The laboratory test stand of the miniature jet engine to research aviation fuels combustion process

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Abstract

This article presents innovative laboratory test rig with a miniature turbojet engine (MiniJETRig – **Mini**ature **J**et **E**ngine **T**est **Rig**), that was built in the Air Force Institute of Technology. The rig has been developed for research and development works aimed at modelling and investigating processes and phenomena occurring in full scale jet engines.
In the article construction of a test rig is described, with a brief discussion on the functionality of each of its main components. Additionally examples of measurement results obtained during the realization of the initial tests have been included, presenting the capabilities of the rig.

1. Introduction

In today's research and development works relating to transport more and more space is devoted to issues related to the process of fuel combustion in various types of engines and the reduction of harmful emissions into the atmosphere. Many international research programs are aimed at developing new, greener solutions for various industries. Also international conferences and symposia are organized, with environmental impact as main topics, to promote and initiate actions aimed at reduction of harmful substances emission during operation of various means of transport.
The problem of CO_2 emissions reduction into the atmosphere, and measurements of harmful components, is especially important and actual for global aviation. Air transport is currently the fastest growing source of carbon dioxide emissions. For this reason, the European aviation sector has been put within the emissions trading system, designed to reduce harmful emissions. Airlines have begun to monitor CO_2 emissions and must prepare for implementation of environmental regulations.
These activities have been initiated by the designation by the International Air Transport Association (IATA), that set three goals for aviation sector [1]:

- A short-term goal to improve fuel consumption efficiency by an average of 1.5% per annum through 2020 on the basis of CO_2 emissions per revenue tone kilometer (RTK);
- a mid-term target to stabilize net CO_2 emissions in aviation from 2020 onward (carbon-neutral growth);
- a long-term goal to reduce aviation net carbon emissions by 50% in 2050, as compared to 2005.

One of major methods of harmful combustion products emissions reduction is implementation to the fossil fuel various components, including biocomponents and biofuels. In recent years in the Air Force Institute of Technology (AFIT) many research works have been carried out [2, 3, 4] dealing with the use of alternative fuels for aviation. Due to the technical feasibility, cost and biofuels availability, the majority of these works ended up at the laboratory level. In authors' opinion, nowadays availability of new, experimental fuels, or components is the major restriction for large-scale tests on real jet engines. The reason for that situation is that most of innovative technologies for aviation biofuels are in experimental scale, and just small volumes of such products are available for tests.
AFIT, being leading research organisation in Poland within fuels for aviation, recognised as extremely important to create a specialized research facilities, that can work with small volumes of fuels. As a result of efforts undertaken in this area, in the Department of Fuels and Lubricants laboratory special test rig has been designed and developed, equipped with miniature turbojet engine. The project was financed by the Ministry of Science and Higher Education.
One of the basic research applications of MiniJETRig is testing of aviation fuels combustion process (fossil and alternative). With the possibility to switch between fuels in one test run, the rig enables simultaneous measurements of specified parameters in the same conditions. This feature is essential to compare fossil and alternative fuels. The test rig allows also to link the quality of tested fuels with their combustion process and environmental impact.

2. Laboratory test rig

MiniJETRig (Fig. 1) is equipped with the following elements:

1) miniature turbojet engine;
2) dedicated measuring equipment, which includes:
   - exhaust analyser;
   - particulate matter analyser;
   - control system with data acquisition based on the measurement cards.

Additionally test rig is fully adjustable to specific user's needs. It is possible to add any other measuring instrumentation.

Figure 1: MiniJETRig

2.1 Miniature turbojet engine

The key component of the test rig is the miniature turbojet engine, working in the range of 33 000 – 120 000 rpm and with the maximum thrust of 140 N. It includes single – stage radial compressor driven by a single – stage axial turbine and an annular combustion chamber with a set of vaporizer tubes. For research purposes miniature jet engines have been prepared in two versions: metal and glass housings. Furthermore two exhaust systems: with straight duct and convergent nozzle are available (Fig. 2).

