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EXHAUST EMISSIONS OF JET ENGINES POWERED BY BIOFUEL

Summary. Biofuel use is one of the basic strategies to reduce the negative impact of aviation on the environment. Over the past two decades, a number of biofuels produced from plants, lubricants and maintenance products have been developed and introduced. New fuels must have specific physicochemical parameters and meet stringent standards. This article presents a comparative analysis of the exhaust emissions measurement results from jet engines powered by traditional aviation kerosene and its blends with ATJ (Alcohol to Jet) biofuel. The concentrations of carbon dioxide, carbon monoxide and hydrocarbons were measured. Measurements were conducted in laboratory conditions for various engine load values. Based on the analysis, it was found that the use of biofuel increases the concentration of carbon monoxide and hydrocarbons in the exhaust gas relative to aviation kerosene. The use of biofuel did not result in an increase in fuel consumption and related carbon dioxide emissions. Based on the conducted research, it was found that biofuel use did not affect the ecological properties of the engine significantly. In addition, a correlation analysis of the measurement results from both engines was carried out.

1. INTRODUCTION

Transport, as one of the most important economic fields, is characterized by continuous development, which is particularly visible in developing countries, where travel time has begun to gain significant importance. The dynamic development of air transport results in an increase in the number of air operations and the fleet. New carriers and flight connections cause even greater interest in air transport [1, 2]. This resulted not only in many economic benefits but also negative environmental effects of pollution with toxic exhaust compounds [3, 4].

Exhaust emissions emitted by aircraft largely depend on the engine, the structure of the aircraft and the fuels used [5, 6]. Pollutants emitted from turbine engines not only pollute the air but also negatively affect human health [1, 7], contributing to a number of diseases and mutagenic changes. Due to the constantly deteriorating condition of the environment, increasingly stringent standards for toxic exhaust compounds are being introduced. These issues are covered by international regulations contained in the second volume "Emissions from aircraft engines" of Annex 16 "Environmental Protection" to the Convention on International Civil Aviation ICAO [8, 9]. It covers the methodology for measuring individual exhaust gas components and provides their limit values for jet turbine engines over 26.7kN [8]. Particulate matter (PM) emission is regulated by two directives. The first is

EU Directive 1999/30 / EC and concerns limit values for sulfur dioxide and nitrogen oxides as well as concentration of particles with a diameter of up to 10 µm in the ambient air. The second is included in Directive 2008/50 / EC of the European Parliament and of the Council of the 21st May 2008 on air quality and cleaner air for Europe and includes particles with a diameter of 2.5 µm.

Considerable scientific research is being undertaken, which will result not only in modern constructions and aviation drives but also development of new technologies for manufacturing biofuels and their mixtures for aircraft. Development and creation of new mixtures of biofuels are difficult because fuels for aircraft engines must meet strict requirements not only in terms of the appropriate physicochemical properties to promote the combustion process but also to meet the high requirements for flight safety. Fig. 1 shows the materials and production technology of alternative aviation fuels.

