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Article

Performance and Emissions of a Microturbine and Turbofan Powered by Alternative Fuels

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Abstract: Alternative fuels containing biocomponents produced in various technologies are introduced in aviation to reduce its carbon footprint but there is little data describing their impact on the performance and emissions of engines. The purpose of the work is to compare the performance and gas emissions produced from two different jet engines: the GTM-140 microturbine and the full-size DGEN380 turbofan, powered by blends of Jet A-1 and one of two biocomponents: 1) ATJ and 2) HEFA produced from used cooking oil (UCO) in various concentrations. The acquired data will be used to develop an engine emissivity model to predict gas emissions. Blends of the mineral fuel with synthetic components were prepared in various concentrations, and their physicochemical parameters were examined in the laboratory. Measurements of emissions from both engines were carried out in selected operating points using the Semtech DS gaseous analyzer and the EEPS spectrometer. The impact of tested blends on engine operating parameters is limited, and their use does not carry the risk of a significant decrease in aircraft performance or increase in fuel consumption. Increasing the content of biocomponents causes a noticeable rise in the emission of CO and slight increase for some other gasses (HC and NOx), which should not, however, worsen the working conditions of the ground personnel. This implies that there are no contraindications against using tested blends for fuelling gas-turbine engines.

Keywords: turbofan; microturbine; sustainable aviation fuel; ATJ; HEFA; emissions; alternative fuel; biocomponent; combustion; fuel blend; drop-in fuel; synthesized kerosene

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1. Introduction

In order to reduce CO_2 emissions, as well as make use of inedible raw materials from renewable sources, alternative fuels containing biocomponents produced in various technologies are introduced in aviation [1–3]. However, there is much less experience in using biofuels to propel aircraft than in using mineral fuels. Currently, ASTM D 7566 standard allows for seven synthetic fuel production technologies to be used in aircraft turbine engines (Table 1), including Alcohol-to-Jet (ATJ) and Hydroprocessed Esters and Fatty Acids (HEFA). ATJ and HEFA belong to well-established sustainable aviation fuels (SAF) which do not require modifications in engines, aircraft or ground infrastructure (drop-in fuels) if used within the permissible mixing ratio.

Air-quality measurements clearly show that a single take-off or landing operation noticeably increases the concentration of toxic compounds in the air [4]. The widespread use of gas-turbine engines contributes to the deterioration of air quality in and around airports, and the negative impact of emitted gases and particles on health is of concern within ground personnel and neighbouring communities. Although emissions of all large engines are controlled during aircraft certification, the high intensity of air operations causes an accumulation of pollutants. Therefore, it is necessary to

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widely monitor air quality [5], especially in the vicinity of airports. After many years, the introduction of new rules for the certification of aircraft engines by ICAO began, which is associated with the use of a new measurement methodology, which has been proposed in publications over the past years [6]. Recent research efforts [7] are aimed at measuring gaseous and particulate emissions under real conditions and better understanding their toxicity and impact on health [8–10].

Alternative fuels are expected not to increase emissions and provide a comparable or better engine performance. Blends with the ratio of biocomponents lower than the maximum allowable one are used mainly due to the higher cost of the alternative fuel or for fear of their impact on engine durability or performance. Therefore, when an alternative fuel is introduced into the fleet, the ratio of the biocomponent is gradually increased, observing its impact on the parameters and health of the engines.

New types of alternative fuels are synthesised in small quantities, insufficient to power large engines. This is why microturbines are often used to test new blends [11–14] despite the fact that their structure differs considerably from one of the commercial engine.

More and more often, scientific activity is focused on the development of models of emissions of toxic compounds from aviation [3] and their validation in real flight conditions and laboratory tests. To describe various fuels and blends, it is necessary to define their thermophysical parameters. In zero-dimensional models of engines, which are developed in GSP [15] or GasTurb [16,17], a simplified analytical description of combustion and tabulated values of temperature for fuel blends are often used. In the modelling of combustors, thermodynamic equations are used to describe combustion and heat transport [18,19]. When designing new combustors with reduced emissions, complex numerical CFD models are used [20,21]. An engine emissions data bank [22] and machine learning [23] models using statistical methods [24] or artificial intelligence are also used to predict emissions.

Reducing emissions from aircraft

have adverse effects on the air quality in and around airports, contributing to public health concerns within neighbouring communities.

Table 1. Certified processes for Sustainable aviation fuel [25]

Abbreviation	Conversion Process	Possible Feedstocks	Ratio
FT-SPK	Fischer-Tropsch hydroprocessed synthesized paraffinic kerosene	Coal, Natural Gas Biomass	$\leq$ 50%
HEFA-SPK	Synthesized paraffinic kerosene produced from hydroprocessed esters and fatty acids	Bio-Oils, Animal Fat Recycled Oils	$\leq$ 50%
SIP	Synthesized kerosene isoparaffins produced from hydroprocessed fermented sugars	Biomass used for sugar production	$\leq$ 10%
SPK/A	Synthesized kerosene with aromatics derived by alkylation of light aromatics	Coal, Natural Gas Biomass	$\leq$ 50%
ATJ-SPK	Alcohol-to-jet synthetic paraffinic kerosene	Biomass from ethanol or isobutanol production	$\leq$ 50%
CHJ	Catalytic Hydrothermolysis Jet from hydrothermally processed fatty acid esters and fatty acids	Triglycerides such as soybean oil, jatropha oil	$\leq$ 50%
HC-HEFA	Synthesized paraffinic kerosene produced from hydroprocessed hycracarbons, esters and fatty acids	Algae	$\leq$ 10%

In this work, both a microturbine and full-size engine are used to generalise some results that can only be obtained with a microturbine. The purpose of the study is to compare the performance and gas emissions produced from two different jet engines: the GTM-140 microturbine and the DGEN380 geared turbofan. The acquired data will be used to develop an engine emissivity model to predict emissions of exhaust gas compounds.