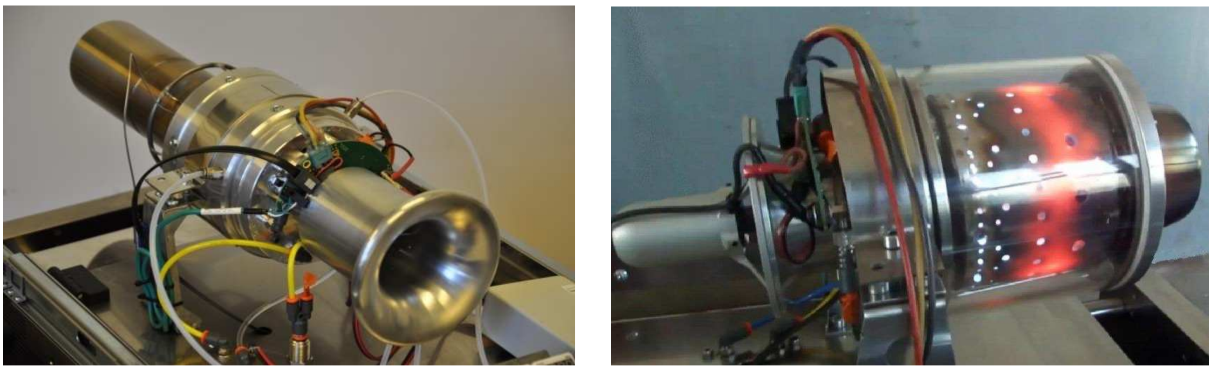


Figure 2: The miniature jet engine in two versions: metal and glass housing

During the tests it is possible to display online and record basic jet engine parameters: thrust, rotational speed, exhaust gas temperature and fuel consumption. It is also possible to measure the pressure and temperature along the engine gas path in selected characteristic points:

1. pressure measurement – inlet, behind compressor;
2. temperature measurement – inlet, behind compressor, behind combustion chamber (around combustion chamber in 6 selected points), behind turbine.

Miniature jet engine is protected by an Electronic Control Unit (ECU). ECU controls: maximum and minimum value of exhaust gas temperature (EGT) and revolutions per minute, pump control voltage as a function of RPM. The derogation in each of the above parameters is treated as an emergency and then jet engine is automatically shut down.

The main advantage of the miniature turbojet engine application is small amount of fuel necessary for tests. Fuel consumption is approximately 0.5 litre per minute at the maximum thrust.Triple valve used in the test rig allows for switching between different fuels during the same test run. Those factors allow for cost reduction and verification (in conditions similar to those specific for full scale jet engines) of technologies being at the early or experimental stage, when only small amounts of fuel is available.

2.2 Portable exhaust analyser

MiniJETRig is also equipped with portable exhaust analyser (Fig. 3), which is used to take samples of exhaust gases from the engine and deliver it through a heated hose to the analyzing unit. In block of analyser electrochemical sensors are assembled for measurement of O_2, CO, NO, NO_2, SO_2 and two NDIR sensors for measuring infrared CO_2 and C_xH_y. The individual components of exhaust gas are measured in a defined range and resolution of 1or 0.1 ppm.

Exhaust gas concentrations may be presented on the display of the analyser as: volumetric concentration (% or ppm), mass concentration (mg/m^3) and mass concentration in relation to the oxygen (mg/m^3).

Exhaust analyser also allows to measure exhaust gas temperature. All measured or calculated values may be displayed on computer, saved in reports on the MMC / SD card or in the internal memory. In addition, the analyser has a built-in integral box of analog outputs that allow to send information about the analysed concentration of exhaust gases to external measurement cards.

