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Analysis of the Environmental Parameters of the GTM 400 Turbojet Engine During the Co-Combustion of JET A-1 Jet Oil with Hydrogen

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ABSTRACT

The aim of the research was to determine the possibility of co-combustion of conventional aviation fuel (JET A-1 jet fuel) with hydrogen (H_2). The tested miniature turbojet engine was adapted to co-combust of both fuels. The results obtained from the research provide a positive premise for the application and implementation of hydrogen co-combustion (or combustion) technology in aircraft turbojet engines, which has not yet found industrial application. Observations and research show that co-combustion of jet fuel with hydrogen helps reduce the carbon footprint of the use of turbojet aircraft engines and also reduces other harmful substances (e.g. carbon monoxide, nitrogen oxides or solid particles). During the tests, no deterioration of the engine's operating parameters was observed and the set operating parameters were maintained. To summarize, the technology of co-combustion or hydrogen combustion in miniature turbojet engines is an indicated direction in the development of pro-ecological aircraft engines.

Keywords: emission, turbojet engine, co-combustion, jet oil, hydrogen.

INTRODUCTION

The process of globalization, urbanization and broad cultural exchange results in an increasing interest in means of communication that enable quick movement, especially over long distances. These types of requirements are best met by aircraft. Most modern aircraft structures are equipped with advanced engine systems, including jet engines. Unmanned aerial vehicles (UAVs) are also becoming faster around the world. In the case of UAVs operating in formations (or swarms) and as a loyal wingman with manned aircraft, significant speeds can only be achieved thanks to the use of jet engines [Prokopowicz and Śnieguła 2020]. An example of such an engine is a miniature jet engine with low thrust. The construction of such an engine is not complicated and has been described in many publications. Miniature jet engines are most often composed of an intake, a radial compressor, a combustion chamber, a turbine and an exhaust nozzle [Benini and Giacometti 2007; Gieras 2016]. Various scientific and technical centers around the world analyze these engines both in terms of the impact of thermodynamic and mechanical parameters on the engine and the related environmental loads [Dinara and Bramantya 2021; Muckova et. al. 2023; Ziya Sogut 2020], in addition, various types of CFD numerical analyzes are performed [Joy et al. 2019], JET A-1 fuel is also subject to testing to determine its emission characteristics and environmental impact [Gawron and Białecki 2018; Joy et al. 2020; Aygun et al. 2021; Metin and Aygün 2019]. Research on miniature jet engines is carried out towards the combustion of various fuels [Mansor and Shioji 2016; Antolini et al. 2023]. Research is also using artificial intelligence to improve engine control [Koleini et al. 2018, Zhao et. al. 2019, Zhao 2018]. All this is being done to increase the technical and operational capabilities of miniature jet engines.

The rapidly progressing process of globalization and uncontrolled demographic growth, especially in less developed areas, negatively impacts the environment, primarily through the increase in anthropogenic pollution. The basic anthropogenic gaseous pollutants studied and registered around the world are: greenhouse gas - carbon dioxide (CO_2) and other gaseous harmful substances such as carbon monoxide (CO), nitrogen oxides (NO_x) or particulate matter (PM) [Ciupek and Gołoś 2020; Synak et. al. 2021; Šarkan et. al. 2022]. Most emissions from energy sources or transport are registered, monitored and controlled [Ciupek et al. 2021; Hunicz et. al. 2023; Rayapureddy et. al. 2022]. Interesting research from Slovakia in this area was presented by Kendra et al. [Kendra et al. 2023], as well as Veselik et al., from Brno, Czech Republic [Veselik et al. 2020]. Observation of changes in nature as well as increasingly widely researched environmental changes show that over recent decades, environmental pollution caused by human activity has been getting more severe and affects climate change, hence taking action to use previously unpopular energy sources with a reduced carbon footprint and lower emissions of harmful substances is becoming an important direction in the development of science in the 21st century. To meet these challenges, a lot of various research is being conducted on alternative fuels for combustion engines [Dittrich et al. 2023; Małek et al. 2023; Gardyński et al. 2020] used by various means of transport, including air transport [Szewc et al. 2021].

The aim of the work is to present the impact of the use of a mixture of JET A-1 fuels and hydrogen in a miniature jet engine on the formation of harmful substances as a result of combustion processes [Prokopowicz W. and Frąckowiak A. 2023; Kobaszyńska-Twardowska et al. 2022], as a combination of standard aviation fuel with an energy source with minimized environmental impact and a significantly smaller carbon footprint.