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2. Methods

Blends of the mineral fuel with synthetic components were prepared in various concentrations and their physicochemical parameters were examined in the laboratory. The engines were powered by blends of Jet A-1 and one of two biocomponents: 1) ATJ and 2) HEFA produced from used cooking oil (UCO). Measurements of gas emissions from the GTM-140 microturbine were carried out in selected operating points using the Semtech DS gaseous analyzer and the EEPS spectrometer. Similar emission measurements were made for the DGEN380 engine in a test cell. Measurements were averaged for each operating point, visualised and compared. Results were analyzed in the scope of physicochemical parameters of fuel blends, engine operating parameters and gas emissions (Figure 1).

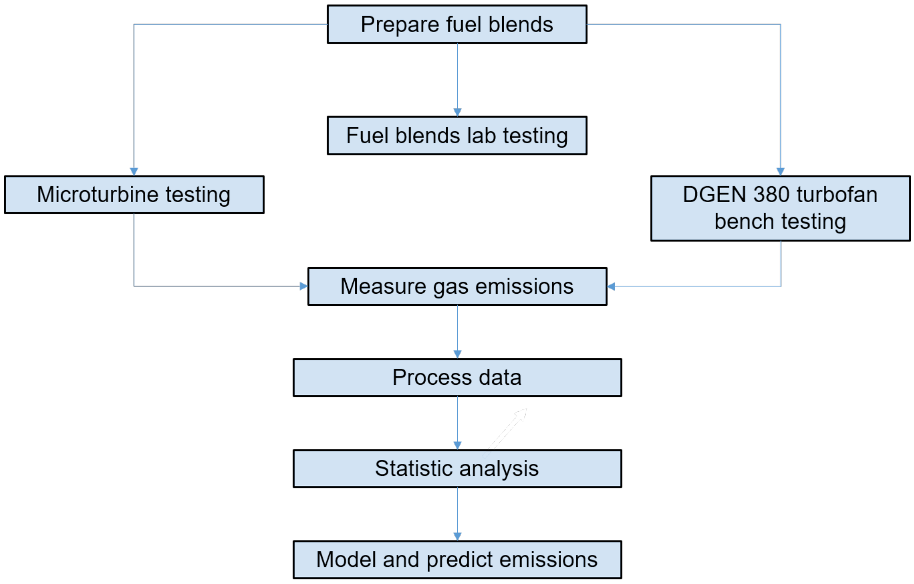

Figure 1. Testing methodology

2.1. *Fuel lab testing*

In the fuel lab , physicochemical properties of prepared blends were tested such as: density at 15°C, viscosity at -20°C and -40°C, calorific value, the aromatics and naphthalenes content, flash point, crystallisation temperature, non-smoking smoke point and distillation. The selected properties are important for the combustion process and engine operation and are also defined in the ASTM D1655-18a and ASTM D7566-18 documents.

2.2. *GTM-140 microturbine*

The GTM-140 microturbine (Figure 2) consists of a single-stage radial compressor, driven by a single-stage axial turbine, and an annular combustion chamber with a set of evaporators. It operates in the range of 33,000 - 120,000 rpm and can produce take-off thrust up to 140 N. The tested variant of the microturbine played the role of a combustor rig and was devoid of a converging nozzle. For this reason, the generated thrust was limited to 70N, and consequently SFC values were high (above 200 kg / kN / h). However, in this work, the absolute values of the parameters were less important than their relative changes in response to the increased biocomponent ratio.

The test bench is equipped with a portable GA60 gas analyzer (Figure 3) which was used in previous emission research [26–28]. Exhaust gases are sampled from the engine nozzle using a probe and delivered through a heated exhaust hose to the instrument. The analyzer is equipped with electrochemical sensors to measure O_2, CO, NO, NO_2, SO_2 gases and two NDIR sensors for infrared measurement (CO_2 and C_xH_y). The exhaust gas components are measured with the resolution of 0.1

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ppm and uncertainty of 5%. The analyzer also enables the measurement of exhaust gas temperature through a thermocouple built inside the probe. Operating parameters and emissions are presented and stored by the data acquisition system developed in LabVIEW [29] Additionally, the Semtech DS gaseous analyzer (Figure 4) and Engine Exhaust Particle Sizer (EEPS 3090, Figure 5) operated by Poznan University of Technology were used with a respective exhaust sampling system (Figure 6). Exhaust gases were introduced to the Semtech DS analyzer through a probe maintaining the temperature of 191°C and the exhaust sample was directed to the flame-ionizing detector (FID) where HC concentration was measured. Then the sample was cooled down to temperature of 4°C and the concentration measurement of NOx (NDUV analyzer), CO, CO2 (NDIR analyzer) was performed.