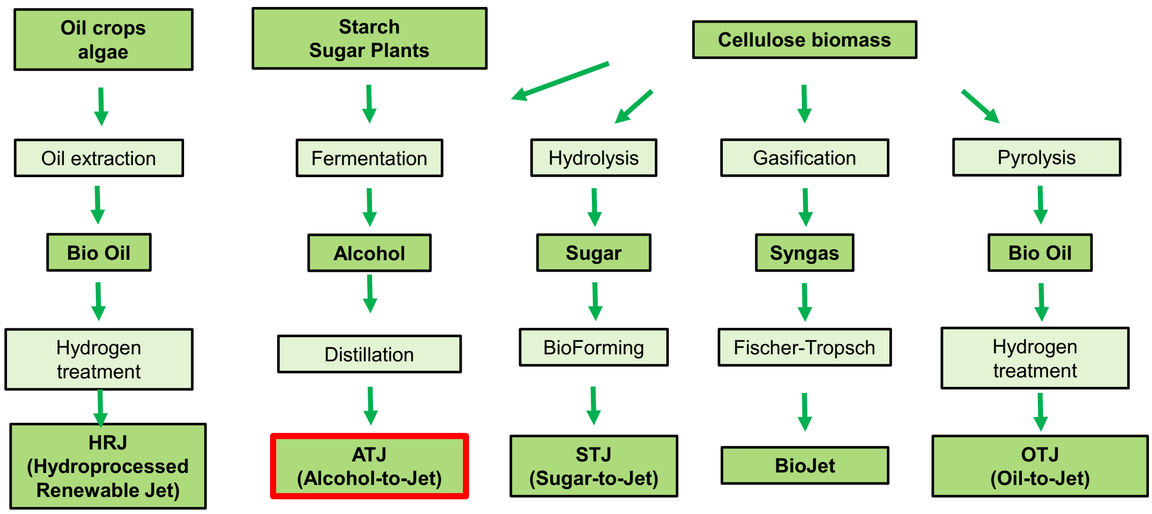

Fig. 1. Division of aviation alternative fuels

It is expected that in 2030, 30% of aviation fuels used will be biofuels, and by 2040 even 50% [10, 11]. The use of alternative fuels allows reduction in exhaust emissions, in particular, carbon dioxide. It can be concluded that the development of biofuels for aviation is inevitable, and ongoing work in this area is at various levels of progress [12–14].

2. METHODOGOLY

2.1. Purpose and scope of the research

The tests were carried out to determine the impact of biofuel addition on the concentrations of harmful compounds in the exhaust gas of jet engines. The assessment covered Jet A-1 and Jet A-1 blend containing 20% ATJ. The tests were performed for the entire engine load range.

The tests were carried out on two different jet engines differing significantly in terms of the maximum thrust generated. Based on the collected results, a correlation analysis was carried out to determine the possibility of inferring about the ecological properties of the engine based on measurements made on another test object.

2.2. Test object and apparatus

The focus of research was the GTM-120 turbine engine (Fig. 2) made of a single-stage radial compressor, driven by a single-stage axial turbine. The engine is started using the starter motor. The test stand enables measurement of the shaft speed, the temperature of exhaust gas at the nozzle and thrust. The maximum thrust of the engine is 100 N and its weight is 1.5 kg.

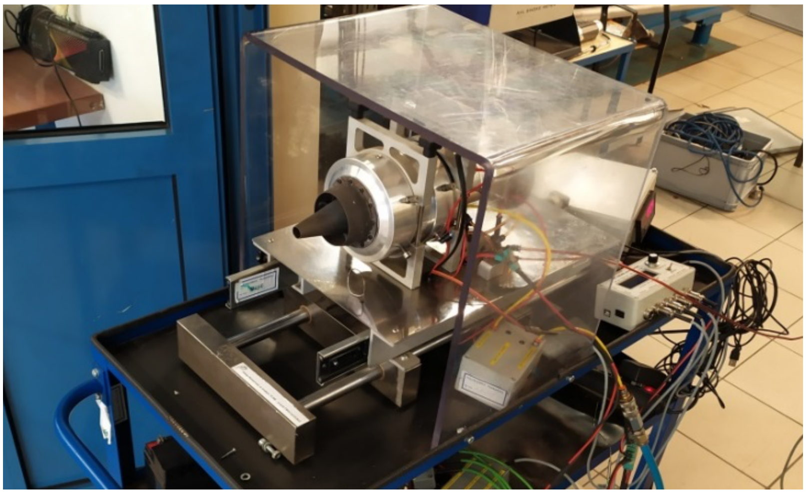

Fig. 2. View of the GTM-120 engine

The second object tested was the DGEN 380 engine (Fig. 3), which is a two-spool unmixed flow turbofan jet engine. It has a light weight, small dimensions and a high bypass ratio. Its construction reduces noise emissions. The maximum thrust of the DGEN 380 engine is 2 550 N and its weight is 85 kg.

Fig. 3. View of the DGEN 380 engine

A mobile Semtech DS apparatus was used to measure gaseous exhaust compounds. An exhaust gas analyser used in this research allowed for the measurement of the concentrations of carbon monoxide, carbon dioxide and hydrocarbons. The exhaust gases were introduced into the analyser via a cable, whose temperature was 191° C, which was required to measure the hydrocarbon concentration in the flame-ionization analyser. In the next stage, after cooling the flue gas to a temperature of 4° C, the measurements of the concentrations of carbon monoxide and carbon dioxide were performed.

