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Combustion and Emissions Characteristics of the Turbine Engine Fueled with HEFA Blends from Different Feedstocks

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Abstract: In the next decade, due to the desire for significant reduction in the carbon footprint left by the aviation sector and the development of a sustainable alternatives to petroleum, fuel from renewable sources will play an increasing role as a propellant for turbine aircraft engines. Currently, apart from five types of jet fuel containing synthesized hydrocarbons that are certified by the ASTM D7566 standard, there is yet another synthetic blending component that is at the stage of testing and certification. Hydroprocessed esters and fatty acids enable the production of a synthetic component for jet fuel from any form of native fat or oil. Used feedstock affects the final synthetic blending component composition and consequently the properties of the blend for jet fuel and, as a result, the operation of turbine engines. A specialized laboratory test rig with a miniature turbojet engine was used for research, which is an interesting alternative to complex and expensive tests with full scale turbine engines. The results of this study revealed the differences in the parameters of engine performance and emission characteristics between tested fuels with synthetic blending components and neat jet fuel. The synthetic blending component was obtained from two different feedstock. Noticeable changes were obtained for fuel consumption, CO and NO_x emissions. With the addition of the hydroprocessed esters and fatty acids (HEFA) component, the fuel consumption and CO emissions decrease. The opposite trend was observed for NO_x emission. The tests presented in this article are a continuation of the authors' research area related to alternative fuels for aviation.

Keywords: alternative fuels; emissions; HEFA process; synthetic blending component; turbine engine

1. Introduction

Aircraft engines emit pollutants, among which carbon dioxide (CO_2) is the most significant greenhouse gas (GHG), which boosts climate change. The aviation industry is responsible for approx. 2% of all anthropogenic CO_2 emissions worldwide [1]. Non-CO_2 emissions of jet fuel combustion (vapor trail, nitrous oxide and soot aerosols) raise the contribution of aviation to climate change up to 4.9% [2].

International Air Transport Association (IATA), the global airlines trade association, adopted ambitious targets to mitigate CO_2 emissions. There has been an average improvement in fuel efficiency of 1.5% per year from 2009 to 2020, carbon-neutral growth from 2020 and a halving of emissions by 2050 relative to 2005 levels [3]. The widespread use of fuels from renewable sources is a key measure to meet the set assumptions.

One of the ways to reduce the negative impact of aviation on the environment is the use of alternative fuels. The ASTM D7566 standard [4] has approved five types of aviation turbine fuels for turbine engines from a feedstock other than petroleum, which can contain up to 50% synthetic component. Hydroprocessed esters and fatty acids (HEFA) are one of the approved processes for obtaining alternative fuels which are also known as hydroprocessed renewable jet (HRJ).

The HEFA process consists in obtaining paraffins by chemical conversion of triglycerides by hydrogenation of triglycerides, monoglycerides, diglycerides, as well as free fatty acids and their esters. Hydrogenation removes oxygen from the molecules of esters of fatty acids and free fatty acids. The next production stages include hydrocracking, hydroisomerization, isomerization, fractionation or the combination of these. The production of these hydrocarbons can use other typical refinery processes [5,6]. The produced fuel containing synthesized hydrocarbons is chemically almost identical with conventional fuel, and it even exceeds some requirements set down for conventional turbine aviation fuel. It differs from fossil fuel in that it consists of exclusively paraffin hydrocarbons. These fuels do not contain aromatic compounds or sulfur. The feedstocks which are used for HEFA blending component production include vegetable oils (jatropha, camelina), animal fats (tallow), waste cooking oils and microalgal oils.

Fuels from HEFA process, as other alternative fuels obtained from the technologies approved for aviation, constitute the so-called drop-in fuel, which means that they are fully interchangeable and compatible. They do not require any changes in engines, fuel systems and fuel distribution networks. If a synthetic blending component is blended with conventional fuel, it must comply with ASTM D7566 requirements. However, each subsequent fuel recertification is carried out only and exclusively for compliance with the conventional fuel requirement—ASTM D1655 [7].

Alternative fuels tests may have a different nature and scope. It is possible to find numerous publications [8–13] on the tests of alternative fuels for gas turbines; these, however, do not mention a direct possibility of using them in aviation. There are several researchers who have tested alternative fuels for aviation application [14–18]. Some authors focused only on the tests of HEFA blends obtained from different feedstock [19–24].