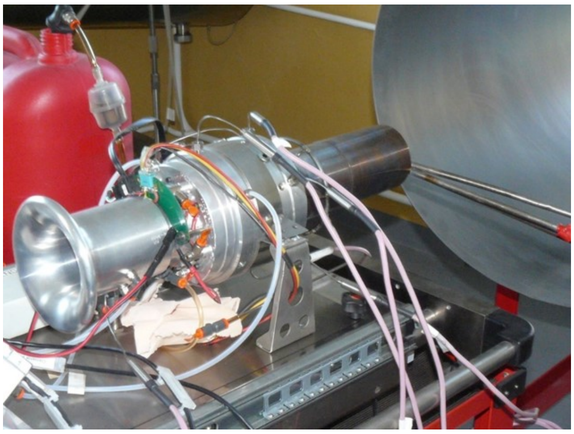

Figure 2. GTM-140 microturbine

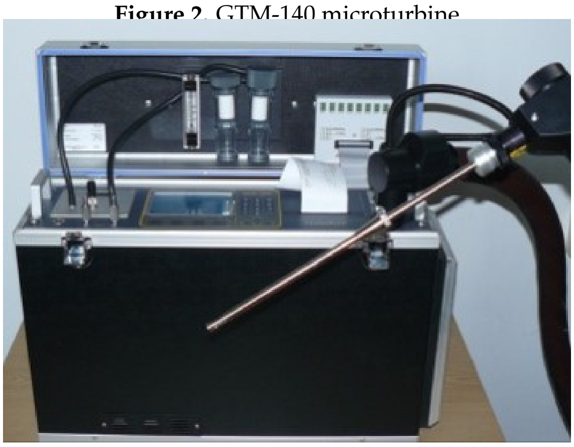

Figure 3. GA-60 emissions analyser

2.3. *DGEN 380 turbofan*

DGEN 380 is a high bypass ratio (7.6) geared turbofan, producing 255 daN of thrust (Figure 7). It has a layout similar to modern commercial engines, low fuel consumption and is well instrumented. The data acquisition system of the WESTT test cell (Figure 8) enables data acquisition and analysis of several engine performance parameter such as thrust, fuel consumption, temperature and pressure. The turbofan was developed for ultralight aircraft but has not been certified yet, so it is not covered by the ICAO emissions databank. In this work, the Semtech DS analyzer was used to measure CO, CO_2, HC and NO_x emissions. These are probably the first published results of gaseous emissions for this engine.

During tests of the DGEN380 turbofan with biocomponents, a finite amount of fuel in the tank was used to maintain a constant blend ratio throughout the test. This means that the tank was not constantly refilled with fuel as was the case with testing on the Jet A-1 fuel. With the tank almost empty, the flow resistance may have increased, but no lower fuel pressure was observed, nor was the

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Figure 4. SEMTECH-DS

Figure 5. EEPS 3090

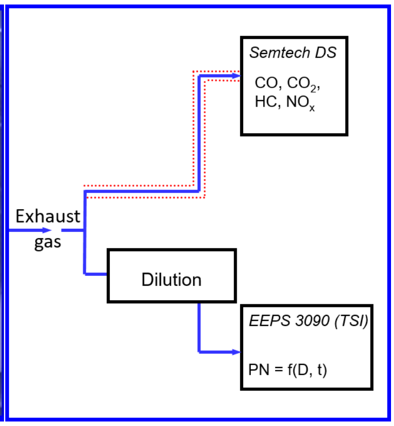

Figure 6. Exhaust gas sampling

fuel pump running at higher RPM. Nevertheless, it turned out that the fuel flow was slightly lower (by 2%) and as a result, it the nominal thrust was not achieved, despite the PLA set at 100%.

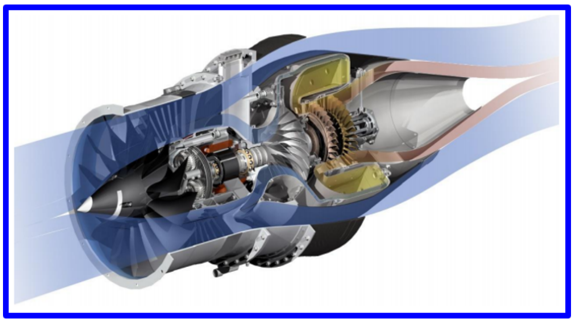

Figure 7. DGEN 380 geared turbofan

Figure 8. Test cell

2.4. Engine testing

Engine emissions significantly depend on its operating mode (Figure 9), so they are tested in selected operating points that belong to the Landing and Take-Off cycle (LTO), according to the ICAO procedure [30]. Engine test steps correspond to the following operating modes: takeoff, climb, cruise, approach and taxi/ground idle. The tests performed on both types of engines consisted of a series of operating points, where the speed was increased in subsequent steps (Figure 10). Performance parameters and emissions were measured and averaged over 30 seconds for the microturbine and 60 seconds for the turbojet. Tests with ATJ blends were performed one day under stable ambient conditions while tests with HEFA were performed one year later under similar conditions.