3. RESEARCH RESULTS AND THEIR ANALYSIS

3.1. Measurement results

The results of measurements of the concentrations of harmful compounds in the exhaust gas of GTM-120 and DGEN 380 engines powered by Jet A-1 fuel are presented in Fig. 4. The highest concentration of carbon monoxide (Fig. 4a) for both engines was recorded for the lowest value of engine load, respectively, 308 ppm and 281 ppm for the GTM-120 and DGEN 380 engines. Increasing the engine load to the medium and high load range resulted in a reduction in the carbon monoxide concentration for both engines. At maximum load, a slight increase in the CO concentration to 251 ppm was observed for GTM-120 and 180 ppm for DGEN 120.

The highest concentration of hydrocarbons was recorded for the lowest engine load (68 ppm for GTM-120 and 38 ppm for DGEN 380) and the lowest for very high and maximum values of thrust (Fig. 4b). For both engines, a clear relationship was found between the decrease in the HC concentration and the increase in engine load.

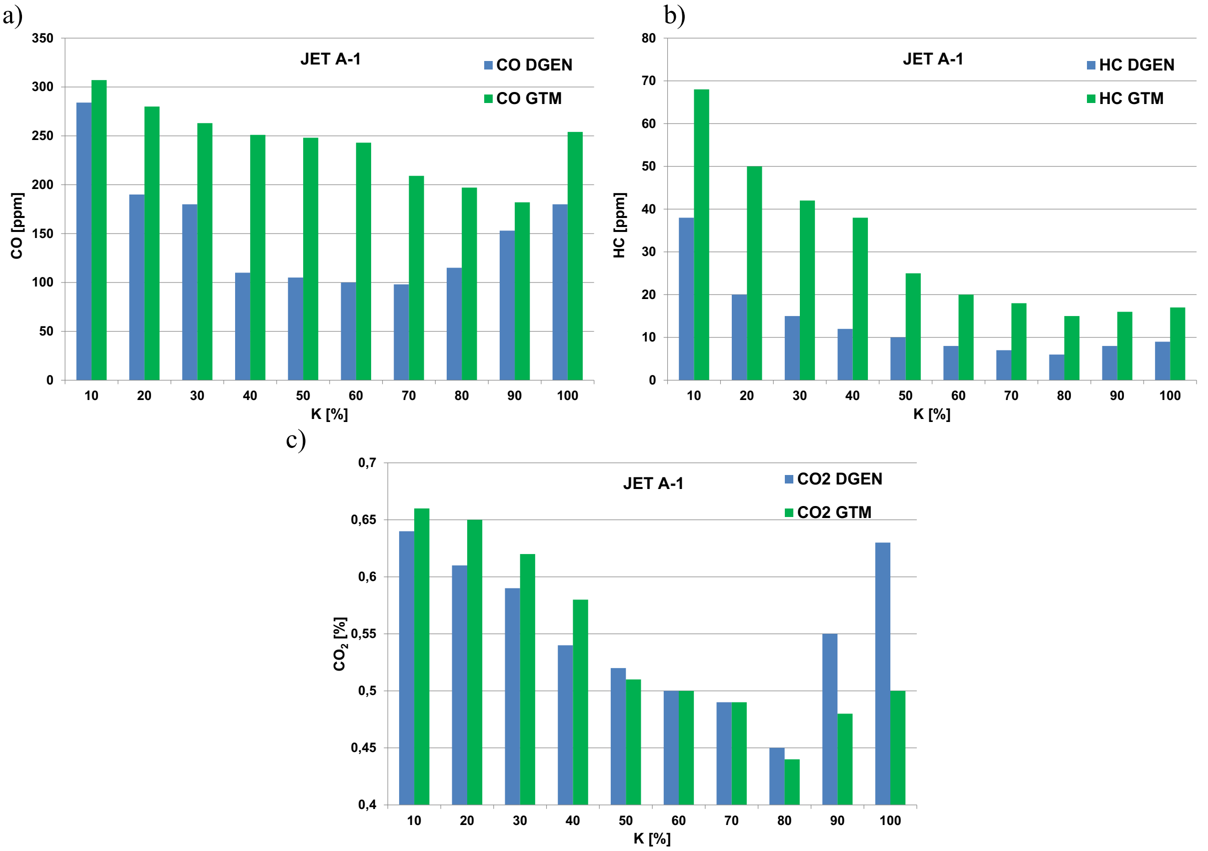

Fig. 4. Concentration of exhaust gas compounds (Jet A-1 fuel)

