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Evaluation of jet engine performance parameters fueled with sustainable aviation fuel

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As sustainable aviation fuels are one of the mid and long term solutions for aviation emissions reduction, this article focuses on jet engine performance with different HEFA-SPK blends. Blends used in the tests were 30% and 50% of HEFA-SPK fuel, and also pure Jet A-1 as a conventional fuel. Experiments were carried out on a miniature jet engine, GTM 400, and the aim was to assess the impact of SAFs on operational parameters. Selected engine performance parameters were calculated and analyzed for the tested blends. One of the results is that the blend of HEFA-SPK led to an average improvement of thrust-specific fuel consumption by about 3%, and an increase of static thrust by 2.7–11.2%.

Key words: *GTM, miniature jet engine, SAF, HEFA, engine performance*

1. Introduction

The growing requirements of air transport have resulted in an increased need for jet fuel. Roughly 300 billion liters of jet fuel are produced annually on a global scale. The significant utilization of jet fuel results in considerable emissions of greenhouse gases, contributing to the aviation sector being accountable for 3% of the total current GHG emissions [8]. Many new technologies, initiatives, and solutions are being developed to reduce the impact of aviation on the environment, and the actions in the aviation sector can be divided into changes in the construction of aircraft and engines, to make the aircraft and engines more ecological, and to find alternative fuels that have better emission indexes than conventional aviation fuel. As sustainable aviation fuels (SAF) have been seriously developed since 2009, when the first production pathway of SAF was certified, sustainable aviation fuels are currently one of the most promising mid-term solutions to reduce greenhouse gases in the aviation sector [14]. Nowadays, more than 700 thousands of flights have been operated using SAF since 2011, and 69 airports are regularly supplied with SAF [1]. According to Fit for 55, the percentage of SAF used in air transport should be 6% by 2030, 20% by 2035, 34% by 2040, 42% by 2045 and 70% by 2050 [24].

Currently, there are 8 production pathways certified in the standard for sustainable fuels in aviation, ASTM D7566, and 3 co-processing pathways described in ASTM D1655 standard [13]. Most of this attention has been around streamlining the conversion pathways to produce a drop-in fuel, which is also achieving good emission results compared to conventional aviation fuel. Drop-in fuel is a term used to describe sustainable aviation fuels that are compatible with existing fuel infrastructure, aircraft engines, and fuel distribution networks [8]. It can be used in the aircraft engine as a blend with conventional aviation fuel in proportions specified by the standard ASTM D7566. The proportions in which SAF can be mixed with conventional fuel vary depending on the production process, from a maximum of 10% (e.g. HFS-SIP, HHC) to 50% (e.g. HEFA-SPK, ATJ-SPK). Mixing limits result from the physicochemical properties of individual fuels and their degree of mixing with conventional fuel, e.g. SIP fuel, with a blending limit of 10%, has a high viscosity value, which makes energy consumption and mass-based fuel consumption the highest among certified SAF fuels and can indicate inefficient energy conversion, often stemming from challenges associated with flow dynamics [15]. Some of the physicochemical properties of SAF fuels make them attractive for consideration as high-performance fuels, e.g. low aromatic content, high thermal stability, and high specific energy. Additionally, the energy efficiency of the engine can be affected by various other physicochemical properties of the fuel. First one is viscosity, which plays a significant role in influencing the heat transfer coefficients, which in turn dictate the amount of waste heat that is recovered by the fuel and reintroduced into the engine through the combustor, the other one is thermal stability of the fuel drives numerous overarching design choices concerning the thermal regulation of an engine and mainly depends of chemical composition and physical conditions of fuel. Another parameter that has an impact on the energy efficiency is the hydrogen-to-carbon ratio, which affects the composition of exhaust gases in the combustor, leading to a slight influence on the ratio of heat capacities and the temperature at the combustor exit. Energy density directly influences volumetric flow rates, which in turn affect heat transfer coefficients. Also, the specific heat directly affects the temperature increase in the fuel per unit of absorbed heat energy, potentially impacting the rate of coking [6]. Volatility impacts the fuel's vaporization and is one of the most desired fuel qualities for ignition [12]. According to Kroyan et al. [15], among certified sustainable aviation fuels, FT-SPK/A (Fischer-Tropsch Synthetic Paraffinic Kerosene with Aromatics) stands out with the highest carbon content, the highest volumetric lower heating value, and very high density. Studies show that the aromatic content in sustainable aviation fuels plays a crucial role, as it significantly influences both the fuel properties and the performance of jet engines, and too low aromatic content may affect fuel leakage problems [12]. The fuel properties of FT-SPK/A closely resemble those of conventional aviation fuel Jet-A1, primarily due to its aromatic content, and the end-use performance of FT-SPK/A is also very similar to standard Jet A-1. The purely FT-SPK (Fischer-Tropsch Synthetic Paraffinic Kerosene), compared to other certified SAFs, features low density, the lowest carbon content, intermediate mass-based net calorific value, and the lowest volumetric net calorific value. According to studies [15] HEFA-SPK (Hydroprocessed Ester and Fatty Acids Synthetic Paraffinic Kerosene) and ATJ-SPK (Alcohol-to-Jet Synthetic Paraffinic Kerosene) also have low density, so the volumetric fuel consumption is higher, but both these fuels also have the lowest fuel consumption mass compared to other certified sustainable aviation fuels and conventional aviation fuel [15]. Studies made by Mazlan et al. [19] show that as the proportion of SAF fuel in the fuel mixture increases, the maximum engine thrust increases and fuel consumption decreases. The studies also show that the heat capacity has an influence on engine thrust increase and that the density of the fuel impacts the specific fuel consumption: an increase in density increases specific fuel consumption [19]. For pure CSPK (Camelina Bio-Synthetic Paraffinic Kerosene), the maximum thrust was slightly higher than for JSPK (Jatropha Bio-Synthetic Paraffinic Kerosene), although the lower heating value of JSPK is higher (44.3 MJ/kg) than that of CSPK (44.0 MJ/kg), which reveals that not only the lower heating value impacts the maximum thrust [19]. Table 1 presents selected physicochemical parameters of certified SAF fuels according to ASTM D7566 standard [25].