The ASTM D7566 allowed five technologies with which synthetic blending components can be produced. The aforesaid standard contains detailed information on manufacture that must be applied to obtain each synthetic component but does not indicate which feedstock can be used. Feedstock is known to affect the chemical composition of jet fuel, which translates into its physicochemical properties, and this may have an adverse effect on the operation of the turbine engine.

The combustion characteristics of fuel, especially in the context of gaseous emissions, are very much important due to GHG emissions and climate change. Zhang et al. [25] reviewed turbine engine tests to evaluate their performance and pollutant emissions while using alternative jet fuels. Engine tests have been conducted on various engines: many types of aero-engines such as turbofan, turboshaft and APUs. Yang et al. [26] presents a review of the characteristics including gaseous emissions of bio-jet fuels. He remarks/observes that engine tests with alternative fuels are carried out on full-size engines, which entails huge costs. It is worth noting that there was one research related to small scale engine tests (SR-30 engine) [25]. The miniature engine tests, especially stationary power units, are an interesting solution in the field of alternative fuels.

The aim of this study is the performance and emissions characteristics of a small scale turbojet engine fed with Jet A-1/HEFA blending component obtained from camelina and used cooking oil (UCO). The blend results were compared with those obtained for neat Jet A-1.

2. Materials and Methods

2.1. Description of the Test Rig

The tests were carried out on the GTM-140 miniature turbojet engine, being a part of the laboratory test rig, MiniJETRig (Miniature Jet Engine Test Rig), for aviation fuel combustion process research.

Gawron and Białecki [27] presented in detail the construction and research capabilities of the test rig and the technical specification and measurements of the miniature turbojet engine [28] (Table 1). For these tests, the engine with pneumatic start-up and a straight duct in the exhaust system was selected, which allows for obtaining the maximum thrust of 70 and enables the measurement of the mass flow rate. In order to minimize the effect of dilution of exhaust gas, a gas analyzer measuring probe was placed centrally at a distance of not more than $\frac{1}{2}$ of the diameter of the engine exhaust nozzle, in accordance with ARP 1256 [29].

Table 1. Details of measurement equipment for gas emissions.

Parameter	Sensor Type	Range	Least Count	Accuracy
CO	electrochemical	0–2000	0.1 ppm	±5% measured value
CO_2	infrared	0–25	0.01%	±5% measured value
NO	electrochemical	0–500	0.1 ppm	±5% measured value
NO_2	electrochemical	0–100	0.1 ppm	±5 ppm

The fact that lubrication of bearings is mainly carried out in the open system by adding oil to the fuel is an unfavorable factor for conducting the research work on miniature engines because it has a negative impact on combustion assessment, especially in terms of exhaust emissions. Oil flow contained in the fuel was eliminated by splitting the power supply into two independent systems. Owing to this fact, the fuel reaching the combustion chamber becomes neat test fuel.

The miniature turbojet engine GTM-140 is used not only in aviation alternative fuels research area but also for emission toxicity tests. The results of the preliminary studies were presented by Gawron et al. [30,31] and Janicka et al. [32].

2.2. Tested Fuels

The tests made use of the widely used Jet A-1 fuel and its blends with the component obtained from HEFA technology, described by Gutiérrez-Antonio et al. [5] in detail. The feedstocks of synthetic blending components are camelina oil plant and UCO. A blend of Jet A-1 with the HEFA component derived from camelina was marked as HEFA CAM, whereas, the one from UCO was marked as HEFA UCO. The synthetic blending component content makes up respectively 48% and 50%.

UCO is a waste from the food industry, and it has a limited use. Since it does not compete with a food chain, and offers a significant reduction in CO_2 emissions, it is qualified as sustainable feedstock, whereas camelina sativa is a plant that produces inedible oil seeds. This feedstock can be grown on marginal land, which is not currently used, does not compete with other plants and yields an excellent crop.

The tested conventional fuel meets the requirements of ASTM D1655, while the synthetic components and its blends complies with the standard of ASTM D7566. Table 2 presents the selected physicochemical properties of all tested fuels.

Table 2. Jet A-1 and Hydroprocessed esters and fatty acids (HEFA) blends selected properties.