For small and medium load values, the concentration of carbon dioxide for both engines were very similar (in the range of 0.65–0.45%) (Fig. 4c). Increasing the load resulted in a decrease in the CO_2 concentration, except for 90% and 100% of load. In the above case, the concentration of carbon dioxide increased, which is associated with a very large increase in fuel consumption in the range of very high engine loads. The results of measurements of the concentrations of harmful compounds in the exhaust gas of GTM-120 and DGEN 380 engines powered by Jet A-1 fuel with the ATJ admixture are presented in Fig. 5. The highest concentration of carbon monoxide (Fig. 5a) for both engines was recorded for the lowest value of engine load, respectively, 426 ppm and 300 ppm for the GTM-120 and DGEN 380 engines. The use of biofuel admixture did not cause any significant changes in the engines' operating parameters; therefore, it can be concluded that the use of ATJ fuel resulted in an increase in carbon monoxide emissions. Increasing the engine load to the medium and high load range resulted in a reduction in the carbon monoxide concentration for both engines, up to a value of about 200 ppm. At maximum load, a slight increase in the CO concentration to 200 ppm was observed for GTM-120 and 240 ppm for DGEN 120.

The highest concentration of hydrocarbons was recorded for the lowest engine load (65 ppm for GTM-120 and 38 ppm for DGEN 380) and the lowest for very high and maximum thrust values (Fig. 5b). For both engines, a clear relationship was found between the decrease in the HC concentration and the increase in engine load. Use of ATJ fuel led to a slight increase in the concentration of hydrocarbons in the exhaust gas of both engines.