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When comparing the individual blends, an identical mission profile was repeated, consisting of a series of operating points. Efforts were made to ensure that the rotational speeds were the same in subsequent tests, but it was difficult, especially for intermediate speeds. The engine operation range was selected using PLA and FADEC and it was not possible to fine-tune speed or thrust. There are slight but significant speed differences between the test-runs, which is especially important when analysing changes in engine performance.

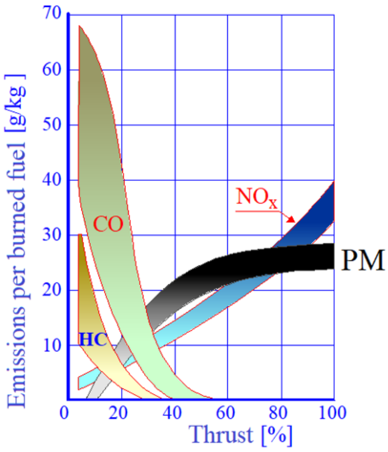

Figure 9. Emissions vs thrust

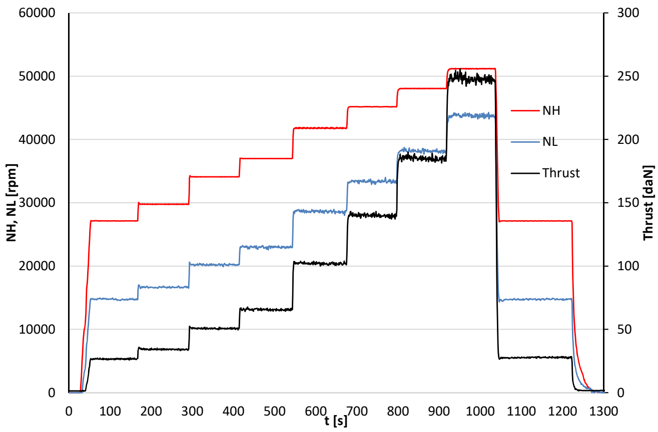

Figure 10. Engine test profile

3. Results

3.1. Fuel lab testing

Lab testing confirmed that the mineral fuel meets the requirements of the ASTM D1655 standard, while ATJ and HEFA biocomponents and their blends comply with ASTM D7566. Table 2 presents the selected physicochemical properties of all tested fuels. The results show that neat biocomponents and their blends are characterised by a lower density than Jet A-1. This has an impact on fuel mass flow. Moreover, biocomponents have a slight higher calorific value, which may result in higher values of the produced heat and a higher EGT. As it is well known, higher combustion temperature increases NO_x emissions. Moreover, neat bio-components are free from aromatics which generally have the least desirable combustion characteristics among kerosene's major components .

Table 2. Fuel lab testing results

Fuel	Density at 15°C kg/m3	Viscosity at -20°C mm2/s	Calorific value MJ/kg	Aromatics (v/v)%	Naphtha-lenes (v/v) %	Flash point °C	Freezing point °C	Smoke point mm
ASTM	775-840	Max 8.0	Min 42.8	Max 25	Max 3.0	Min 38	Max -40	Min 18
Jet A-1	798	3.40	43.2	16.7	0.58	49.5	-63.5	20
5% ATJ	796	3.45	43.3	15.7	0.55	49.0	-65.5	23
20% ATJ	790	3.57	43.4	13.0	0.46	49.0	-66.5	25
30% ATJ	786	3.66	43.4	11.3	0.40	49.0	-66.8	28
50% ATJ	776	3.65	43.6	8.8	0.27	44.5	-60.0	30
ATJ	759	4.78	44.0	0.0		47.5	-67.5	
Jet A-1	796	3.25			0.55	49	-62.6	23
5% HEFA	794	3.29			0.52	48	-62.8	27
20% HEFA	787	3.40			0.44	46	-59.6	28
30% HEFA	783	3.47			0.39	46	-56.0	
HEFA	752	4.09	44.2			45	-39.9	

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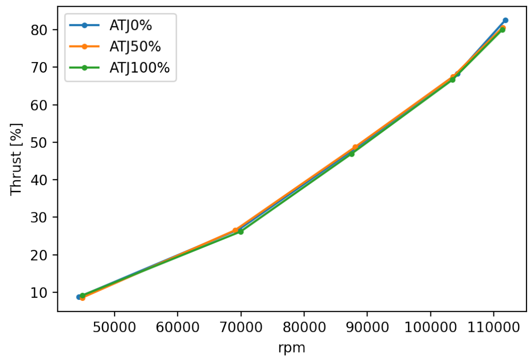
3.2. Microturbine - ATJ

During engine tests, the operating parameters such as thrust (Figure 11) and SFC (Figure 12) remain stable, with insignificant differences between tests. Plots below (Figures 13-16) present the CO, CO2, HC and NO_x emissions of engine fuelled by blends with increasing ratio of the biocomponent (Jet A-1, 50% blend of Jet A-1 with the ATJ component and neat ATJ component). Values are averaged for 30 seconds while error bars show the triple standard deviation from the mean.