Property	Unit	Limits ASTM D1655/D7566	Results		
			Jet A-1	HEFA CAM	HEFA UCO
Density at 15 °C	kg/m^3	775.0 ÷ 840.0	790.2	779.9	771.1
Viscosity in −20 °C	mm^2/s	Max 8.0	3.117	4.968	3.514
Heat of combustion	MJ/kg	Min 42.8	43.307	43.691	43.744
Flash point	°C	Min 38	42.0	44.5	43.5
Freezing point	°C	Max −40	−63.8	−57.5	−51.5
Smoke point	mm	Min 18	25.0	25.0	26.0
Naphthalenes	(*v*/*v*) %	Max 3.0	0.47	0.57	0.24
Aromatics	(*v*/*v*) %	Max 25	15.0	9.1	7.2

The analysis of laboratory results shows that input of HEFA component did not cause significant changes in selected physicochemical properties. The density and the content of aromatics reduction was observed in relation to neat Jet A-1. However, there occurred an increase in viscosity at the temperature of −20 °C and in the heat of combustion. High viscosity can contribute to poor atomization, which in turn causes incomplete combustion.

It was also observed a deterioration of properties of HEFA blends at low temperatures, the parameter, in which case the fulfilment of requirements was unreachable by first generation biofuels (candidates for the aviation turbine fuel). However, the obtained values are sufficient to meet the requirements of the applicable standards.

2.3. Procedure and Test Conditions

Bench tests were carried out in accordance with a methodology and profile of the engine run presented in Reference [28]. The selected four rotational speeds correspond to various characteristic operating modes of the turbine engine. The engine run time at a given speed has been selected to guarantee the stability of the measured parameters.

A slight change was made in the above-mentioned methodology. The rotational speed of 39,000 rpm (idle) was replaced with 45,000 rpm, which was necessitated by the problems connected with the fuel flow measurement in the initial operating range of a fuel consumption sensor at the low rotational speed. Figure 1 demonstrates the modified test profile.

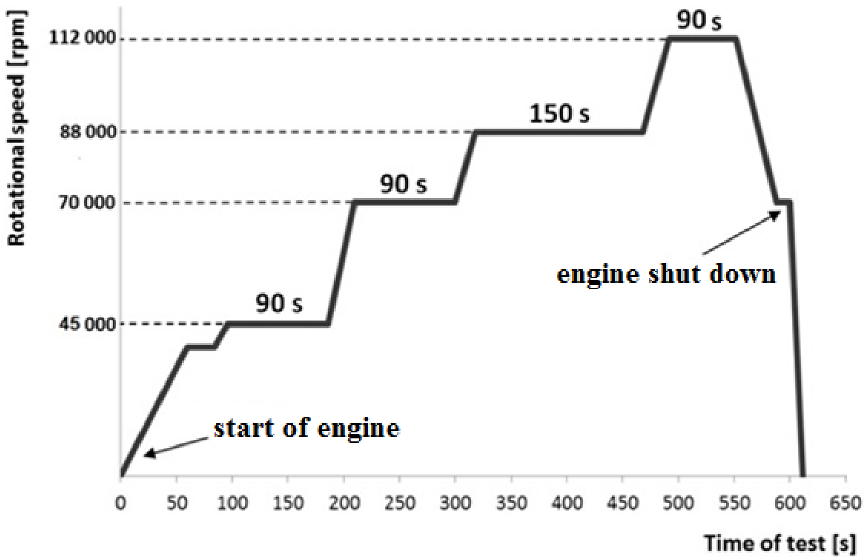

Figure 1. Modified profile of engine test.

In order to minimize the impact on ambient conditions, which affects both the engine performance and the characteristic of gaseous emissions, the bench tests were carried out in the same day. Table 3 presents the detailed ambient conditions, i.e., pressure, temperature and relative humidity.

Table 3. Ambient test conditions.

Fuel	Test No.	P_o (hPa)	T_o (°C)	RH (%)
Jet A-1	Test 1	995.2	27.9	62.0
	Test 2	995.1	28.8	60.3
HEFA CAM	Test 1	994.3	30.7	50.2
	Test 2	994.1	31.0	48.5
HEFA UCO	Test 1	994.8	29.4	55.9
	Test 2	994.7	29.9	52.8

2.4. Uncertainty Analysis

Experiments for each tested fuel were executed twice. The analyzed parameters in every individual test were averaged in selected sets of measurement data, characterized by small values of standard deviations. Next, the results were averaged. The average value of each parameter was supplemented with a maximum and minimum value, which correspond to the extreme values from single engine runs [21]. Uncertainty of measurement equipment was presented in [28] (engine sensors) and [13] (gas analyzer sensors).

3. Results and Discussion

3.1. Combustion Characteristics

The results of the engine tests for two different synthetic blending components obtained from the same HEFA technology were compared with those for conventional aviation turbine fuel Jet A-1. Due to high measurement uncertainty of the performance parameters at 45,000 rpm, the analysis of results at this speed was omitted.