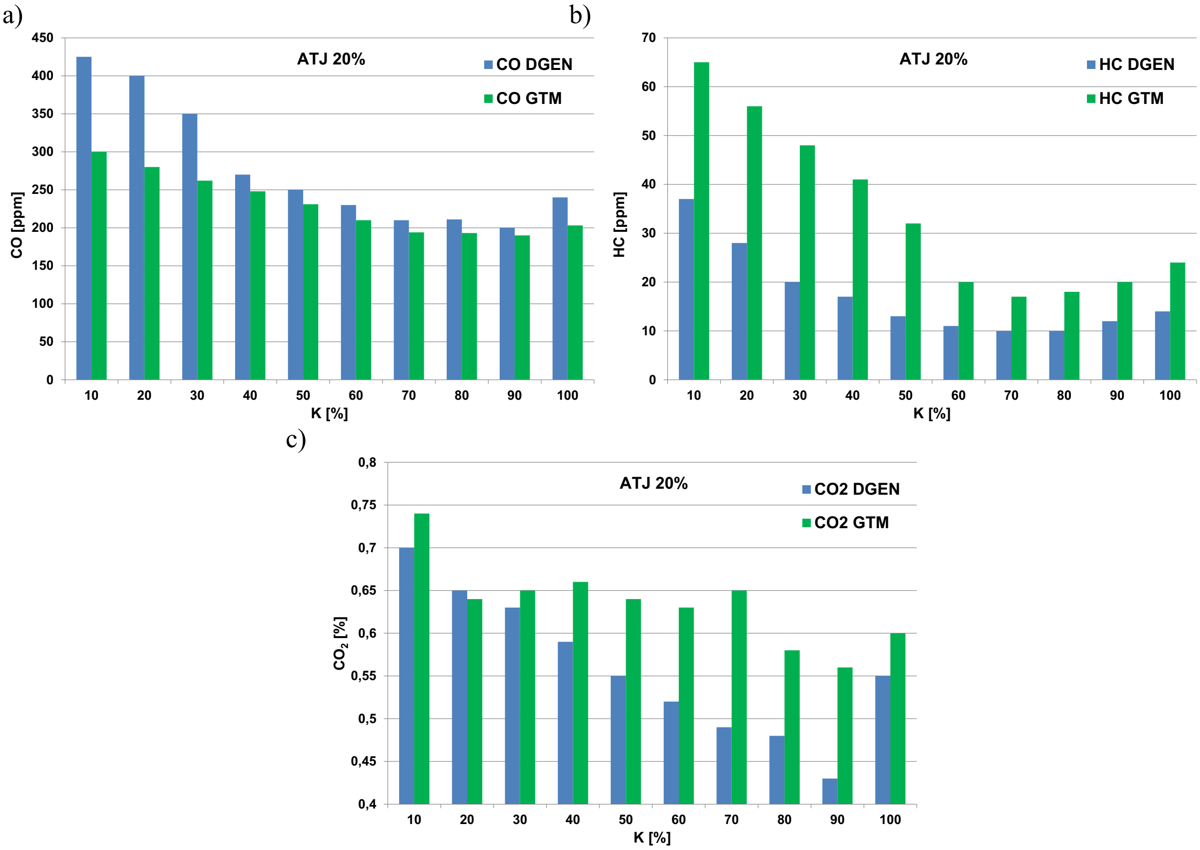

Fig. 5. Concentration of exhaust gas compounds (20% of ATJ)

For small and medium load values, the concentration of carbon dioxide for both engines was very similar (in the range of 0.75–0.60%) (Fig. 5c). Compared to fueling of the engine without the ATJ admixture, it can be seen that the CO_2 concentration increased. This is due to increased fuel consumption. Increasing the load resulted in a decrease in the CO_2 concentration, except 90% and 100% load values. In the above case, the concentration of carbon dioxide increased, which is associated with a very large increase in fuel consumption in the range of very high engine loads.

3.2. Correlation analysis

The correlation analysis was aimed at determining the possibility of inferring the ecological properties of a given engine based on the results of tests carried out on another engine of a different size. For this purpose, a correlation analysis was performed of the concentration values of individual harmful exhaust compounds for two engines and given load values. Pearson's linear correlation coefficient (r) was adopted as a measure of the variables' correlation, which is defined as the quotient of the covariance and the product of the standard deviation of the variables studied.

Five operating points of the engine were analyzed, respectively, from 10% to 100% of the both engines' thrust. As variables for the correlation studies, the values of the concentration of individual harmful exhaust gas compounds (CO, HC, CO_2) were used during the operation of two jet engines at the indicated operating points. The determined Pearson correlation coefficients were checked in terms of statistical significance, and the results are shown in Fig. 6. The STATISTICA 13 software package was used for the calculations.

Fig. 6 presents scatter plots of carbon monoxide, hydrocarbon and carbon dioxide concentration values at various loads of the engine powered by Jet A-1 fuel without any additives. The Pearson correlation coefficient for carbon monoxide measurements (Fig.6a) was equal to 0.63. A moderate correlation was found between the parameters tested. For the correlation analysis of the hydrocarbon concentration value (Fig. 6b), the linear correlation coefficient was 0.94. A strong positive correlation was found between the values obtained during tests of the GTM-120 engine and DGEN 360.