ATJA.png

Figure 11. GTM-140/ATJ: Thrust

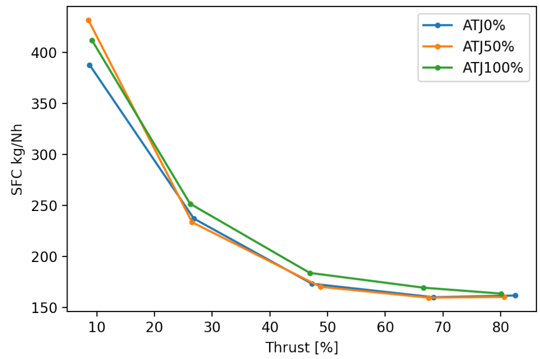


Figure 12. GTM-140/ATJ: SFC

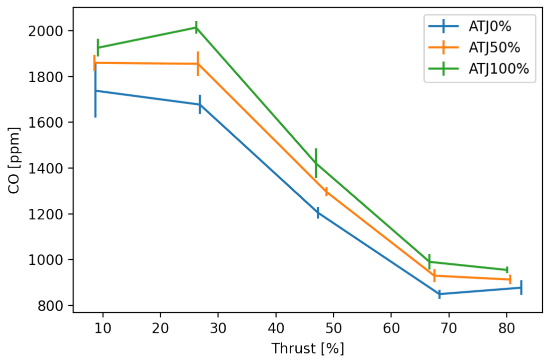


Figure 13. GTM-140/ATJ: CO emission

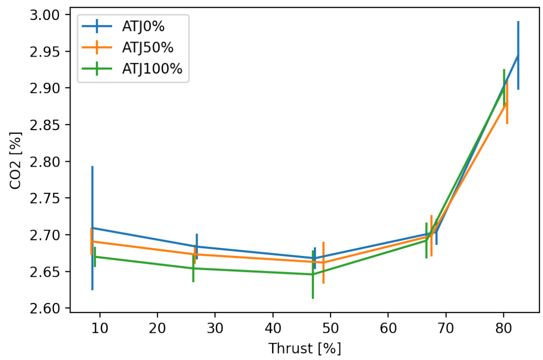


Figure 14. GTM-140/ATJ: CO_2 emission

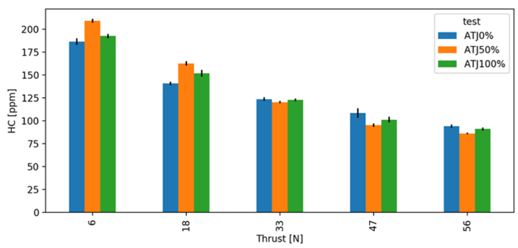


Figure 15. GTM-140/ATJ: HC emission

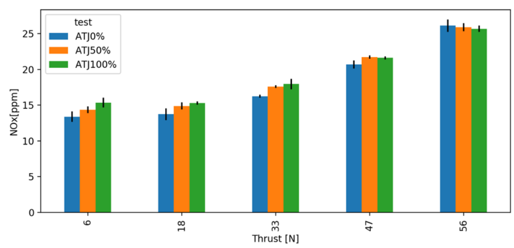


Figure 16. GTM-140/ATJ: NOx emissions

The results show that the addition of the ATJ component caused an increase in CO emissions compared to the Jet A-1 aviation fuel in all operating points (Figure 13). The greater the proportion of ATJ in the mixture, the greater the increase in CO emissions. In terms of CO_2 emissions (Figure 29), ATJ component causes a slight decrease in CO_2 emissions in relation to the neat Jet A-1 fuel.

In the case of HC emissions (Figure 15, the change in emissions of this parameter with the addition of the ATJ component is not conclusive. At the first two rotational speeds, an increase in HC emissions

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was obtained after adding the ATJ component in relation to Jet A-1. At three successive operating points, the addition of the ATJ component resulted in a decrease in HC emissions for the Jet A-1 fuel.

3.3. Microturbine - HEFA

Similarly, the test-runs with HEFA blends did not affect significantly engine performance (Figures 17 and 18). Adding the HEFA component to aviation fuel causes an increase in CO emissions (Figure 19) in all analysed operating points. In terms of NO emissions, a similar direction of changes for this parameter was obtained, i.e. the HEFA component generally increases NO emissions (Figure 22). The reverse trend was obtained for the emissions of hydrocarbons (HC, Figure 21). Adding HEFA component resulted in decrease in HC emissions in relation to pure Jet A-1 fuel.