Figure 2 shows the results for thrust (K), fuel consumption (C_f), thrust-specific fuel consumptions (TSFC) and turbine temperature (T4), whereas Figures 3–5 present relative changes of thrust, fuel consumption and TSFC of a different feedstock of the synthetic-blending-component-fed engine in relation to neat Jet A-1.

This section may be divided by subheadings. It should provide a concise and precise description of the experimental results, their interpretation as well as the experimental conclusions that can be drawn.

Within the range of the engine thrust (Figure 3), values of this parameter for HEFA blends are higher as compared with those for neat Jet A-1. The higher thrust values obtained for HEFA blends result from their higher combustion heat. However, as the speed increases, these differences are becoming smaller. This may be related to measurement accuracy of the applied sensor, which is characterized by greater inaccuracy when measuring low thrust.

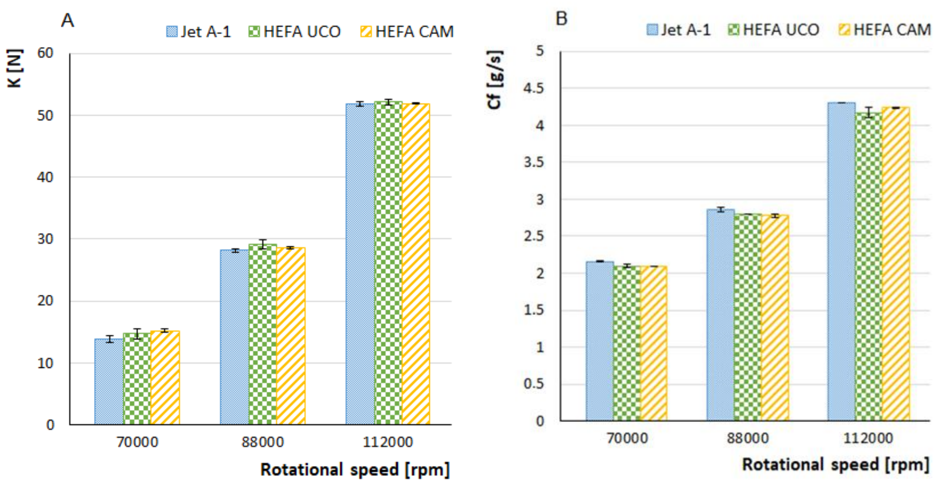

Figure 2. *Cont.*

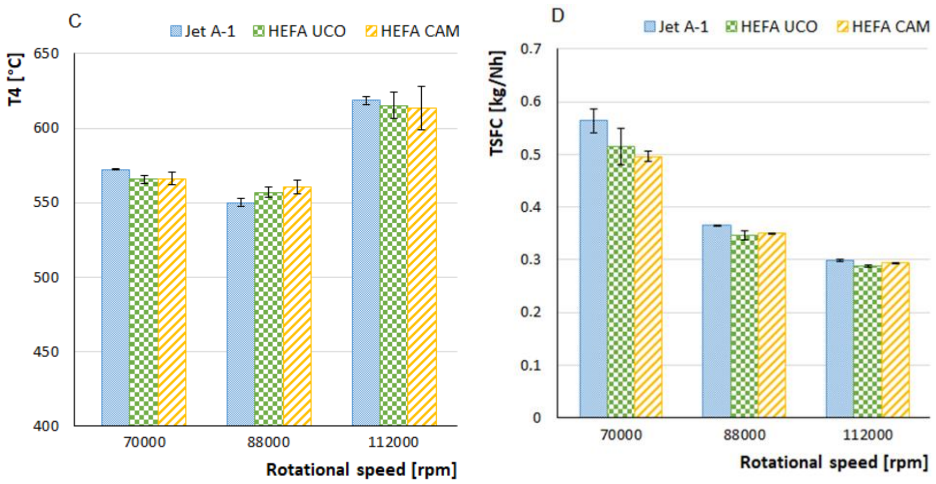

Figure 2. Selected engine parameters as a function of rotational speed. (**A**) thrust, (**B**) fuel consumption, (**C**) turbine temperature, (**D**) thrust specific fuel consumptions.