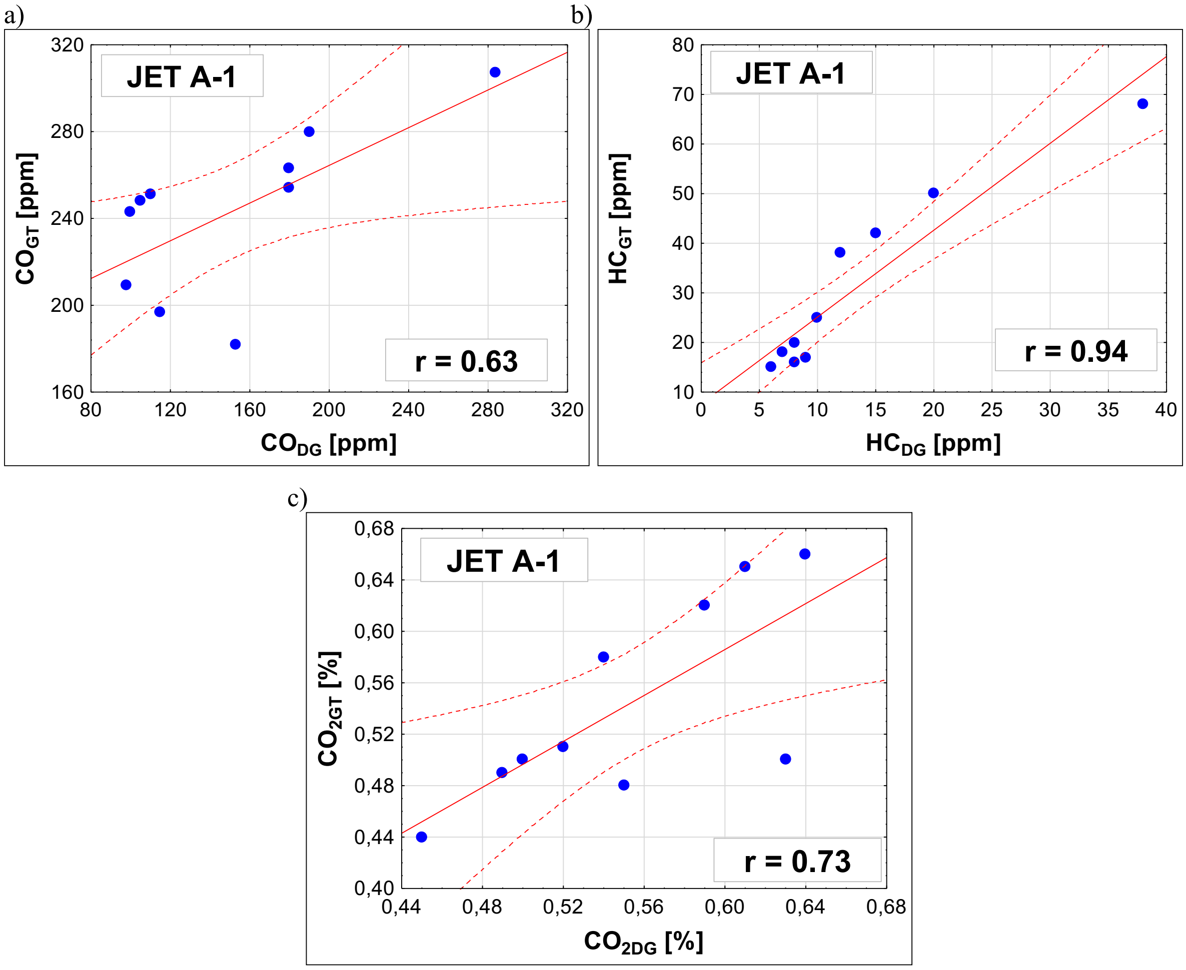

Fig. 6. Scatter plots of carbon monoxide (a), hydrocarbon (b), and carbon dioxide concentration values (c) for the engine powered by Jet A-1 fuel

The scatter plot of the carbon dioxide concentration in the exhaust gas of jet engines is shown in Fig. 6c. Pearson's correlation coefficient was equal to 0.73, which indicates a strong correlation between the parameters tested.

Fig. 7 presents scatter plots of carbon monoxide, hydrocarbon and carbon dioxide concentration values at various loads of the engine powered by Jet A-1 with 20% of the ATJ fuel additive. The Pearson correlation coefficient for carbon monoxide measurements (Fig.7a) was equal to 0.96. A strong correlation was found between the parameters tested.

For the correlation analysis of the hydrocarbon concentration value (Fig. 7b), the linear correlation coefficient was 0.95. A strong positive correlation was found between the values obtained during tests of the GTM-120 engine and DGEN 360.

Fig. 7c presents a scatter graph of carbon dioxide concentration values. The determined linear correlation coefficient was 0.82. A strong correlation was found between the carbon dioxide concentration values determined for the GTM-120 and DGEN 380 engines.

4. CONCLUSIONS

The presented results of analyses are only for the concentrations of harmful exhaust compounds, but not their emissions. However, taking into account the fact that the measurements were carried out in steady conditions and the engine operating parameters were constant, it can be concluded that the ecological properties of the tested engines were analyzed. On the other hand, taking into account the emissions of engines that are significantly different in terms of maximum thrust does not allow any direct comparative analysis.