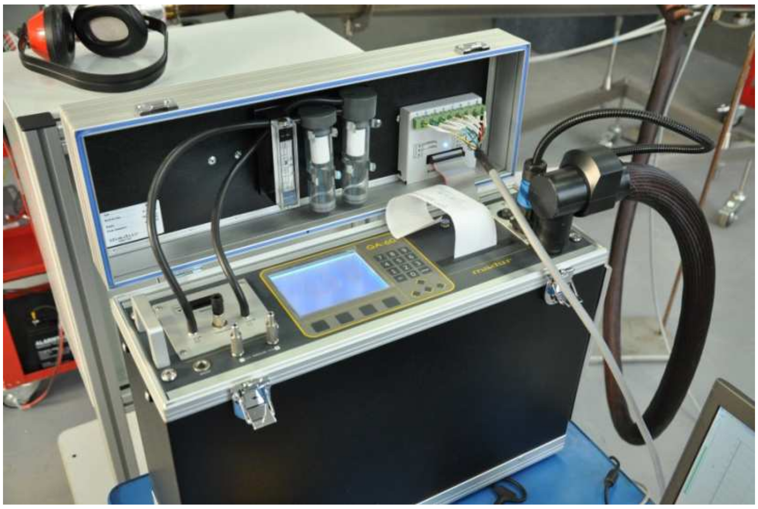
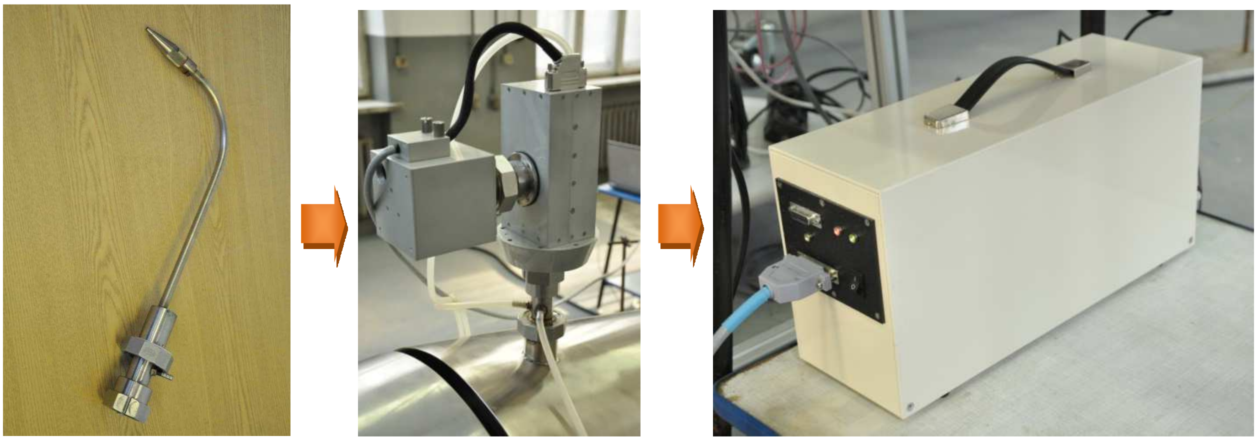


Figure 3: The exhaust analyser

2.3 Particulate matter analyser

Another main element of the test rig is particulate matter analyser (Fig. 4). This analyser allows to measure online of the size and amount of particulate matter emitted by the engine. It consists of measurement head and electronic unit controlled by a computer. The analyser uses the method of transmitted light measurement, where the flux of infrared radiation is scattered by particles passing through the measurement zone. Each particle represents electrical signal proportional to the diameter of the spherical particles. If the particle is not spherical, amplitude pulse depends on the orientation of the particles in the measurement zone. The analyser allows for:

- fast and multiple measurements of particulate matters in the range of from 0.5 to 300µm;
- particulates size distribution, divided into 256 equal measurement class, or 11 any user-defined classes;
- gravimetric measurement.



a) probe b) measurement head c) electronic unit

Figure 4: The analyser of particulate matter

Probes of the two analysers are mounted in a specially designed collector (Fig. 5), located directly behind the engine. Measuring points for the probes of the analysers have been chosen to allow simultaneous measure of both gaseous components and particulate matters.