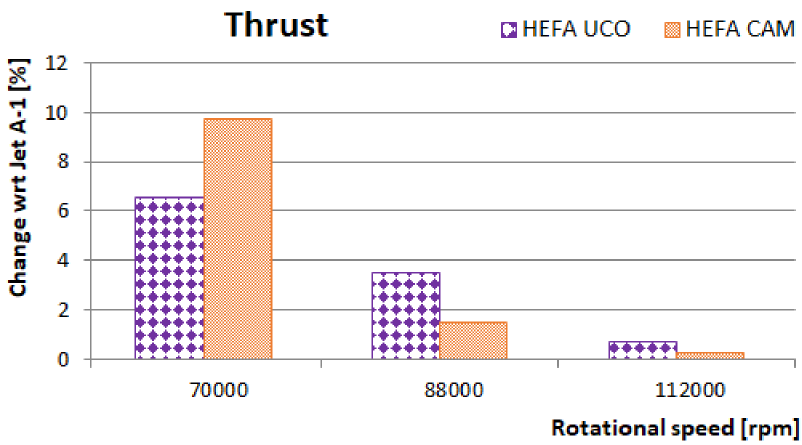

Figure 3. Changes of engine thrust for synthetic blending components with regard to Jet A-1.

The fuel consumption for both blends with synthetic blending component (Figure 4) during engine tests on all rotational speeds is characterized by a lower value than that for Jet A-1. Most of these differences are above the range of measurement error of the sensor (accuracy ±2% for turbine flow meter). The results are determined by the physicochemical properties of tested fuels. Both HEFA blends compared to Jet A-1 fuel are characterized by lower density and higher combustion heat.

TSFC (Figure 5) for the HEFA blends are characterized by lower values compared with Jet A-1. The differences between fuels are getting smaller as the speed increases. This is caused by smaller differences in engine thrust at higher rotational speeds.

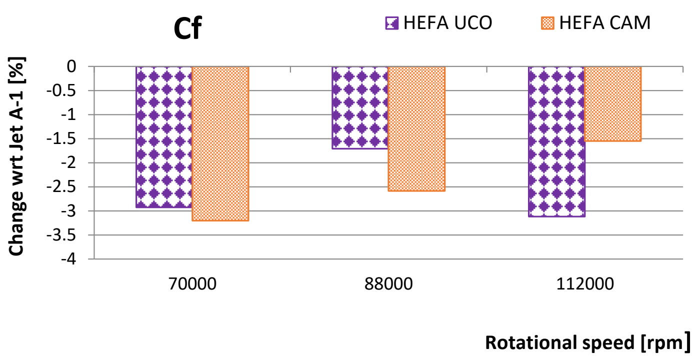

Figure 4. Changes of fuel consumption for synthetic blending components with regard to Jet A-1.

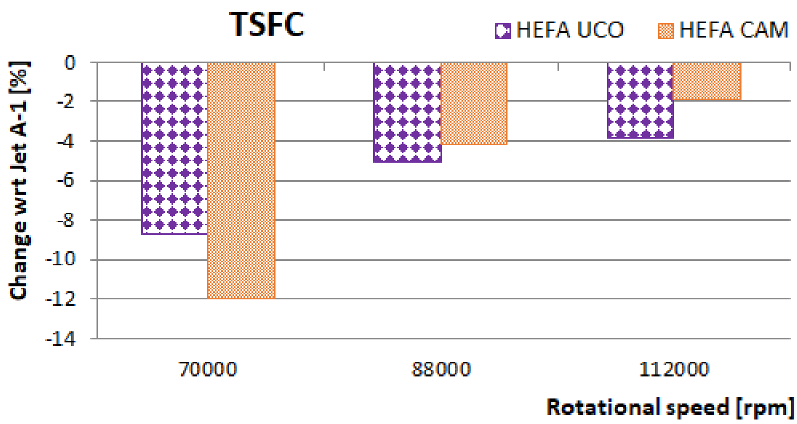

Figure 5. Changes of thrust-specific fuel consumptions (TSFC) for synthetic blending components with regard to Jet A-1.

3.2. Exhaust Emissions Characteristics

Figure 6 provides results for oxygen (O_2), carbon oxide (CO), carbon dioxide (CO_2) and nitrogen oxides (NOx) whereas Figures 7–9 present relative changes of the emissions of O_2, CO and CO_2 for different feedstocks of synthetic-blending-component-fed engine as compared to the emissions for neat Jet A-1. The data for CO, CO_2 and NO_x were converted from the value of parameters measured in ppm or % to emission indices expressed in g/kg of fuel.