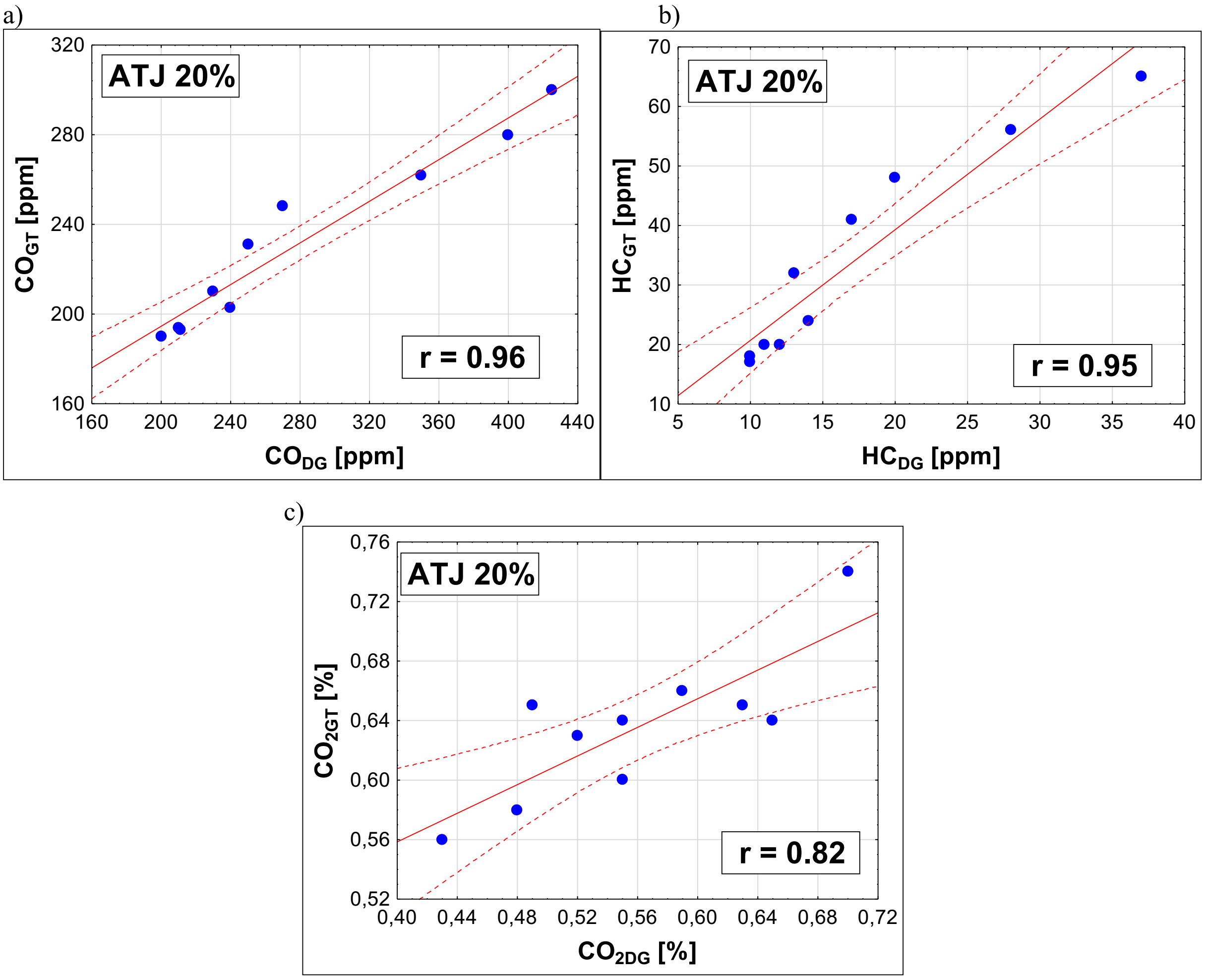

Fig. 7. Scatter plots of carbon monoxide (a), hydrocarbon (b) and carbon dioxide concentration values (c) for the engine powered by Jet A-1 with ATJ additive

The tests showed the effects of biocomponent additives on the concentration (and thus emissions) of exhaust harmful compounds of the tested engines. The use of Jet A-1 blend containing 20% ATJ resulted in small changes in hydrocarbon and carbon monoxide concentrations. Comparative analysis showed that in both the GTM-120 and DGEN 380 engines, the biofuel use resulted in increased HC and CO concentrations in the exhaust gas. On this basis, it can be concluded that the biocomponent probably negatively affected the combustion conditions.

In addition, an increase in the carbon dioxide concentration was found relative to the operation of the JET A-1 fuel engine without additives. This indicates an increase in fuel consumption. However, it should be kept in mind that the purpose of biofuel use is mainly to reduce exhaust emissions throughout the entire life cycle of the fuel and not only during its combustion.

