

Impact of a Jet A-1/HEFA blend on the performance and emission characteristics of a miniature turbojet engine

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Received: 13 April 2017/Revised: 24 July 2017/Accepted: 5 September 2017
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Abstract It is forecast that in the future, alternative fuels derived from non-petroleum sources will become the basic propellant for turbine aircraft engines. Currently, five types of aviation turbine fuel containing synthesized hydrocarbons are certified and accepted, and allow adding a maximum of 50% of synthetic component to conventional fuel. The experimental performance and the emission characteristics of a turbojet engine were investigated in this paper. The studies were conducted with the use of a miniature turbojet engine, which is the main component of a laboratory test rig. The test rig is an interesting solution for engine research, due to the fact that studies concerning full-scale aircraft engines are very complex and expensive. The literature of the subject contains many papers using small-scale turbojet engines for testing alternative fuels. However, most of them concern components of fuels, e.g. biodiesel, butanol, which do not have direct application in aviation. Two different fuel samples, a conventional Jet A-1 fuel and a blend of 48% synthesized paraffinic kerosene from hydroprocessed esters and fatty acids process with Jet A-1 were tested. This process is one of the routes of producing alternative fuel for aviation, approved by ASTM standard. The test rig studies were performed according to a specific profile of engine test, which models different modes of a turbojet engine's operation. The obtained results are compared in relation to the results for neat Jet A-1 fuel and then discussed.

Keywords Biofuels · Combustion process · Effect on environmental · Synthesized paraffinic kerosene · Turbine engine

Introduction

The field of researching and testing new fuels/biofuels for air transport is a globally important issue. This is confirmed by the recently undertaken research programmes, e.g. ITAKA—Initiative Towards Sustainable Kerosene for Aviation (Velarde 2015), BFSJ—Production of a fully synthetic jet fuel from timber and other biomass, BIOREFLY—Industrial scale demonstration biorefinery on lignin-based aviation fuel (Buffi et al. 2017). The aim of these programmes is to promote the use of alternative jet fuels derived from non-conventional sources.

Environmental effects of emissions from aircraft engine were considered in paper (Braun-Unkloff et al. 2017). Generated emission from aircraft industry has not only a negatively effect on climate and air quality but also human health. One of major methods of harmful combustion products emissions reduction is implementation to the fossil fuel various components, including biocomponents and biofuels (Chishty et al. 2011; Şöhret et al. 2015).

The procedure of approving new fuels for use in turbojet aircraft engines is defined in the ASTM D4054-14 (1981). It is a very complex process, starting with laboratory research in the field of physical and chemical fuel properties and ending with tests on full-scale turbine engine. Opportunities and challenges in the development of alternative fuels for aviation were shown by Hari et al. 2015. Scientific and technological advances related to the existing pathways to produce biojet and future implementation

Editorial responsibility: Necip Atar.

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of a sustainable production chain for renewable aviation fuel were reviewed by Gutierrez-Antonio et al. 2017.

A review of the most important achievements of the last 10 years in the scope of studies conducted on alternative fuels for aircraft turbine engines was presented by Zhang et al. 2016. Many experiments executed both, on different types of real aircraft engines, as well as with the use of different alternative fuels were presented in the field of engine studies. Worth noting is the fact that the authors referred to the results of the research (Badami et al. 2014), executed on a small-scale turbojet engine.

Experimental tests on full-scale turbojet engines are very complex and expensive. For this reason, the possibility to conduct tests with the use of small-scale engines is an interesting solution. Such engines are used not only in the scientific and research works (Badami et al. 2013; Benini and Giacometti 2007; Gawron and Białocki 2015, 2016; Nkoi et al. 2013), but also used as propulsion for aerial targets, unmanned aerial vehicles (Andrei et al. 2016) and drones (Dutczak 2016). Studies on small-scale engines will not replace the need to perform tests on large engine but can, however, be an element, which supplements and support the research process. Due to a lower fuel demand in small-scale engine tests, investigations may be executed in a much broader range, e.g. by testing fuels from experimental production plants, which are often characterized by limited quantities. Works in the scope of creating numerical models, which simulate the processes in real aeroengines (Gaspar and Sousa 2016), and using exergy and exergoeconomics analyses are also conducted (Coban et al. 2017).