Table 1. Specified physicochemical parameters of selected certified production pathways of SAF [25]

	Jet A-1	FT-SPK	FT-SKA	HEFA-SPK	SIP	ATJ-SPK
Aromatics [vol %]	8–25	0.5	20/21.2	0.5	0.5	0.5
Cycloparaffins, mass [%]		15	15	15		15
Sulfur [mg/kg]	0.3	15	15	15	2	15
Final boiling point, [°C]	300	300	300	300	225	300
Distillation T90–T10 [°C]		22	22	22	5	21
Flash point [°C]	38	38	38	38	100	38
Freezing point [°C]	–40	–40	–40	–40	–60	–40
Density at 15°C [kg/dm^3]	775–840	730–770	755–800	730–770	765–780	730–770
Energy density [MJ/kg]	42.8	–	–	44.1	43.5	–
Antioxidants [mg/dm^3]	24	17–24	17–24	17–24	17–24	17–24

Sustainable aviation fuel tested in this research is HEFA-SPK (Hydroprocessed Esters and Fatty Acids Synthetic Paraffinic Kerosene). HEFA-SPK is a production pathway certified in 2011 and described in Annex 2 in ASTM D7566 standard [14]. The feedstock used in the production of HEFA-SPK is mostly used cooking oil, oily biomass like camelina or jatropha, municipal solid wastes, and other raw materials [18]. The range of raw materials used in the production of HEFA-SPK fuel is constantly expanded by producers to include more wastes and residues from different sectors of the economy.

The aim of this article is to analyze the impact of the blend ratio of HEFA-SPK and Jet A-1 on the combustion parameters and the engine's performance. The research was made on 30% of HEFA-SPK and 50% of HEFA-SPK and reference conventional fuel Jet A-1.

2. Methodology

2.1. Tested engine

The tests were carried out on the engine GTM 400. It is a microjet turbine engine which consist of the following elements: inlet duct, single stage radial compressor, annular combustion chamber with vaporizers, single stage axial turbine, exhaust duct with constant geometry, electrical starter, digital controller FADEC, geared fuel pump, engine starting solenoid valve, fuel shut-off solenoid valve, rpm optical sensor transmitter-receiver and Exhaust Gas Temperature thermocouple (EGT) mounted in the exhaust nozzle. In jet engines, variable geometry refers to adjusting the shape or size of specific components to optimize engine performance across different flight conditions. This can involve changing the area of the nozzle, the pitch of the compressor blades, or even the geometry of the inlet. "Constant geometry" refers to an engine design where the physical dimensions of key components, such as the nozzles, are fixed and do not change during operation.

The schematic view of the tested engine is presented in Fig. 1. Engine stations designations were marked by the engine manufacturer and do not comply with the aviation industry.