Correlation analysis based on Pearson's linear correlation coefficient indicated a strong correlation between the results of ecological tests from both engines. Therefore, on the basis of the above result, it can be stated that in the case of the tested engines, a similar nature of changes in the concentrations of harmful exhaust gas compounds can be observed for the given engine operating parameters. The possibility of inferring about the ecological properties of a high-thrust object based on a smaller engine requires further work. Certainly, there are phenomena characteristic of jet engines in terms of their operating parameters and exhaust emissions. Extension of the presented issue should include work on the repeatability of the obtained results.

References

1. Zhang, M. & Huang, Q. & Liu, S. & et al. Assessment method of fuel consumption and emissions of aircraft during taxiing on airport surface under given meteorological conditions. *Sustainability*. 2019. Vol. 11. No. 6110. P. 1-21.
2. Markowski, J. & Pielecha, J. & Jasiński, R. Model to assess the exhaust emissions from the engine of a small aircraft during flight. *Procedia Engineering.* 2017. Vol. 192. P. 557-562.
3. Zhang, X. & Karl, M. & Zhang, L. & et al. Influence of aviation emission on the particle number concentration near Zurich airport. *Environ. Sci. Technol*. 2020. Vol. 54. P. 14161-14171.
4. Woody, M. & Haeng Baek, B. & Adelman, Z & et al. An Assessment of Aviation's Contribution to Current and Future Fine Particulate Matter in the United States. *Atmos. Environ*. 2011. Vol. 45. P. 3424-3433.
5. Reksowardojo, I. & Duong, L. & Zain, R. & et al. Performance and exhaust emissions of a gas turbine engine fueled with Biojet/Jet A-1 blends for the development of aviation biofuel in tropical regions. *Energies.* 2020. Vol. 13. No. 6570.
6. Jasiński, R. Mass and number analysis of particles emitted during aircraft landing. *E3S Web of Conferences.* 2018. Vol. 44. No. 00057.
7. Levy, J.I. & Woody, M. & Baek, B.H. & Shankar, U. & et al. Current and Future Particulate-Matter-Related Mortality Risks in the United States from Aviation Emissions During Landing and Takeoff. *Risk Anal.* 2011. Vol. 32. P. 237-249.
8. Quadros, F.D.A. & Snellen, M. & Dedoussi, I.C. Regional sensitivities of air quality and human health impacts to aviation emissions. *Environmental Research Letters*. 2020. Vol. 15. No. 105013.
9. Jasinski, R. & Markowski, J. & Pielecha, J. Probe positioning for the exhaust emissions measurements. *Procedia Engineering.* 2017. Vol. 192. P. 381-386.
10. Arunachalam, S. & Wang, B. & Davis, N. & Baek, B.H. & et al. Effect of Chemistry-Transport Model Scale and Resolution on Population Exposure to PM2.5 from Aircraft Emissions During Landing and Takeoff. *Atmos. Environ.* 2011. Vol. 45. No. 19. P. 3294-3300.
11. Liu, X. & Hang, Y. & Wang, QW. & et al. Drivers of civil aviation carbon emission change: A two-stage efficiency-oriented decomposition approach. *Transportation Research Part D-Transport and Environment*. 2020. Vol. 89. No. 102612.
12. Malinowski, A. Biopaliwa dla lotnictwa. *Czysta energia.* 2011. Vol. 9. No. 121. [In Polish: Biofuels for aviation. *Pure energy*].
13. Anderson, A. & Karthiheyan, A. Kumar, & CR. & et al. Lowest emission sustainable aviation biofuels as the potential replacement for the Jet-A fuels. *Aircraft Engineering and Aerospace Technology*. 2020. Vol. 93. No. 3. P. 502-507.
14. Capaz, R.S. & Guida, E. & Seabra, J.E.A. & et al. Mitigating carbon emissions through sustainable aviation fuels: costs and potential. *Biofuels Bioproducts & Biorefining-Biofpr*. 2021. Vol. 15. No. 2. P. 502-524.
15. Stettler, M.E.J. & Boies, A.M. & Petzold, A. & et al. Global Civil Aviation Black Carbon Emissions. *Environmental Science Technology.* 2013. Vol. 47. No. 18. P. 10397-10404.

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