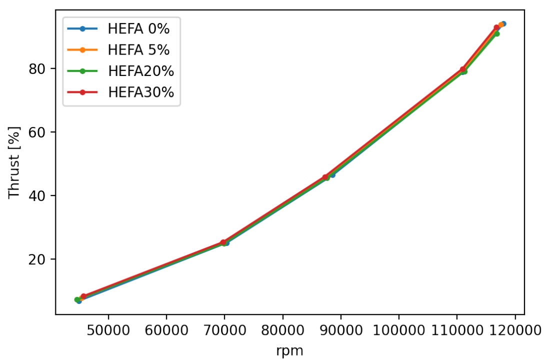

Figure 17. GTM-140/HEFA: Thrust

HEFA.png

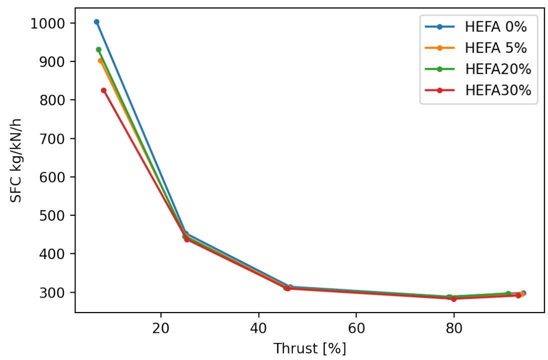

Figure 18. GTM-140/HEFA: SFC

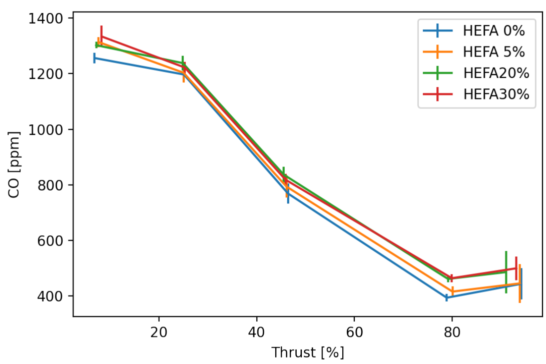

Figure 19. GTM-140/HEFA: CO emission

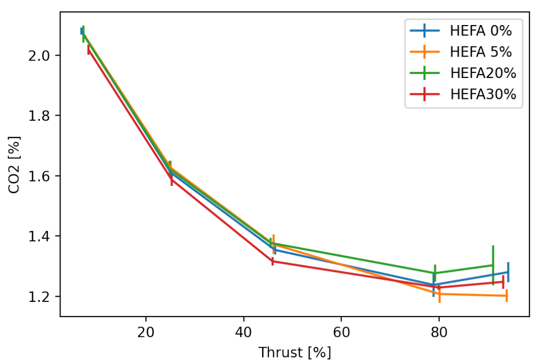

Figure 20. GTM-140/HEFA: CO_2 emission

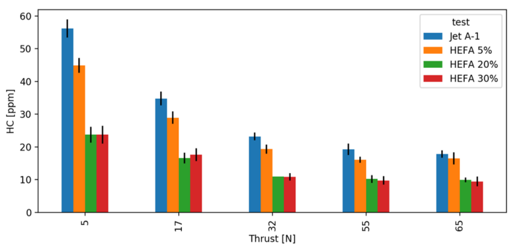

Figure 21. GTM-140/HEFA: HC emission

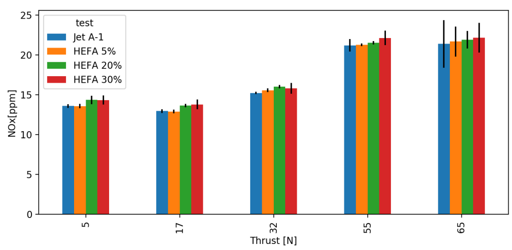

Figure 22. GTM-140/HEFA: NOx

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3.4. Turbofan

Based on the collected performance data of the DGEN 380 turbofan, it can be concluded that the relative differences in thrust (Figure 23 and 24) and fuel consumption (Figure 25 and 26) between the tests are usually less than 1%. The biggest ones are for the take-off range, but they do not exceed 5%. They are more related to the testing and engine control methods than to the used fuel blend.