METHODS

Experimental tests were carried out on the GTM400 turbojet engine produced by JETPOL. The engine has a modified combustion chamber and is characterized by the following technical parameters:

- thrust: 15 [N] – 300 [N];
- rotational speed: 30,000 [rpm] – 81,000 [rpm];
- maximum air mass flow: 0.59 [kg/s];
- maximum fuel consumption: 1.03 [kg/min].

The engine is the main element of the test stand, which is shown in Figure 1, and its technical diagram is shown in Figure 2. In addition to the engine, the test stand also contains additional components, which include:

- control and measurement equipment with data acquisition with a touch screen and temperature and pressure sensors;
- external digital engine control module equipped with a power setting knob for JET A-1 fuel and technical hydrogen, as well as a starting switch;
- protective housing made of polycarbonate;
- a platform with elements for mounting the engine and its equipment, as well as other components of the station.

Two types of fuel were used for the tests: jet fuel with the designation: JET A-1 and technical hydrogen. The purity of technical hydrogen is 99.96%. During tests of the turbojet engine during co-combustion of jet fuel with hydrogen, special care had to be taken and safety rules should be followed, as hydrogen poses a very high explosive risk, described in detailed regulations, presented in more detail in [Semkło Ł. 2022]. During the first start-up, the engine speed was set to 40,000 rpm. During operation, after adjusting the speed, the cylinder valve was opened and hydrogen was supplied to the combustion chamber. The following values of hydrogen volume flow were set on the flowmeter: 25.00 l/min, 50.00 l/min. and 93.40 l/min. During the second start-up, the rotation speed was set to 50,000 rpm. In this case, the following hydrogen volume flows were used during operation: 50.00 l/min. and 93.40 l/min.

As a result of the hydrogen flow into the engine, the rotational speed increased. After the recorded increase in rotational speed, it was reduced to the initial value, i.e. 40,000 rpm (during the first start-up) and 50,000 rpm (during the second start-up). The equipment installed at the station recorded and compared the values of the volume flows of both fuels. When hydrogen was supplied to the engine, the proportion of jet fuel

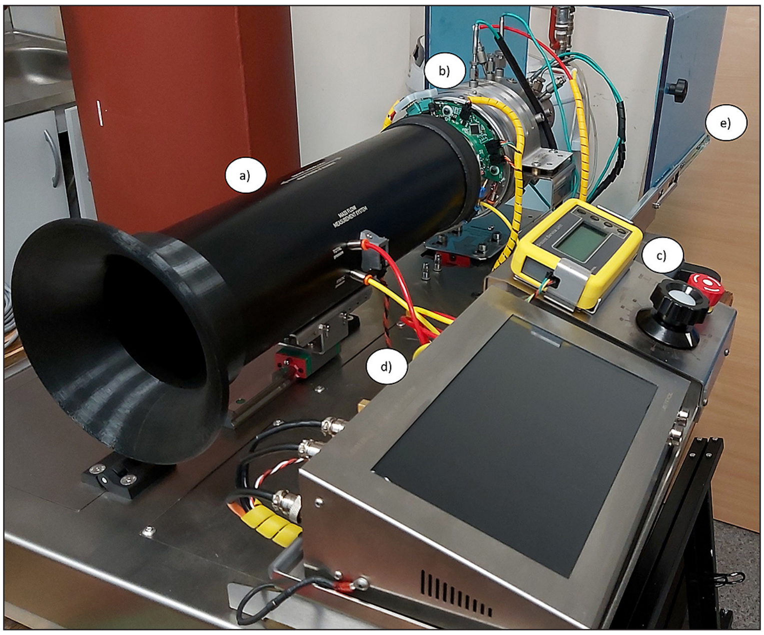

Fig. 1. GTM 400 turbojet engine used in test: (a) inlet; (b) engine; (c) engine control; (d) measurement equipment; (e) polycarbonate protection