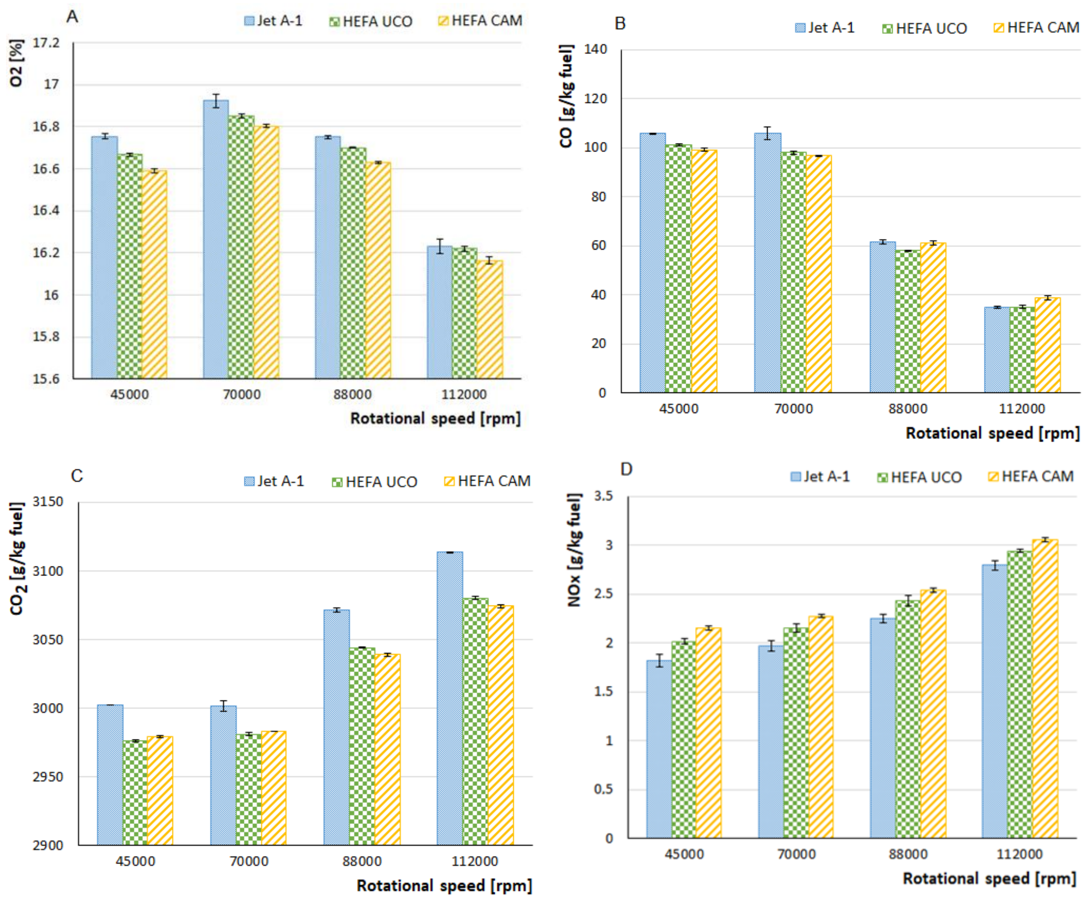

Figure 6. Selected gas component emission as a function of rotational speed. (**A**) O_2, (**B**) EI CO, (**C**) EI CO_2, (**D**) EI NO_x.

Figure 7 demonstrates that the combustion in the engine for all the tested fuels was carried out with the same proportion of oxygen in the chamber (changes do not exceed 1%).

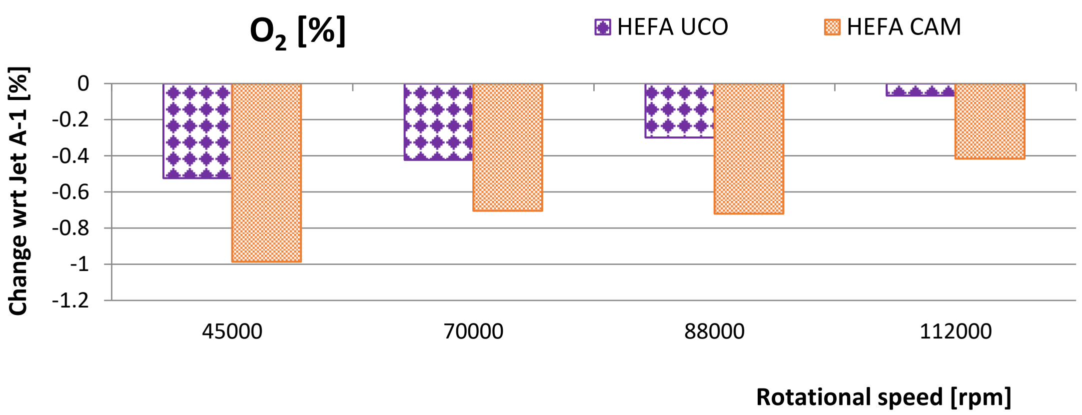

Figure 7. Changes of O_2 emission for synthetic blending components with regard to Jet A-1.