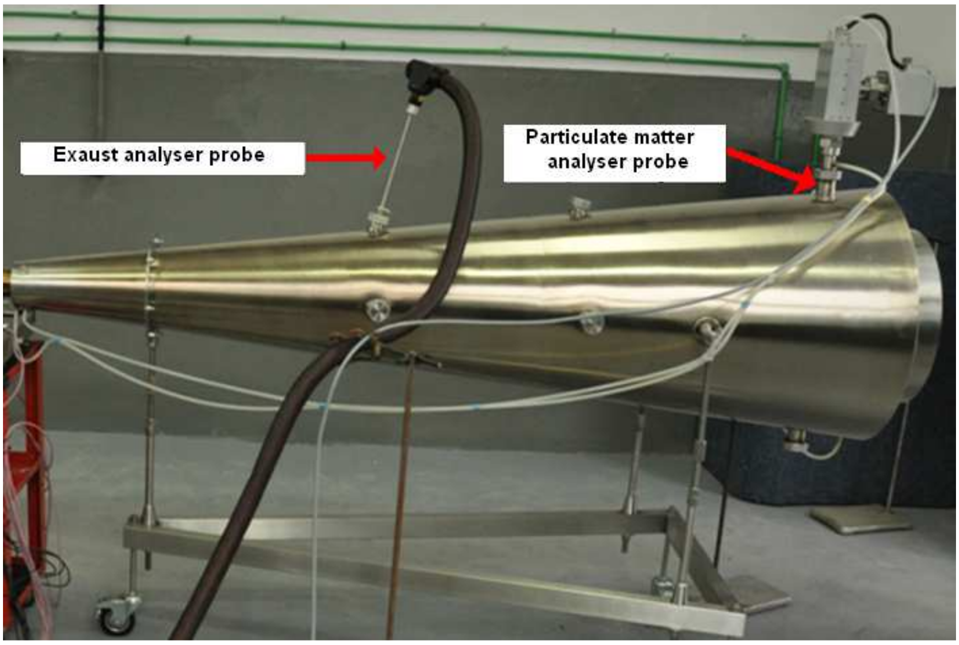


Figure 5: Measuring collector

2.4 Control system with data acquisition

Special software has been developed for MiniJETRig, allowing for data collection from active measurement channels during the test. Data recording system is based on block of measurement cards registering following signals: current, voltage, thermocouple and digital. The block is connected with the computer workstation where the application is installed (Fig. 6). The software has been developed in LabView – graphical programming language, and – as well as data registration – it allows to control the operation of jet engine and e.g. define the profile of the test run.

There are three ways to control the operation of mini jet engine:

- manually: user controls the engine by built-in driver;
- semi-automatically: user controls the engine and measurement process by application in LabView;
- automatically: profile of the test run is selected from the library and is controlled by application.

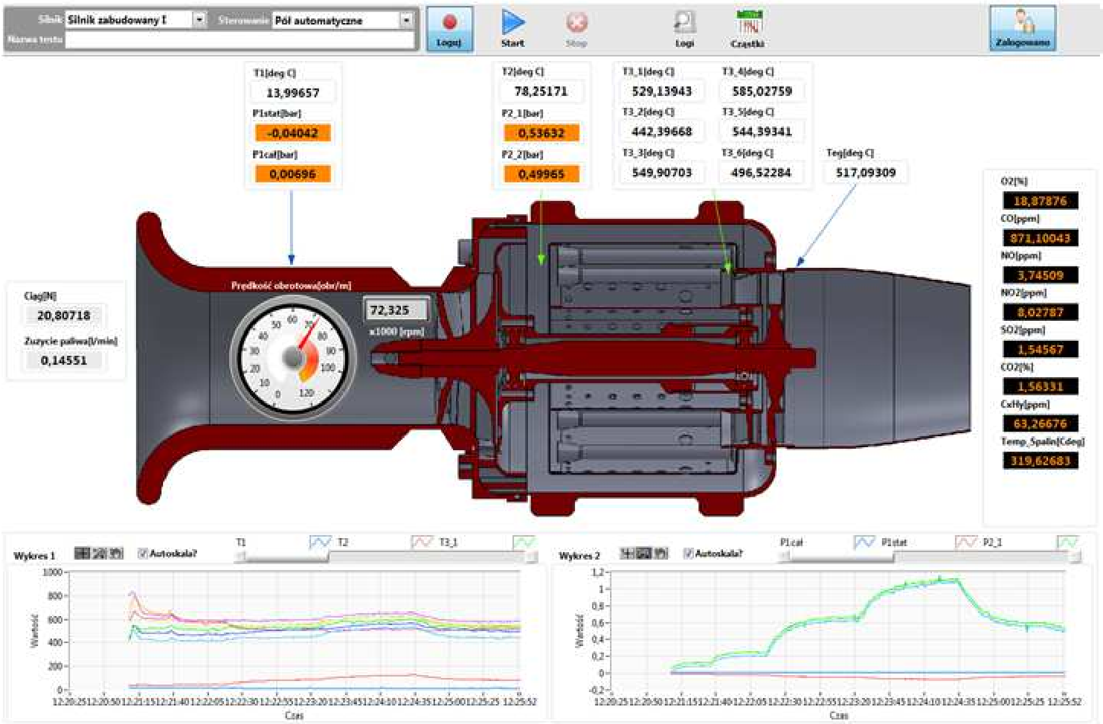


Figure 6: LabView software

3. Measurement capabilities

All of the test were carried out in the Department of Fuels and Lubricants at the Air Force Institute of Technology. Measurement capabilities are shown below, on Fig. 8 – 13. MiniJETRig was run on conventional fuel used in the aviation industry Jet A–1 with 4% AeroShell Turbine Oil 560. This volume of oil is recommended by the engine manufacturer for bearing lubrication.
Selected physical and chemical properties of fuel were evaluated and are shown in Table 1.