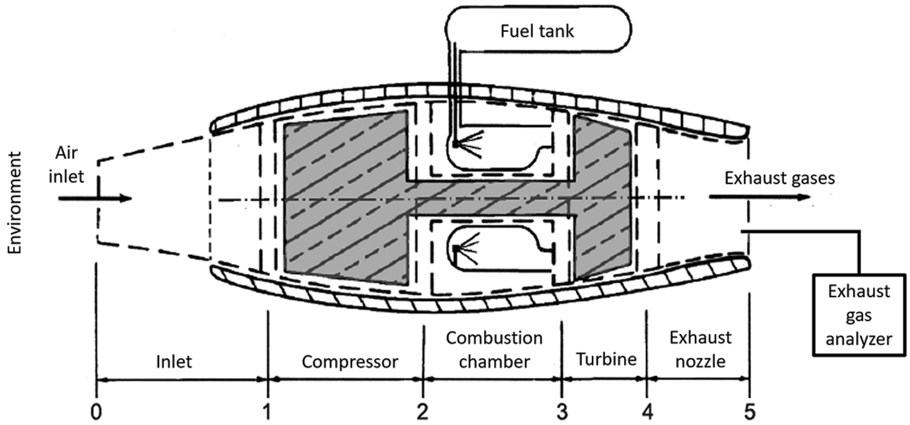

Fig. 2. Scheme of turbojet engine [Gieras 2016]

was reduced accordingly based on these values. The following exhaust gas analyzers were used to test harmful substances in exhaust gases: TESTO 330-2 LL and TESTO 380. The analyzers operated in a hybrid system and were used to measure mass concentrations of O_2, CO_2, CO, NO_x, and PM (Fig. 3). The location of the analyzers during the tests is shown in Figure 2. The emission was converted into 3% of oxygen content in the exhaust gases (3% O_2) resulting from the total and complete combustion of liquid fuels, referred to Siegert's stoichiometric equations [Ciupek 2022]. The measurement accuracy for O_2, CO_2, CO, and PM is ±10%, and for NO_x ±8%. Lifetime photochemical measurement cells were used to measure gas components in exhaust gases. The solids content in exhaust gases was measured using the gravimetric method. The exhaust gas temperature was measured using a thermoelectric thermometer type K (NiCr-Ni) with a measurement range from 73 K to 1643 K and a measurement error of ±1 K in the temperature range of 673–1173 K. The analysis time was set at one sample per second, and a single research cycle was based on the full load characteristics for the operation of the GTM 400 engine with jet fuel and during its co-combustion with hydrogen. Emission parameters were developed for average values for which the uncertainty interval was calculated with a 95% confidence level. The environmental analysis of the impact of harmful

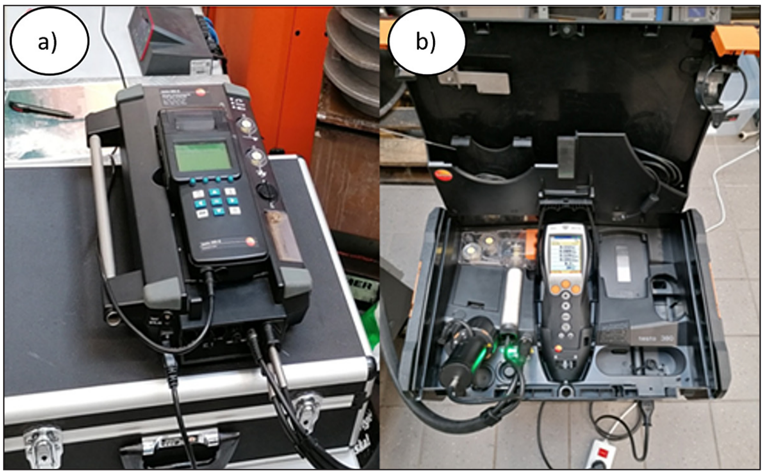

Fig. 3. Exhaust gas analyzers used in the tests: (a) TESTO 330-2 LL; (b) TESTO 380

substances on the parameters focused mainly on CO, NO_x and PM emissions, relating them to the change in gas temperature (T_f) at the engine outlet.

RESULTS

Figure 4 shows CO and NO_x emissions in relation to the change in exhaust gas temperature during the test for the combustion of jet fuel alone. In the case of CO emissions, the average emission for the entire test cycle was observed at the level of 2,790.18 mg/m^3 (min value: 9.00 mg/m^3, max.: 12,351.00 mg/m^3), for NO_x the average value is: 813.08 mg/m^3 (min value: 1.30 mg/m^3, max.: 8,096.00 mg/m^3), and for PM the average value is: 35.27 mg/m^3 (min. value: 5.00 mg/m^3, max.: 293.00 mg/m^3). In the case of CO_2 emissions, the average value is: 11.43% (min. value: 9.28%, max. value: 11.97%). The average exhaust gas temperature was: 495.77 K (min. value: 300.15 K max.: 1,144.95 K).