Figure 8 shows that CO emissions for HEFA blends in relation to Jet A-1 for the analyzed engine operating conditions are lower (except for 112,000 rpm). Measurements of CO emissions at the highest rotational speed, due to a decrease in the value of CO emissions along with an increase in speed, are burdened with the greatest inaccuracy. The biggest difference between these fuels was approx. 9% in the case of the rotational speed of 70,000 rpm.

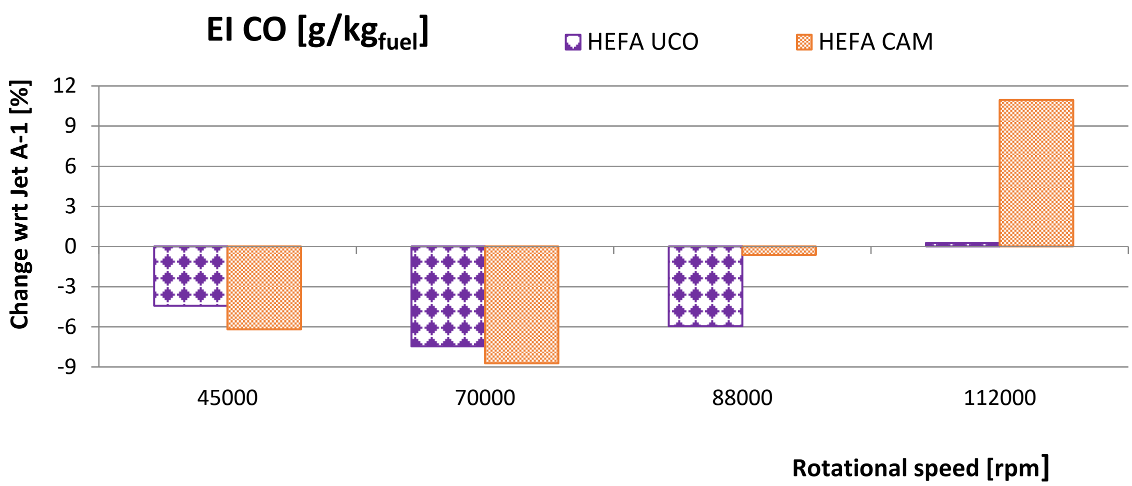

Figure 8. Changes of CO emission index for HEFA blends with regard to Jet A-1.

The CO_2 emission (Figure 9) for both HEFA blends at all the analyzed states of engine operation are lower in comparison with that of Jet A-1. The CO_2 emission changes do not exceed 1.5%. Within the range of this parameter, there are no significant changes between tested fuels.

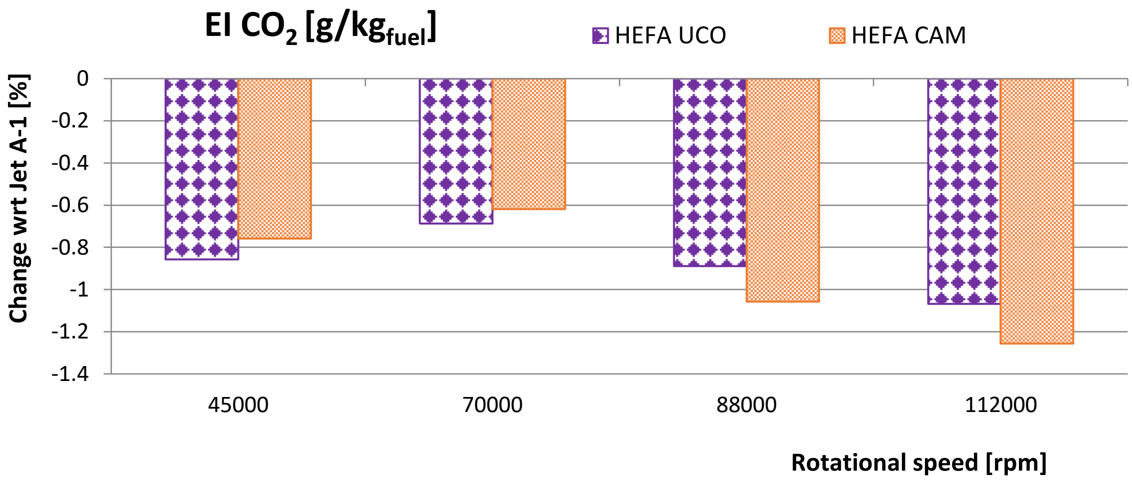

Figure 9. Changes of CO_2 emission index for HEFA blends with regard to Jet A-1.