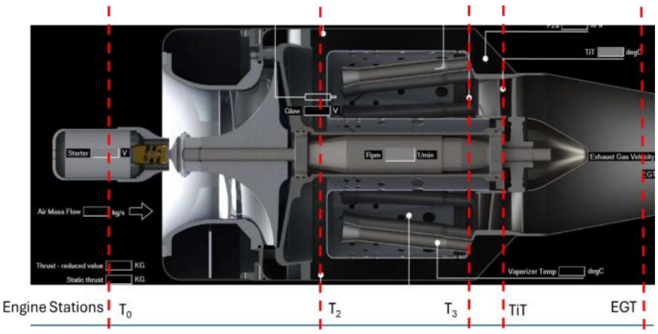

Fig. 1. Schematic view of the tested engine

Tested engine GTM 400 has a maximum thrust of 400 N and minimum thrust of 15 N. It is constructed for conventional fuel Jet A-1, with the possibility of changing the supply fuel to alternative fuels using an additional fuel distributor. The engine is lubricated with the engine fuel supply system using a mixture of JET-A1 and lubrication oil. The lubrication type for this engine is the mixture of 4% Mobil Jet Oil II and Jet-A1 fuel. Specific engine parameters are presented in Table 2.

In addition to the engine performance data, there are some other parameters recorded like engine starter voltage level [V], engine fuel pump voltage [V], engine igniter (glow) voltage signal [V], engine fuel ignition and combustion valves position [%], and engine rotation speed related to maximum rotation speed [%] [23].

In order to be able to conduct engine tests running on the sustainable aviation fuel, the engine was equipped with an additional internal fuel manifold dedicated to the alternative fuel type. This manifold construction was designed with the threaded connector at the end of the manifold, which allows for connecting a sustainable fuel line.

Table 2. Parameters of GTM 400

Parameter	Value
Maximum thrust	400 N
Minimum thrust	15 N
Max. spool rpm	85 000 rpm
Min spool rpm	27 000 rpm
Compression ratio	3.3:1
Mass air flow rate	770 g/s
Exhaust gas temperature	750°C
Fuel consumption	1200 g/min
Diameter	150 mm
Length	390 mm
Total weight	3200 g

An additional sealed access port in the engine case allows borescope inspections of the combustion liner and turbine nozzle vanes.

2.2. Measurements

The tests were carried out on the described engine GTM 400. The atmospheric conditions during measurements were an ambient temperature of 20◦C and an atmospheric pressure of 1000.9 hPa.

Tested fuels were blends of 30% volume of HEFA-SPK with Jet A-1 (HEFA30) and 50% volume of HEFA-SPK and Jet A-1 (HEFA50). The reference fuel was conventional aviation fuel Jet A-1. The feedstock used for this specific HEFA fuel production was mostly used cooking oil.

For every tested fuel, there were 12 measurement points: 7, 10, 20, 30, 40, 50, 60, 70, 80, 85, 90, and 100% Rc, so the measurement points also included the engine setup for the LTO cycle (Landing and Take-off). Every measurement point was set up for 20s, and the results were averaged. Despite changing conventional fuel to a blend with SAF, it was possible to obtain the same relative thrust and fuel flow. During experiments following parameters were recorded: static thrust [N], fuel flow [kg/h], total pressure at compressor diffuser p_2 [hPa], total temperature at combustion chamber exit T_3 [°C], total mass flow [kg/s], rpm [1/min], turbine inlet temperature TIT [°C], and exhaust gas temperature [°C]. Due to measurements of these parameters, it was possible to calculate specific engine parameters, such as specific fuel consumption, specific thrust, engine power, and engine thermal efficiency.

4. Research results

4.1. Thrust specific fuel consumption (TSFC)

Thrust-specific fuel consumption (TSFC) is one of the most important engine performance parameters. It is defined as the amount of fuel used to generate one unit of thrust over a finite period of time. This parameter tells us how efficiently engine power (thrust) is produced. TSFC is frequently given in the dimension of kg of fuel/daN of thrust/hour. In imperial units, its unit is noted as lbm fuel/lbf thrust/hours.

Thrust-specific fuel consumption – TSFC is defined as the relation of the fuel mass burnt in the combustion chamber in one hour to the thrust generated by the engine.

TSFC is the parameter that characterizes jet engine economy. TSFC reduction allows for increased aircraft flight duration and range. Since primary engine design considerations, particularly for commercial air transport, are those of low specific fuel consumption and weight, this is the reason why this parameter was used to analyze engine performance and economy based on the different aviation fuel types [22].

Mathematical expression of the TSFC is noted as a relation of the fuel mass flow provided to the engine, to the thrust generated as a result of the thermal energy produced in the combustion process:

$$\mathrm{TSFC} = \frac{\dot{m}_f}{F_c}\left[\frac{\mathrm{kg}}{\mathrm{daN \cdot h}}\right] \quad (1)$$

where: TSFC – thrust specific fuel consumption, $\dot{m}_f$ – fuel mass flow provided to the combustion chamber, F_c – thrust force generated out of the combustion process.