Figure 5 shows CO and NO_x emissions in relation to the change in exhaust gas temperature during the test for co-combustion of jet fuel with hydrogen. In the case of CO emissions, the average emission for the entire test cycle was observed at the level of 1,279.81 mg/m^3 (min value: 12.00 mg/m^3, max.: 2,443.70 mg/m^3), for NO_x the average value is: 577.39 mg/m^3 (min value: 27.70 mg/m^3, max. value: 954.87 mg/m^3), and for PM the average value is: 16.94 mg/m^3 (min value:

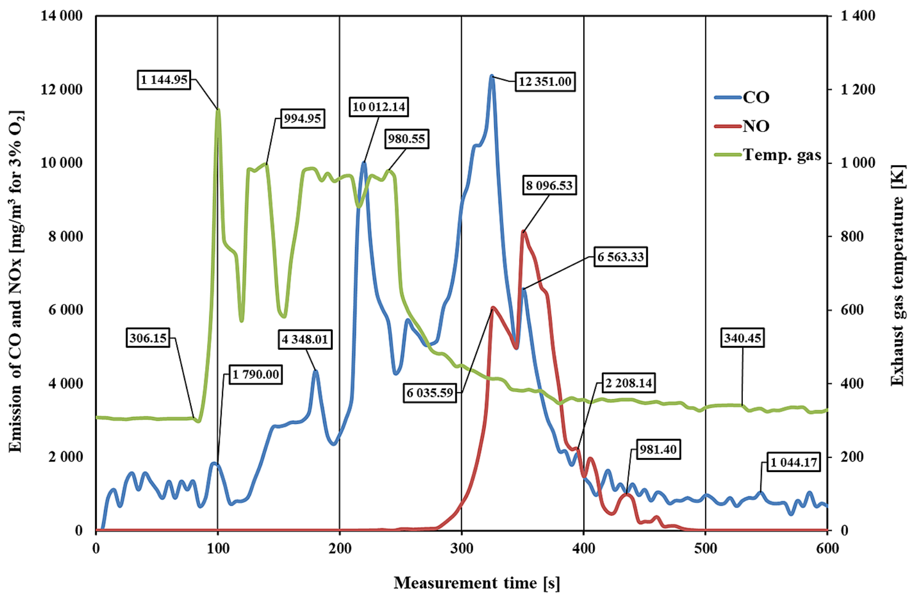

Fig. 4. Test results for the first stage

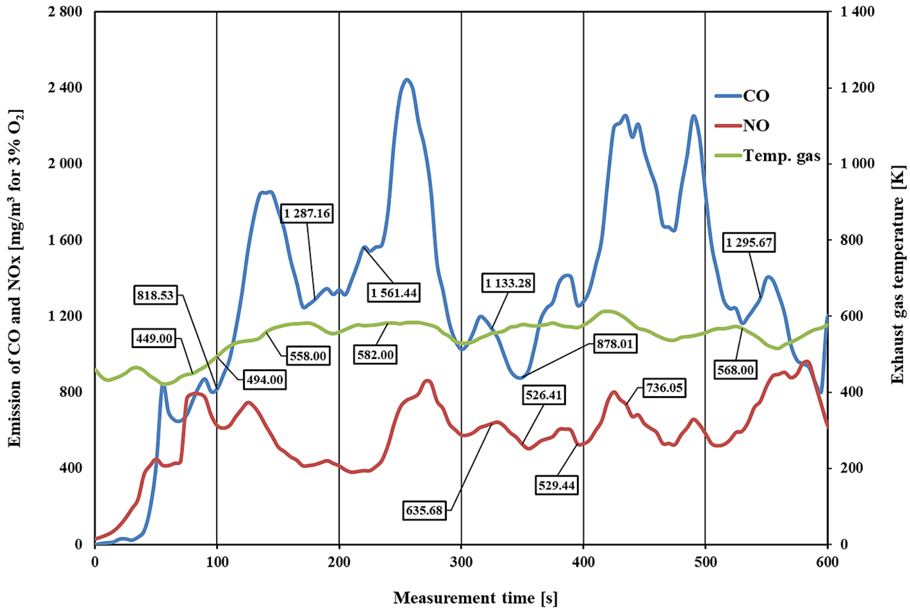

Fig. 5. Test results for the second stage

5.00 mg/m³, max.: 24.00 mg/m³). In the case of CO_2 emissions, the average value is: 10.14% (min. value: 9.22%, max. value: 10.94%). The average exhaust gas temperature was: 543.69 K (min. value: 421.15 K max.: 613.15 K).