The NO_x emission (Figure 10) for both HEFA blends at all the analyzed states of engine operation are higher in comparison with Jet A-1. The biggest differences between tested fuels obtained at 45,000 rpm, approx. 22% for HEFA CAM and approx. 12% for HEFA UCO. As the speed increases, the differences between HEFA blends and Jet A-1 become smaller. The increase in NOx emissions can be explained by the fact that the HEFA blends are characterized by higher heat of combustion than Jet A-1. Whereas higher heat of combustion can translate into higher temperature in the combustion chamber.

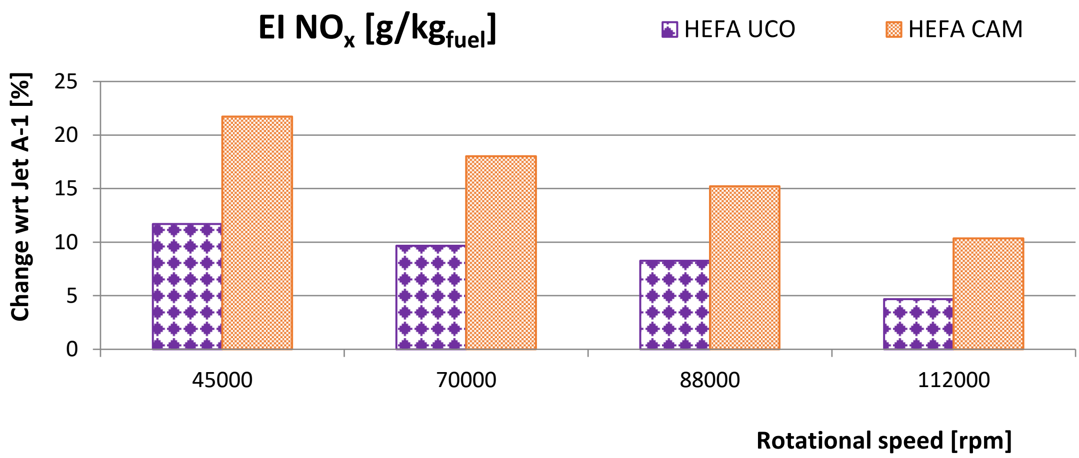

Figure 10. Changes of NO_x emission index for HEFA blends with regard to Jet A-1.

4. Conclusions

Investigation of the performance and emissions characteristics for the miniature turbojet engine using a Jet A-1/HEFA blends were studied. The HEFA component was obtained from two different feedstock: camelina and used cooking oil. The HEFA fuels results were compared with the corresponding values for neat Jet A-1. The tests were carried out according to a specified methodology including authorial profile of engine tests. The presented work contains new studies, which are a continuation of the authors' research area related to alternative fuels.

The main results can be summarized as follows:

- The analysis of experimental data indicates differences in the operation of the miniature jet engine if it runs on neat Jet A-1 or on HEFA blends, which shows especially in fuel consumption and CO emission. Fuel consumption and CO emission for HEFA blends are lower than Jet A-1. HEFA blends have a higher calorific value and lower density compared to neat jet fuel.

- No significant variations in the turbine temperature and CO_2 emissions on all engine operating states for tested fuels.
- Significant differences for tested fuels are obtained for NO_x emissions. HEFA component, for both camelina and used cooking oil, added to aviation fuel increases NOx emissions.

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Abbreviations

Symbol	Definition	Units
CO_2	carbon dioxide	%
K	thrust	N
C_f	fuel consumption	g/s
T_4	turbine temperature	°C
TSFC	thrust-specific fuel consumptions	kg/Nh
O_2	oxigen	%
EI CO	emission index of carbon monoxide	g/kg_{fuel}
EI CO_2	emission index of carbon dioxide	g/kg_{fuel}
EI NO_x	emission index of nitrogen oxides	g/kg_{fuel}

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