TSFC calculated for the specific engine power levels is presented in Fig. 2.

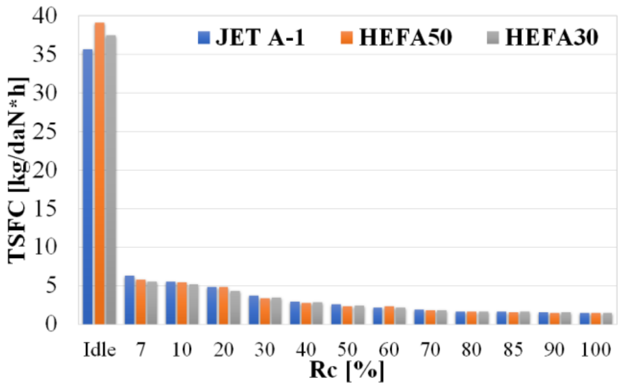

Fig. 2. Comparison of the thrust specific fuel consumption (TSFC) for the very specific engine throttle level Rc [%]

For the idle engine power level, the lowest TSFC was achieved for the clean Jet-A1 fuel, about 8% lower than HEFA50 and 3% than HEFA30. Still, it is worth noting that for such a low engine power level, it was extremely hard to set the same power level. For 7% and 10% of the engine rpm, TSFC was 8-10% higher than for HEFA50 and HEFA30. What is very important to stress is that starting from about 70% of engine rpm, TSFC was always higher than for other mixed fuels, with an average of 3.5%.

4.2. Fuel-to-air ratio

Another important engine performance parameter that is used to determine engine operation efficiency is the fuel-to-air ratio (FAR), noted as τ. Engine combustion efficiency strongly depends on two parameters. The first one is the air mass flow velocity entering the combustion chamber. The second one is the FAR. To achieve the highest combustion efficiency, the FAR for the jet engines should be between 1:60 and 1:130 of kerosene.

FAR is strongly related to the specific thrust and TSFC and might be noted as follows:

$$\tau = TSFC \cdot F_s \tag{2}$$

Fuel to air ration is also calculated as the fuel mass flow rate related to the air mass flow rate – eq. (3).

$$\tau = \frac{\dot{m}_f}{\dot{m}} \tag{3}$$

FAR calculated for the specific engine power levels is presented in Fig. 3.

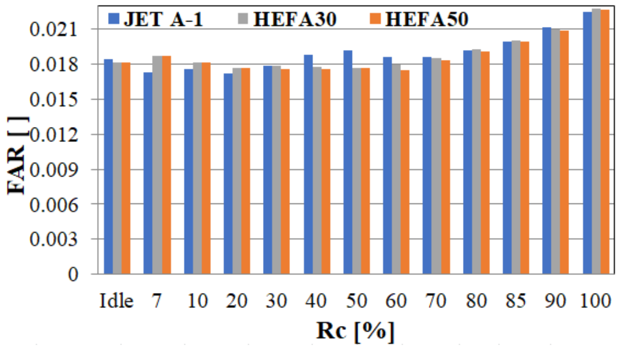

Fig. 3. Analysis of the fuel-to-air ratio for the very specific engine throttle level Rc [%]

What might be deduced from Fig. 3 is the fact that only for the low engine power levels (7–20%), FAR for Jet-A1 is lower than for other mixed fuels (average 0.05%). Starting from 30%, the engine power level was always higher, with an average of 0.1%. Only for 100% engine rpm FAR for mixed fuels was higher. The reason for this could be that the engine control panel allowed for setting 100% still with various physical rpms.

4.3. Specific thrust

Specific F_s thrust is one of the key engine performance parameters. It is the relation of the thrust F_c generated by the engine to the air mass flow through the engine $\dot{m}$ In the physical sense, specific thrust might be treated as a thrust generated out of 1 kg air mass flow through the engine in 1 s.

$$F_s = \frac{F_c}{\dot{m}} \left[\frac{m}{s}\right] \tag{4}$$

Assuming that the mass flow at the engine exhaust equals the sum of the engine inlet air mass flow plus fuel mass flow added, and assigning: $(\dot{m} + \dot{m}_p) = (1 + \tau) \cdot \dot{m}$ eq. (4) could be written as follows:

$$F_s = \frac{F_c}{\dot{m}} = (1 + \tau)(V_8 - V_0) \tag{5}$$

From eq. (5) may deduce that the specific thrust depends on the velocity differences of the engine inlet and outlet airflow.

Engine-specific thrust depends on the engine compression rate, turbine inlet temperature, and compression/expansion efficiency. The higher the specific thrust, the lower the air mass flow required to generate the same level of power or thrust, which allows for the design and build of smaller and lighter aircraft engines.