Numerous publications can be found in the literature (Ali and Nour 2017; Badami et al. 2014; Baranski et al. 2011; Canteenwalla et al. 2016; Cavarzere et al. 2014; Chiamonti et al. 2013; Chiariello et al. 2014; Chishty et al. 2011; Gawron et al. 2016; Habib et al. 2010; Hoxie and Anderson 2017; Ibrahim et al. 2013; Mendez et al. 2014), which are associated with testing different fuels with the use of small-scale turbine engines. It is worth emphasizing that currently fuels containing synthesized hydrocarbons obtained through five specific paths described in ASTM D7566-16 (2009) are approved for direct use as synthetic blending components (up to 50%) in aviation turbine fuels. Most papers mentioned above, concern studies with the use of fuels (e.g. biodiesel, butanol), which do not have direct application for aviation. However, they can be an alternative power source for gas turbine engines for applications other than aviation. Only the following papers (Badami et al. 2014; Baranski et al. 2011; Canteenwalla et al. 2016; Chishty et al. 2011) concern the tests on small-scale engines in the scope of fuels: gas to liquid (GTL), hydroprocessed renewable jet (HRJ), synthetic

aromatic kerosene (SAK), which may be used in aircraft turbine engines.

A conclusion of the literature review is that conducting initial studies in the field of alternative jet fuels with the use of a small-scale turbine engine is fully justified. Such test rigs are currently widely used in test studies regarding fuels, mainly biodiesel, in the scope of stationary gas turbine engines.

This study aims to investigate the performance and emission characteristics of a miniature turbojet engine fed with jet fuel with synthesized paraffinic kerosene (SPK) from hydroprocessed esters and fatty acids (HEFA). It is one of the production paths for alternative aviation turbine fuel approved by the ASTM D7566-16 (2009). The biofuel results were compared with the results obtained for neat Jet A-1 fuel in terms of different engine operating modes, according to a specific methodology.

This research work was carried out in December 2016 at Air Force Institute of Technology, Division for Fuels and Lubricants, Warsaw, Poland.

Materials and methods

Description of the test rig

The experimental activity is carried out by using a specialized test rig—Miniature Jet Engine Test Rig (Mini-JETRig). The main element of the rig is a miniature turbojet engine of the GTM 140 series, which operates in the range of 33 000–120 000 rpm and its maximum thrust is 140 N. The engine has a single-stage radial compressor driven by a single-stage axial turbine and an annular combustion chamber with a set of vaporizer tubes.

The structure of the test rig, together with a description of its components, was presented in the following paper (Gawron and Białocki 2015). The data regarding the technical specification of the miniature turbojet engine, the sensors used to measure the basic operating parameters of the engine and the equipment for measuring gas emissions were described by Gawron and Białocki 2016 and Gawron et al. 2016. The harmful components of exhaust gases were measured using a portable exhaust analyser. The gas sample probe was positioned in the centre of the exhaust stream in the end section of the engine exhaust system.

Engine can be started up in two ways; electrically, via an automatic electric starter, or pneumatically, with the help of compressed air. Mass flow rate measurement on the engine inlet is possible in the second case. Then, it is necessary to use a straight duct in the engine exhaust system, due to lower temperature values in the hot section of the engine (Gawron and Białocki 2015), and such a modification allows to obtain a thrust with a maximum

value of ca. 70 N. The research in this paper was conducted with pneumatic start-up and the use of a straight duct in the exhaust system.

It is worth stressing that in the case of studies conducted with the use of miniature turbojet engines, bearing lubrication is executed mostly in an open system, through adding oil to the fuel. Oil added to the fuel adversely affects the assessment of the combustion process through contamination of the results due to the presence of oil, especially in the scope of emission of gas components of exhaust gases (Baranski et al. 2011). In the case of the presented rig, this problem was solved by a modification including the division of the fuel supply system into two different systems: a primary one, supplying fuel to the combustion chamber, and a secondary one, supplying fuel pre-mixed with oil to the bearings. This solution enables the supply of neat jet fuel to the combustion chamber.

Tested fuels

Conventional Jet A-1 fuel (obtained from a domestic refinery) and a blend of Jet A-1 with 48% of synthetic hydrocarbons obtained from HEFA process were used to supply the engine during the tests. Camelina vegetable oil was the raw material of the component produced according to the above-mentioned technology. It is worth emphasizing that a component of a HEFA production process is approved for use in engines and aircrafts. The tested fossil fuel meets the requirements of ASTM D1655-15d (1959), while the neat sustainable HEFA component complies with the standards of ASTM D7566-16 (2009). The blend of Jet A-1 with 48% HEFA component was marked in this article as HEFA fuel.