Figure 6 shows a summary of CO, NO_x and PM emissions (mg/m³ for 3% of O_2 in flue gases) and changes in exhaust gas temperature (T_f) depending on the type of fuel burned (jet fuel alone or co-combustion with hydrogen). According to the obtained test results, a decrease in CO emissions by 54% was observed for co-combustion of jet fuel with hydrogen, for NO_x by 29%, and for PM by 52% compared to engine operation on jet fuel alone. In addition, a decrease in CO_2 emissions by 11% and an increase in exhaust gas temperature by 22% were observed in the case of co-combustion of jet fuel and hydrogen. Moreover, by comparing the course of the exhaust gas temperature change for both tests, it can be seen that for the combustion of jet fuel alone, the exhaust gas temperature increases rapidly and then decreases naturally. In the case of co-combustion of jet fuel with hydrogen, the 'n' exhaust gas temperature increases in the first phase and then fluctuates in a similar temperature range. This action results from the variable fuel dosage (be it jet fuel or hydrogen with jet fuel) forced by the significantly different calorific value of both fuels and the need to adjust the fuel flow by the engine controller correlated to its rotational speed. An in-depth analysis related to the use of alternative

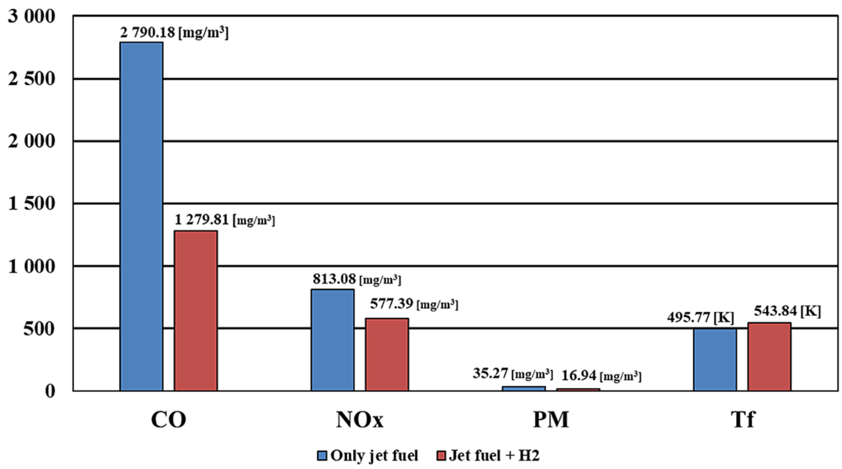

Fig. 6. Summary of results for both tests

fuels, and exploitation of aircraft engines can be found in [Andoga et. al 2021; Cican et. al 2023; Fentaye et. al. 2019; Henzel et al. 2018; Khandare et al. 2023; Sahoo et al. 2020].

CONCLUSIONS

The research conducted for the co-combustion of jet fuel with hydrogen allowed for the synthesis of the following conclusions. It is possible to co-combust conventional fuel with hydrogen in a turbojet engine by slightly modifying the engine. It is necessary to rebuild the fuel supply system for the turbojet engine for co-combustion or hydrogen combustion. Co-combustion of jet fuel with hydrogen in a turbojet engine does not generate an increased environmental burden (greenhouse gases or harmful substances) compared to the conventional combustion process, and is also characterized by a reduction in the amount of undesirable substances emitted. A significant reduction in emissions was observed: CO – 54%, NO_x – 29%, PM – 52%. In addition, a reduction in greenhouse gas (CO_2) emissions was observed by 11%, but an increase in exhaust gas temperature at the engine outlet by 22%.

The observations presented above provide a positive premise for the application of the technology of co-combustion of jet fuel with hydrogen in commercial aviation solutions for turbojet engines. Moreover, the obtained results and observations allow us to assume that in further research on hydrogen combustion in turbojet engines, independent combustion of hydrogen for these machines is possible and from the point of view of environmental burden, it is justified, which allows us to assume that the presented research is highly applicable.

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