Engine-specific thrust is the indicator of the engine efficiency because an engine with a higher F index generates higher thrust, for the same air mass flow. Calculating thrust to specific thrust ratio provides information on the air mass flow rate through the engine, which determines engine cross-section area and, as a result, engine dimensions.

Engine-specific thrust calculated for the specific engine power levels is presented in Fig. 4.

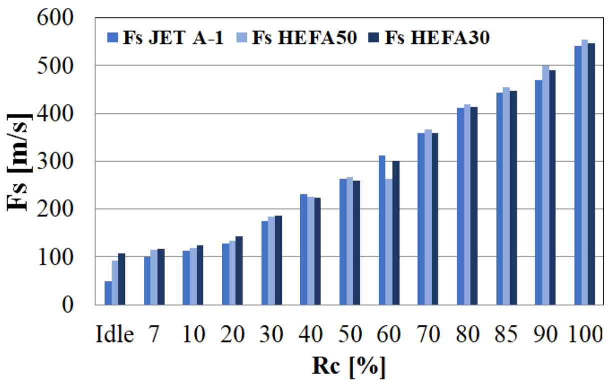

Fig. 4. Comparison of the specific thrust (Fs) for the very specific engine throttle level (Rc)

Having analyzed the comparison of the Specific Thrust at each engine power level, it might be noticed that for all engine rpm levels except 60%, the engine-specific thrust was higher for the HEFA50 mixed fuel type with a difference of 2–9%. The engine on HEFA30 was working with a similar specific thrust to Jet-A1.

4.4. Thermal efficiency

TSFC is directly related to the thermal and propulsive efficiencies and, as a result, the overall engine efficiency [9]. Since specific fuel consumption is directly related to thermal efficiency, let us explain what thermal efficiency is and how it is calculated.

The ability of an engine to convert the thermal energy inherent in the fuel (which is unleashed in a chemical reaction) to a net kinetic energy gain of the working medium is called the engine thermal efficiency, and it is noted as η_c [10]. In combustion-based engines, thermal efficiency depends on the pressure and temperature in the combustion chamber.

Thermal efficiency ($\eta_{thermal}$) is generally defined as the ratio of useful work output (or, in the case of a jet engine, the kinetic energy imparted to the flow) to the energy input (fuel energy).

Considering enthalpy flux for a jet engine, the energy balance involves:

– Fuel energy input: $\dot{m}_f \cdot LHV$ (lower heating value)
– Energy carried away by the exhaust: enthalpy flux, kinetic energy, and pressure work.

The thermal efficiency, considering the enthalpy flux, can be expressed as:

$$\eta_{thermal} = \frac{\text{useful energy output}}{\text{energy input}} \tag{6}$$

Assuming steady-flow and idealized engine cycle and noting:

– Mass flow rate of air: $\dot{m}_a$
– Mass flow rate of fuel: $\dot{m}_f$

- Fuel's lower heating value: LHV
- Inlet (ambient) conditions: temperature T_0, enthalpy h_0
- Exhaust conditions: temperature T_{exit}, enthalpy h_{exit}
- Exhaust velocity: V_{exit}
- Specific heats: c_p (assumed constant)
- Air inlet enthalpy: $h_0 = c_p T_0$
- Exhaust enthalpy: $h_{exit} = c_p T_{exit}$
- Fuel energy input rate: $\dot{Q}_f = \dot{m}_f \cdot LHV$.

Let us calculate the energy balance:

The total energy flux leaving the engine per unit time (per unit mass of air) includes:

- Enthalpy flux: $\dot{m}_a h_{exit}$
- Kinetic energy flux: $\frac{1}{2}\dot{m}_a V_{exit}^2$.

The total energy input from fuel: $\dot{Q}_f = \dot{m}_f \cdot LHV$.

The thermal efficiency reflects the ratio of the useful energy imparted to the flow (enthalpy + kinetic energy) to the energy supplied by the fuel:

$$\eta_{thermal} = \frac{\text{energy increase in the airstream}}{\text{fuel energy input}} \tag{7}$$

Expressed explicitly:

$$\eta_{thermal} = \frac{\dot{m}_a\left(h_{exit} + \frac{V_{exit}^2}{2} - h_0\right)}{\dot{m}_f \cdot LHV} \tag{8}$$

This detailed form captures the essential thermodynamic parameters, including enthalpy flux $c_p(T_{exit} - T_0)$ and kinetic energy flux $\frac{V_{exit}^2}{2}$, normalized by fuel energy input per unit air mass flow, providing a comprehensive measure of jet engine thermal efficiency considering enthalpy flux.

For instance, for the very popular aviation fuel JET-A1 net calorific value LHV should be no less than 42.8 MJ/kg.