Selected physical and chemical properties of the tested fuels are presented in Table 1. The properties were selected to characterize the fuel scope of the fuel–air mixture creation and combustion process as well as to guarantee correct operating conditions of the fuel supply system.

The analysis of properties test fuel samples indicates that the HEFA fuel is characterized by a lower density and higher heat of combustion in relation to neat Jet A-1 fuel. As a consequence, it impacts the parameters associated with engine performance during the execution of engine

tests. Higher viscosity was also identified, which may contribute to the formation of bigger droplets during the combustion process. A lower content of aromatics in the HEFA fuel results in a smaller tendency to carbon deposition and smoking during combustion. On the other hand, low aromatics content may increase the risk of damage to the engine sealing.

Procedure and test conditions

Test rig experiments were conducted according to the methodology described by Gawron and Białocki 2016. The profile of engine test refers to the selected operating modes of a turbojet engine. Operating times at specific rotational speeds have been chosen in such a way, as to obtain stability of the measured parameters, mainly in terms of exhaust gas emissions.

Experiments according to an engine test sample were executed for each tested fuel twice. Within the scope of every individual test, the analysed parameters were averaged in selected sets of measurement data, characterized by small values of standard deviations. The results from the last 30 s of the run (stabilization of measured parameters) on a given engine operating mode were adopted as the sets of measurement data. Next, the results for a given parameter from two independent tests for a given fuel were averaged. The average value of each parameter was supplemented with a maximum and minimum value, which correspond the average values from single engine run.

All engine tests were executed within the same day, so as to ensure the highest stability of ambient conditions as possible (Table 2). It is known that changes of the ambient conditions impact both the engine performance and the character of combustion products emissions.

Results and discussion

Comparative results for the tested fuels, in terms of their impact on the measured engine operating parameters, are presented in Fig. 1. In the case of fuel consumption, and thus, thrust-specific fuel consumption, the analysis for the speed of 39 000 rpm was omitted due to problems resulting

Table 1 Selected results of properties Jet A-1 and HEFA fuel

Property	Test method	Limits ASTM D1655-15d (1959)/D7566-16 (2009)	Results	
			Jet A-1	HEFA fuel
Density in 15 °C	kg/m ³	775.0/840.0	788.0	779.9
Viscosity in –20 °C	mm ² /s	Max 8.000	2.992	5.004
Heat of combustion	MJ/kg	Min 42.80	43.45	43.70
Aromatics	% (V/V)	Max 25.0	15.8	9.4



Table 2 Ambient test conditions

Fuel	Test no.	P_o (bar)	T_o (°C)	RH (%)
Jet A-1	Test 1	1016.5	12.6	22.2
	Test 2	1015.9	–	–
HEFA fuel	Test 1	1018.1	14.5	22.4
	Test 2	1018.0	12.3	25.6

from the measurement of the fuel flow in the initial operating range of an appropriate sensor.

Figure 2 presents relative changes of operating parameters of a HEFA fuel fed engine in relation to neat Jet A-1 fuel.

Initially, the engine performance data showed a reduction in the fuel consumption in all analysed engine operating modes for the HEFA fuel in relation to Jet A-1. The