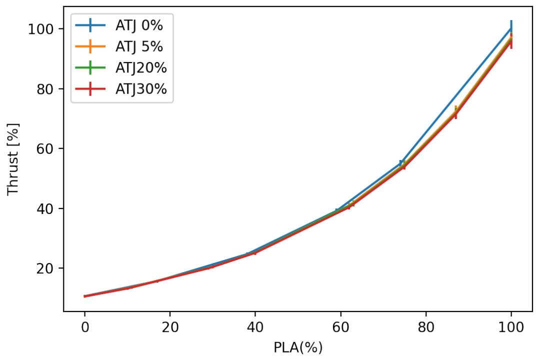

Figure 23. DGEN 380/ATJ: Thrust vs PLA

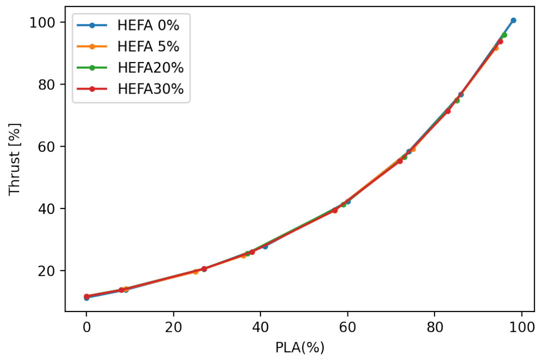

Figure 24. DGEN 380/HEFA: Thrust vs PLA

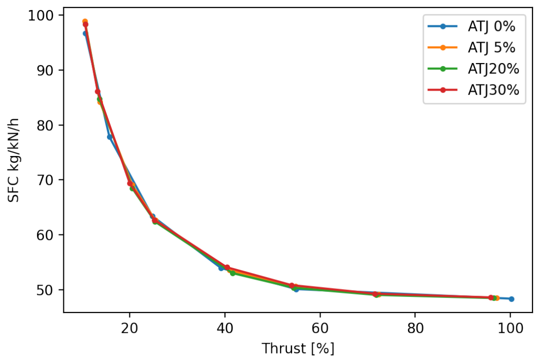

Figure 25. DGEN 380/ATJ: SFC

HEFA.png

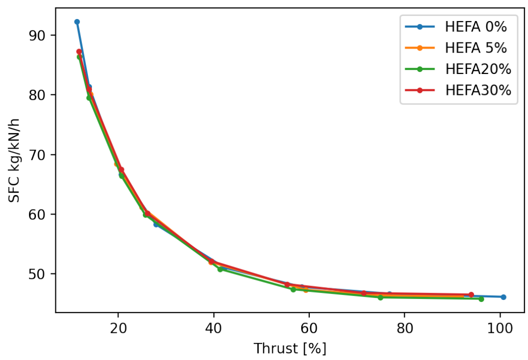

Figure 26. DGEN 380/HEFA: SFC

When analysing the operating parameters, there is no clear trend of their change due to the use of blends with biocomponents. To associate the differences with some fuel characteristics, the model of engine and its control system is necessary. For example, when using ATJ, a slight increase in exhaust gas temperature (EGT) was observed with the increasing ratio of the biocomponent (Figure 27), but a similar trend was not observed for HEFA (28).

Emission-wise, adding the ATJ component to the mineral fuel resulted in a clear increase in CO emissions (Figure 29) and a slight increase in CO_2 emissions (Figure 31) in all the analysed operating points of the DGEN 380 turbofan. The formation of CO is related to incomplete combustion of the fuel, so this process is more apparent when running on a DGEN 380 engine for blends with the ATJ component. In the case of the HEFA component, its addition resulted in a clear increase in CO emission (Figure 30), a slight increase in CO_2 emissions (Figure 32) in all analysed operating points.

A significant increase in CO emissions observed for the DGEN380 engine for both biocomponents has not been completely explained. Its relation to CO_2 behaves well (Figures 33 and 34), which confirms that it is not a simple measurement error. In general, CO emissions are related to incomplete combustion and dominate at low speeds. In this case, the increase was approx. 150 ppm for any speed and for all blends including biocomponents. This engine has a reverse flow combustor which is not typical for turbofans but the CFD simulations confirmed the effective combustion of bioethanol

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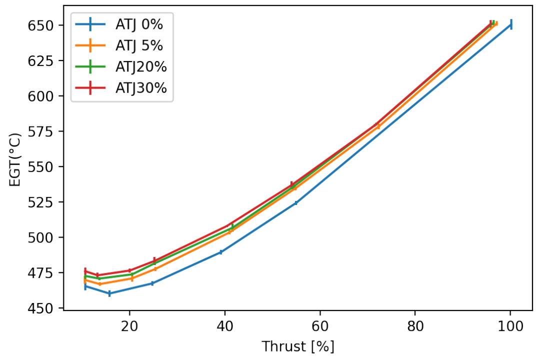