Equation (8) compares the mechanical power production in the engine to the thermal power investment in the engine [11].

Thermal efficiency is a prime factor in gas turbine performance. It is the ratio of the network produced by the engine to the chemical energy supplied in the form of fuel. The three most important factors affecting thermal efficiency are turbine inlet temperature, compression ratio, and the component efficiencies of the compressor and turbine. Other factors that affect thermal efficiency are compressor inlet temperature and combustion efficiency.

Since combustion efficiency depends on the combustion chamber construction, fuel system, and the fuel combustion process efficiency, which directly depends on the type of fuel used in the combustion, that is why it is extremely significant to compare thermal efficiencies for the different types of aviation fuels used and various mixture ratios of the JET-A1 fuel and the sustainable fuel.

A high engine thermal efficiency means low specific fuel consumption and, therefore, less fuel for a flight of a given distance at a given power. Thus, the practical importance of high thermal efficiency is one of the most desirable features in the performance of an aircraft engine.

Thermal efficiencies calculated in accordance with eq. (8) The specific engine power levels and three types of fuel were presented in Fig. 5.

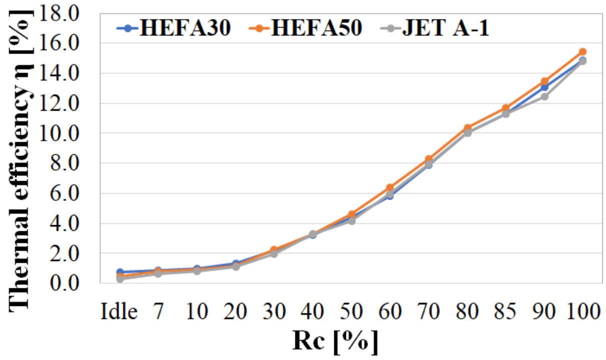

Fig. 5. Thermal efficiency η [%] for the very specific engine throttle level Rc [%]

Engine thermal efficiency for all engine power levels was higher for HEFA50 with about 0.1–0.4%. The results achieved confirm our assumptions that engine thermal efficiency will be higher for the HEFA50 fuel mixture. It is worth noticing that even though thermal efficiency is not very high, reaching about 16%, increasing thermal efficiency increases overall engine efficiency and, as a result, engine performance in return for the lower engine fuel consumption.

4.5. Temperatures

Total temperature – T_3

The results achieved in the engine test were very promising as far as the performance is concerned. However, the question is whether the achieved results resulted in higher temperatures measured in engine control points.

Let us analyze the first measured temperature T_3, which is the combustion chamber outlet. Jet engines achieve better performance when the temperatures achieved out of the combustion chamber are higher.

In Figure 6, T_3 total temperatures measured at specific engine cross-sections in relation to the engine throttle level (Rc) are presented.

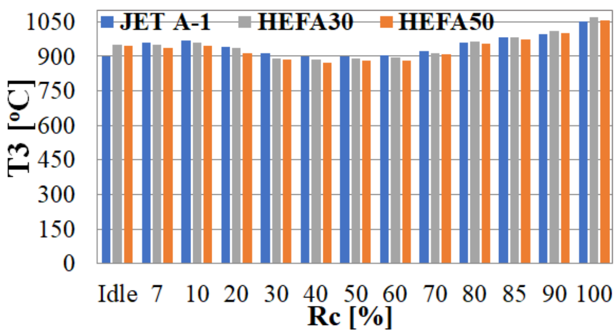

Fig. 6. Total temperature T3 for the very specific engine throttle level Rc [%]

Having analyzed achieved T_3 temperatures it might be concluded that up to 85%, T_3 temperatures generated from the Jet-A1 fuel were about 2% higher than for the sustainable fuels. For 90–100% engine power level T_3 temperatures achieved for HEFA50 and HEFA30 were 1–2% higher.

Turbine inlet temperature – TIT

Turbine inlet temperature (TIT) is one of the crucial temperatures in the jet engine for two reasons. The first one is the engine health status and endurance, while the other one is the engine performance. From the perspective of the engine-generated thrust, the higher TIT, the higher energy generated at the turbine inlet, which is converted to the turbine work as well as engine exhaust gases acceleration.

In Figure 7, TIT measured at specific engine cross-sections in relation to the engine throttle level (Rc) is presented.