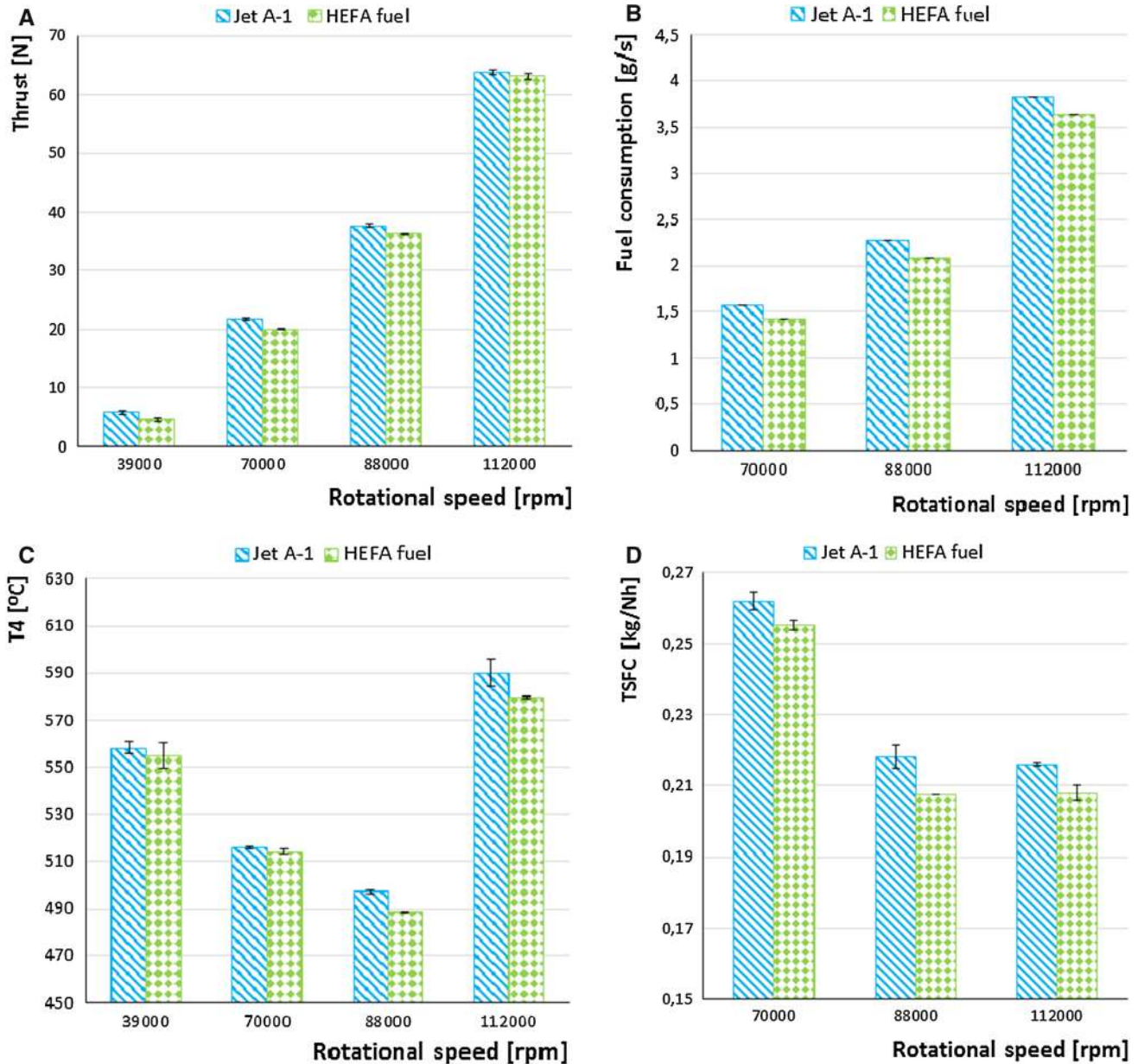


Fig. 1 Selected engine parameters as a function of rotational speed. **a** thrust, **b** fuel consumption, **c** turbine temperature, **d** thrust-specific fuel consumptions



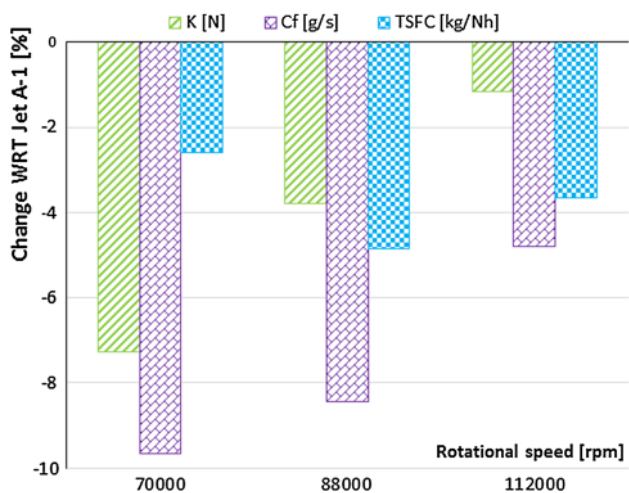


Fig. 2 Changes of engine performance with regard to Jet A-1

biggest difference for that parameter between the tested fuels was about 10%. The thrust of a HEFA fuelled engine was smaller than for the Jet A-1 fuel. However, more significant changes were obtained in the fuel consumption values, which, hence, had ultimately impacted the obtained smaller thrust-specific fuel consumptions (TSFC) values for the HEFA fuel. The lower fuel consumption values obtained for the HEFA fuel are directly associated with a higher heat of combustion and, at the same time, lower density for the HEFA fuel compared to Jet A-1. The biggest differences in the fuel consumption between the tested fuels are visible for low operating modes of the engine, while, together with increasing rotation speed, they are getting smaller. Negligible changes are observed for the temperature value measured downstream of the turbine.