Figure 27. DGEN 380/ATJ: EGT

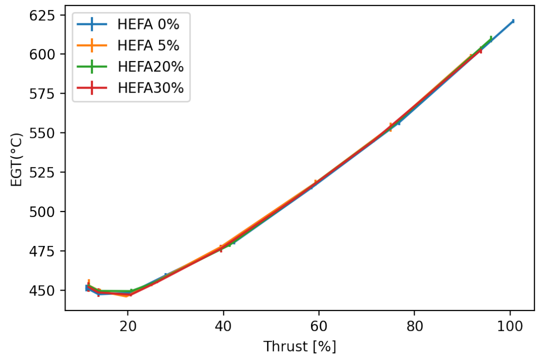

Figure 28. DGEN 380/HEFA: EGT

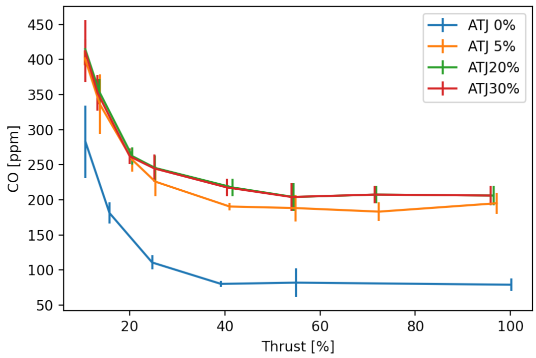

Figure 29. DGEN 380/ATJ: CO

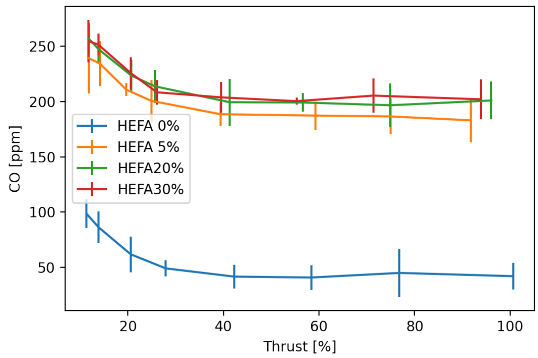

Figure 30. DGEN 380/HEFA: CO

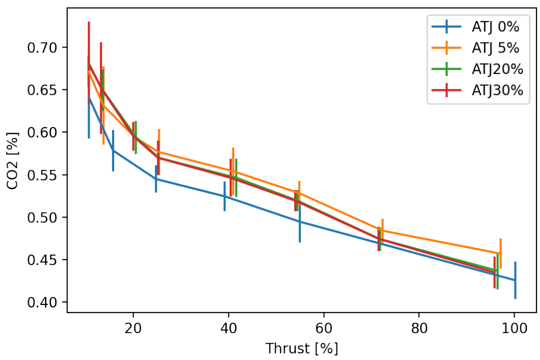

Figure 31. DGEN 380/ATJ: CO_2

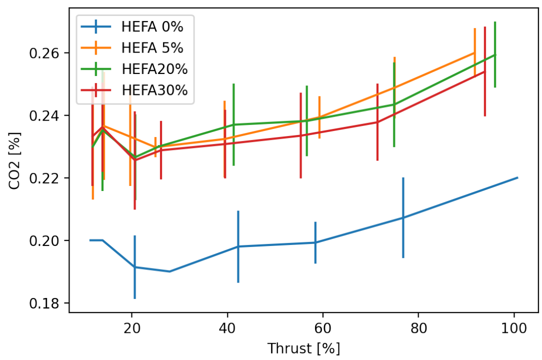

Figure 32. DGEN 380/HEFA: CO_2

and moderate emissions [31]. Custom design of the combustor may have an impact, but should not increase CO emission so much as a result of adding tiny amounts of biocomponent (5%).

Interestingly, the absolute emission values are almost twice as high for ATJ as for HEFA. Relatively low numbers of the CO_2 emissions for both biofuels are due to the dilution of the exhaust gas. It corresponds to the distance between the measuring probe and the engine, which was chosen in relation to the diameter of the outlet nozzle. Placing the probe in close proximity to the engine would make the results more uncertain. In particular, directing the gas stream directly at the probe makes it impossible to take a sample, as the turbulence around the probe caused by high dynamic pressure disturb the measurements.

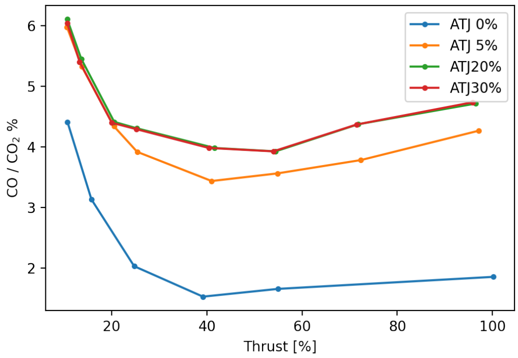

Figure 33. DGEN 380/ATJ: CO vs CO_2

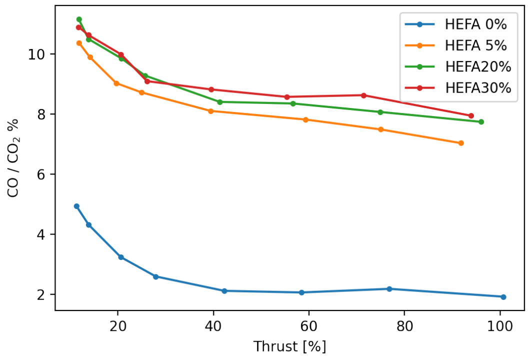

Figure 34. DGEN 380/HEFA: CO vs CO_2

4. Conclusions

For both engines, the analysis of engine performance parameters showed that the tested blends differ so little from the mineral fuel that their impact on the engine operating parameters is limited, and their use does not carry the risk of a significant decrease in aircraft performance or increase in fuel consumption.

The experimental emissions results for the DGEN 380 turbofan have never been published elsewhere. In relation to the previous tests of the microturbine carried out in ITWL, the emissions for the ATJ biocomponent and intermediate ratios of HEFA were studied for the first time. In addition, the Semtech analyzer of a class better resolution was used. Particulate emissions were also measured, but their analysis will be the subject of a separate publication.

It was found that increasing the content of biocomponents causes a noticeable increase in the emission of CO and some other gasses (HC and NOx), which should not, however, worsen the working conditions of the ground personnel. Deeper understanding of the effects of fuel blends on engine performance and emissions requires complex engine models, describing, in particular, its combustor and control system.

The use of small engines, and especially microturbines, for alternative fuels and emissions testing is debatable. They are not scaled large engines, but their structure differ significantly, especially in terms of combustors. Heat cycle losses and SFC are much higher due to relatively large tip clearances. Although the overall emission trends are maintained, the attempt to scale the results from the microturbine to a larger engine was partially successful.

The acquired data will be used to develop an engine emissivity model to predict gas emissions. Statistical methods and the analytical combustion model seem to be suitable for linking the thermophysical parameters of the fuel with the operating parameters and emissions of engines of a basic structure.

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Abbreviations

The following abbreviations and symbols are used in this manuscript:

ATJ	Alcohol-to-Jet
CFD	computational fluid dynamics
CO	carbon monoxide
CO_2	carbon dioxide
EGT	exhaust gas temperature
GSP	Gas turbine Simulation Program
HC	hydrocarbons
HEFA	Hydroprocessed Esters and Fatty Acids
NO_x	nitrogen oxides
PM	particulate mater
rpm	revolutions per minute
SAF	sustainable aviation fuel
SFC	specific fuel consumption
SPK	synthetic paraffinic kerosene
UCO	used cooking oil

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