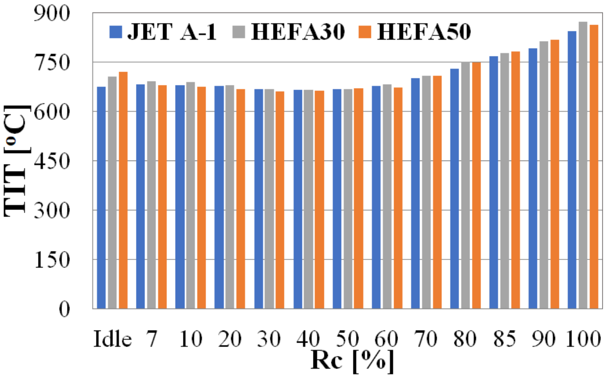

Fig. 7. Turbine inlet temperature TIT for the very specific engine throttle level Rc [%]

As for the TIT, for almost all the engine power levels, exhaust gas temperatures resulting from Jet-A1 were lower by 0–3.3% from the fuel mixtures

Exhaust gas temperature – EGT

Exhaust gas temperature (EGT) is the total temperature, which is measured at various points, depending on the engine construction. This temperature results from the TiT, engine construction, and engine capabilities of the engine conversion to the turbine work. This engine parameter must be controlled and monitored. Exceeding the allowed EGT might result in engine severe failure or even damage.

In Figure 8 exhaust gas temperature EGT measured at specific engine cross-sections concerning the engine throttle level (Rc) is presented.

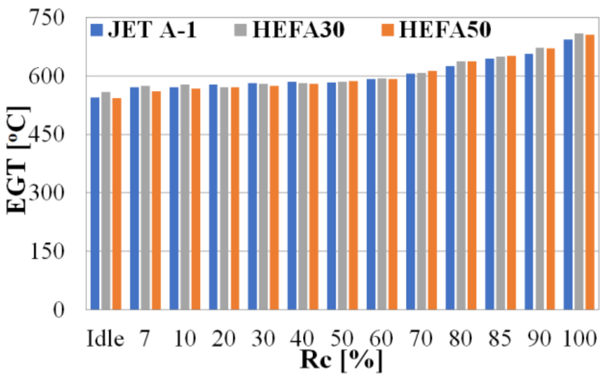

Fig. 8. Exhaust gas temperature EGT for the very specific engine throttle level Rc [%]

Up to 50% of the engine power level EGT generated from Jet-A1 is higher in comparison to HEFA50 and HEFA30 of 0.2–1.3%. Starting from 50% of rpm, the generated exhaust gas temperature is higher for sustainable fuel mixtures from 0.2–2.5%, which is a remarkable increment.

4.5. Engine static thrust – F_c

Having analyzed all the most important engine parameters, it is worth checking how fuel additives affect engine static thrust Fc in comparison to the clean Jet-A1.

Static thrust Fc of the turbojet engine can be calculated in accordance with eq. (9):

$$F_c = (\dot{m} + \dot{m}_f)V_8 + (p_8 - p_0)A \tag{9}$$

where: p_8 – exhaust gases pressure in nozzle cross-section, p_0 – atmospheric pressure, A – exhaust nozzle cross-section area.

Results were presented in Fig. 9.

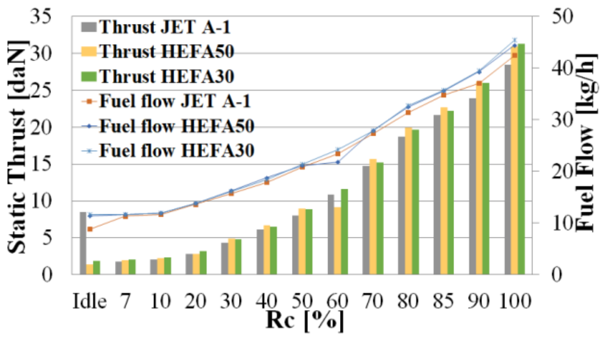

Fig. 9. Engine static thrust Fc for the very specific engine throttle level Rc [%]

As it might be deduced from Fig. 9, the fact that summarizes conducted research case studies is that sustainable aviation fuels not only affect environmental pollution, but they also allow for higher thermal efficiency and engine performance.

Analyzing engine static thrust generated from all the fuel types, it might conclude that engine static thrust Fc achieved from HEFA50 and HEFA30 is higher by about 2.7–11.2%

5. Discussion

According to the literature data, several studies indicate that blending SAFs with conventional jet fuels can lead to a reduction in TSFC. For instance, a 7% FT (Fischer-Tropsch) blend resulted in a 6.67% reduction in TSFC across all thrust settings [17]. Similarly, the use of CHJ (Catalytic Hydrothermolysis Jet) fuel blends showed lower TSFC compared to conventional fuels [16]. Different biofuel blends, such as those containing Jatropha and Camelina, have been tested and found to improve engine performance by reducing TSFC. For example, biofuels like Jatropha Bio-Synthetic Paraffinic Kerosene (JSPK) and Camelina Bio-Synthetic Paraffinic Kerosene (CSPK) showed a 1% to 3% lower TSFC compared to Jet-A fuel [7]. The impact of SAFs on TSFC is influenced by the specific properties of the fuel and the design of the engine. For instance, the lower heating value of the fuel plays a significant role in determining TSFC. Blends with appropriate fuel properties, such as a lower carbon-to-hydrogen ratio and higher combustion efficiency, tend to reduce fuel consumption [21]. The benefits of SAFs in reducing TSFC are observed across various thrust settings. For example, a 10% CHJ fuel blend provided higher thrust and lower TSFC throughout the entire range of thrust output settings