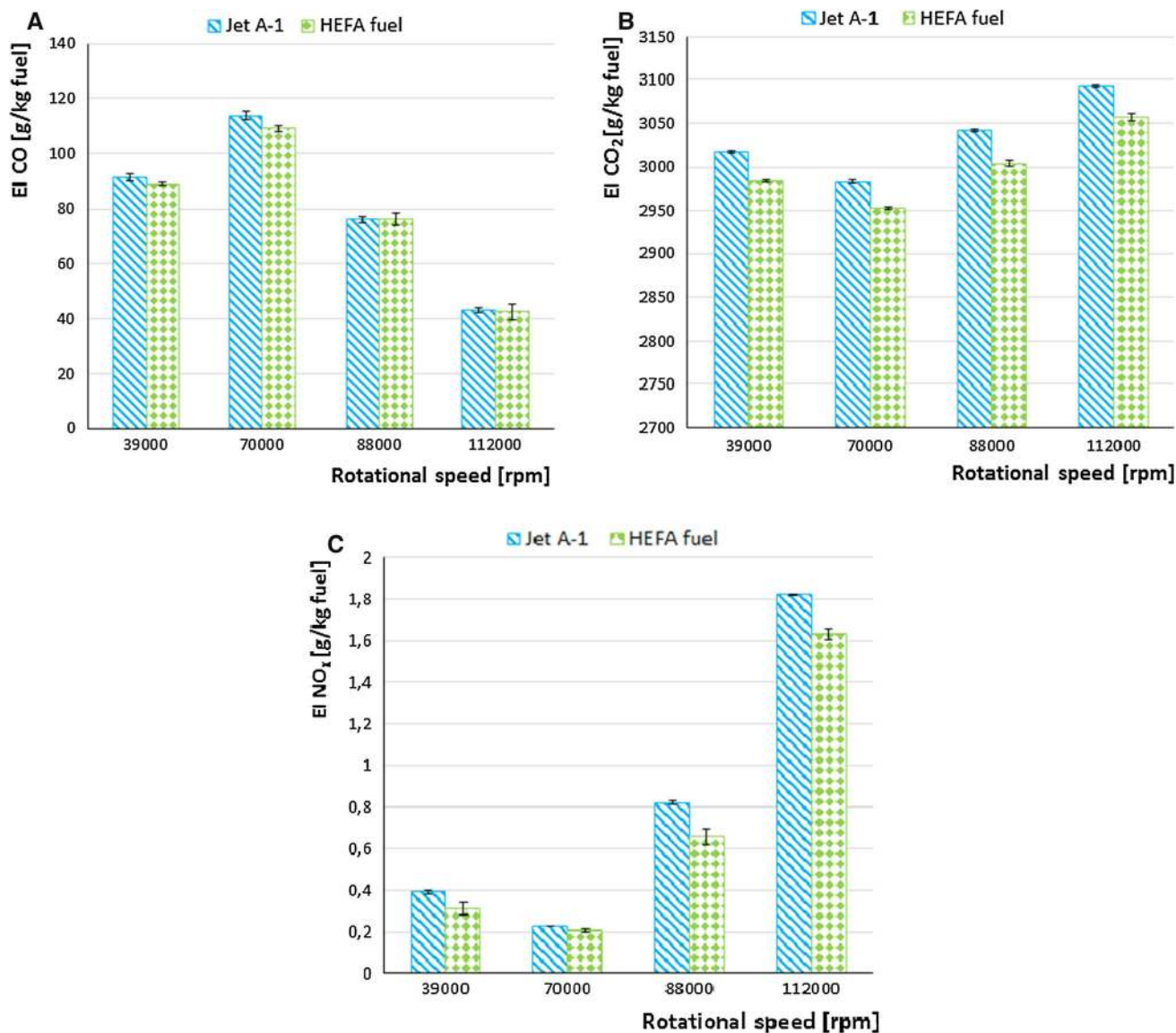


Fig. 3 Selected emission index as a function of rotational speed. a EI CO, b EI CO₂, c EI NO_x

