends drastically decreases the gaseous emissions obtained from the combustion process. This is due to the fact that, on one hand BP brings more oxygen into the chemical formula and decreases the carbon content and, on the other hand it improved the combustion process and thus the need for outside air decreases.

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Data Availability Statement: Data are available on request at the above mentioned email addresses of the authors.

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