[16]. The literature confirms the obtained results for HEFA fuel. In the case of the studies presented in the article, an average reduction in TSFC of 3% was achieved for Jet A-1 and HEFA blends.

SAFs are required to meet higher thermal stability standards than conventional jet fuels, which can be leveraged to improve energy efficiency in new engine designs. Higher energy density fuels, which SAFs can provide, directly impact aircraft efficiency, with an increase in fuel specific energy (enthalpy per unit mass, LHV) leading to a 0.43% improvement in aircraft efficiency per MJ/kg increase in LHV [5].

SAFs composed of cycloalkanes and some aromatics have been found to maximize energy savings in high power engine operating conditions. This is likely due to the effects of the hydrogen-to-carbon (H/C) ratio on turbine performance, which can enhance the thermal efficiency of the engine [16]. However, at low power conditions, SAF mixtures have not yet surpassed conventional petroleum fuels in terms of energy savings [2].

Studies have shown that the use of SAFs can lead to slight improvements in engine efficiency. For instance, leveraging the high thermal stability of synthetic fuels can result in a combined efficiency savings of around 0.5%, with a significant portion attributed to the thermal properties of the fuel [6]. This efficiency gain is partly due to the ability of SAFs to maintain stable combustion at higher temperatures. The ability of SAFs to absorb heat without significant degradation is crucial for maintaining engine performance. This property ensures that the fuel can effectively manage the thermal load, prevent overheating and maintain optimal engine temperatures [3, 4]. The high thermal stability of SAFs means they can withstand higher operating temperatures without forming deposits that could impair engine performance [20]. The conducted studies showed that the thermal efficiency of the engine at all power levels was higher for HEFA50 by approximately 0.1–0.4%.

The presented literature sources indicate trends in jet engine performance parameters following the use of aviation fuels blended with SAF. The research presented in this article also confirms these trends under test conditions, as described in the conclusions of this study. From the perspective of engine performance, the use of SAF may prove beneficial, although not necessarily from an economic standpoint – a matter that, however, is beyond the scope of this paper.

6. Conclusions

The conducted research aimed to assess the impact of sustainable aviation fuel on the operational parameters of the engine. The obtained results were compared with available literature. A thorough analysis of the collected measurements allowed for the formulation of the following conclusions:

- The use of HEFA-SPK fuel resulted in an average improvement of TSFC by approximately 3% across the engine's operating range
- Specific thrust improved by 2–9%, depending on the operating point of the engine powered by the HEFA-SPK fuel blend
- The engine's thermal efficiency increased by an average of 0.4% due to the use of HEFA fuel
- Exhaust gas temperature at various engine points remained similar regardless of the type of fuel used
- Static thrust increased by 2.7%–11.2% for the engine powered by HEFA fuel.

These conclusions indicate that the use of sustainable aviation fuels is beneficial not only for environmental reasons but also for engine performance.

Nomenclature

ATJ-SPK	alcohol-to-jet synthetic paraffinic kerosene
CHJ	catalytic hydrothermolysis synthesized kerosene
CH-SK	catalytic hydrothermolysis synthesized kerosene
CO	carbon monoxide
CO_2	carbon dioxide
CSPK	camelina bio-synthetic paraffinic kerosene
EGT	exhaust gas temperature
FAR	fuel-to-air ratio
FT-SPK	Fischer-Tropsch Synthetic Paraffinic Kerosene
FT-SPK/A	Fischer-Tropsch Synthetic Paraffinic Kerosene with aromatics
GHG	greenhouse gases
HEFA-SPK	hydroprocessed ester and fatty acids synthetic paraffinic kerosene
HFS-SIP	hydroprocessed fermented sugars to synthetic isoparaffins
HHC	hydroprocessed hydrocarbons, esters and fatty acids synthetic paraffinic kerosene
JSPK	jatropha bio-synthetic paraffinic kerosene
LHV	lower heating value
LTO	landing and take off cycle
SAF	sustainable aviation fuel
SIP	hydroprocessed fermented sugars to synthetic isoparaffins
TSFC	thrust-specific fuel consumption

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