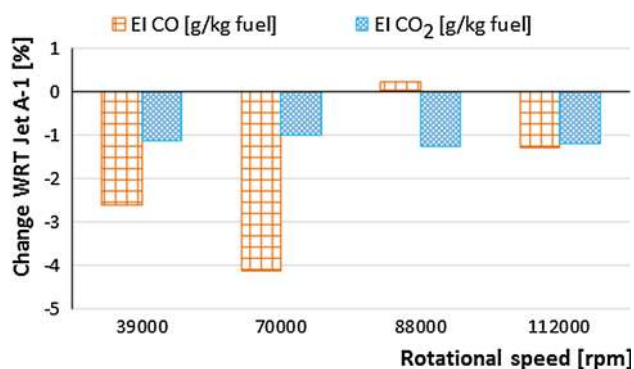


Fig. 4 Changes of EI CO and EI CO₂ with regard to Jet A-1

Comparative results for the tested fuels in terms of their impact on the emissions of selected gas components—carbon monoxide (CO), carbon dioxide (CO₂) and nitrogen oxides (NO_x)—are presented in Fig. 3. The data were converted from the value of parameters measured in ppm or % to emission indices expressed in g/kg of fuel.

The acquired results allow us to formulate a general conclusion that the emission index values for selected gas components of flue gases are lower for the HEFA fuel when compared to Jet A-1. In the case of an analysis conducted for NO_x and CO₂, the differences in emissions of these compounds for all analysed engine operating conditions do not fall in the scope of statistical data analysis for the tested fuels. It is similar in the case of CO analysis for the speeds of 39 000 and 70 000. On the other hand, in the case of the CO analysis for the speeds of 88 000 and 112 000 rpm, the obtained differences between the fuels fall within the scope of statistical data analysis.

Figure 4 shows relative changes of CO and CO₂ emissions index (EI) for the HEFA fuel in relation to neat Jet A-1 fuel. The CO₂ emission in the case of HEFA fuel is smaller by ca. 1% for all of the analysed engine operating modes in comparison with the results for neat Jet A-1 fuel. In the case of CO emissions, the biggest relative change between the fuels was obtained for a rotational speed of 70 000 rpm—ca. 4%.

The relative changes of EI NO_x between tested fuels are not shown. This analysis was omitted because measurement results of NO_x from engine test runs were within the range of small concentrations (ca. dozen ppm). For such small values, the results may be misinterpreted.

Conclusion

The performance and emission characteristics of a miniature turbojet engine using a Jet A-1/HEFA blend were studied. HEFA is currently one of five paths of synthetic

hydrocarbon production, certified and approved by the ASTM standard for use as a synthetic blending component in aviation turbine fuels. The presented results for this blend are compared with their corresponding values for the neat Jet A-1 fuel. The tests were carried out according to a determined engine test profile, which characterizes various operating modes of a miniature jet engine. The biggest differences in terms of operating parameters were achieved in fuel consumption. It was concluded that this parameter and individual fuel consumption are smaller for a Jet A-1/HEFA blend than in the case of the Jet A-1 fuel. Emission indices of selected components of exhaust gases: CO, CO₂ and NO_x are also smaller compared with Jet A-1. In the process of reviewing the literature, it can be concluded that there are very few papers utilizing small-scale engines in the scope of testing alternative jet fuels. This paper confirms the usefulness of such a research tool in studies of such type, especially as a complementation of tests performed on full-scale aircraft engines.

Acknowledgements The authors would like to thank the Ministry of Science and Higher Education for the project financed within the framework of the statutory activity (Decision No 4111/E-282/S/2016), which covered the execution of the research presented in this paper.

Compliance with ethical standards

Conflict of interest The authors have declared no conflict of interest.

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Abbreviations

ASTM	American standard for testing and materials
Biofuel	Alternative fuel obtained from renewable feedstock
C _f	Fuel consumption (g/s)
CO	Carbon monoxide
CO ₂	Carbon dioxide
EI	Emission index (g/kg fuel)
GTL	Gas to liquid
HEF	Hydroprocessed esters and fatty acids
HEFA fuel	Blend 48% HEFA with 52% Jet A-1
HRJ	Hydroprocessed renewable jet (also known as HEFA)
Jet A-1	Conventional (fossil) jet fuel
K	Thrust of engine (N)
MiniJETRig	Miniature jet engine test rig
NO _x	Nitrogen oxides

P_o	Ambient pressure (bar)
RH	Relative humidity (%)
RPM	Revolutions per minute
SAK	Synthetic aromatic kerosene
SPK	Synthesized paraffinic kerosene
T_o	Ambient temperature (°C)
T_4	Turbine temperature (°C)
TSFC	Thrust-specific fuel consumptions (N/kg h)

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