Table 1: Selected properties of testing fuel

	Unit	**ASTM method**	**Limit**	**Jet A-1**	**Jet A-1 with 4% Oil**
Density at +15°C	kg/m^3	D 4052	775.0 – 840.0	794.7	802.8
Viscosity at -20°C	mm^2/s	D 445	max 8.000	3.330	3.799
Heat of combustion	MJ/kg	D 3338	min 42.80	43.285	43.271
Smoke point	mm	D 1322	min 19.0	24.0	25.0
Naphthalenes, (V/V)	%	D 1840	max 3.00	0.36	0.49
Sulfur, (m/m)	%	D 5453	max 0.30	0.119	0.115

The research was carried out with different rotational speed according the profile of the engine test (Fig. 7). Tests were conducted with the miniature turbojet engine, which was equipped of exhaust system with: straight duct and convergent nozzle. Tests were repeated for each listed below type of exhaust system at least three times.

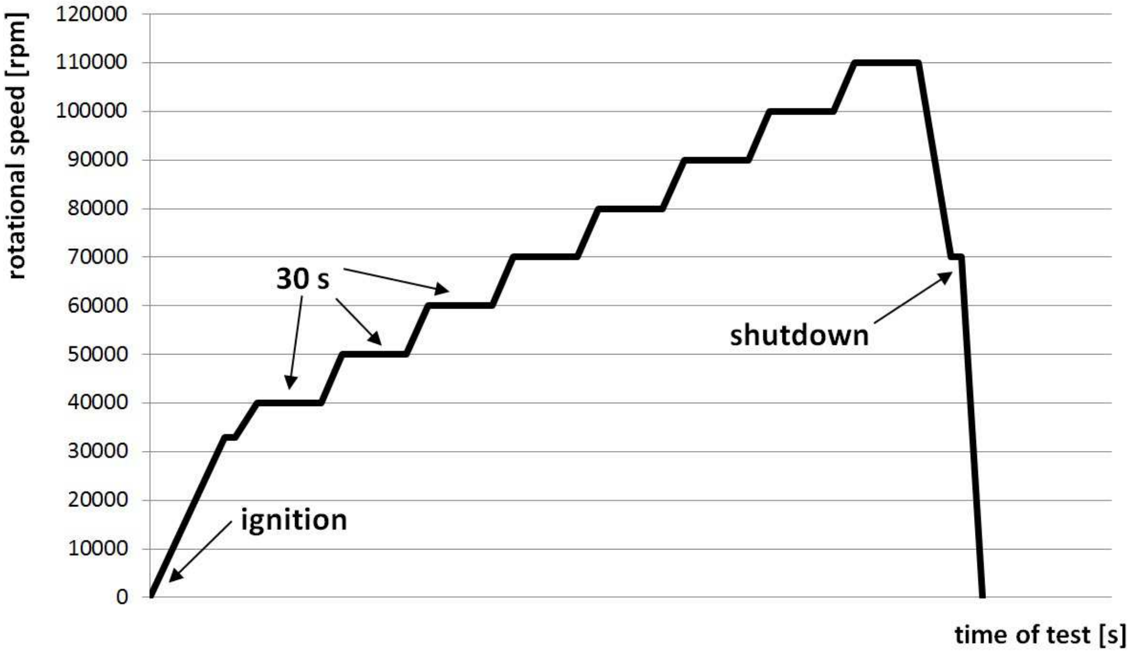


Figure 7: Profile of the engine test

Upon ignition, the engine was given maximum of 60 seconds to reach a steady state whereby the engine speed remained constant at an approximately 33 000 rpm (idle speed). Rotational speed was raised from 40 000 to 110 000 rpm for exhaust system with straight duct or to 100 000 rpm for exhaust system with convergent nozzle with the interval at 10 000 rpm. Steady state (in the range ± 2 000 rpm) on each interval lasted 30 seconds. At the end of a profile of the test run, rotational speed was decreased to 70 000 rpm and engine was shut down. Sampling rate was five times per second.
Fig. 8 - 10 present miniature jet engine main parameters trends as a function of engine speed.

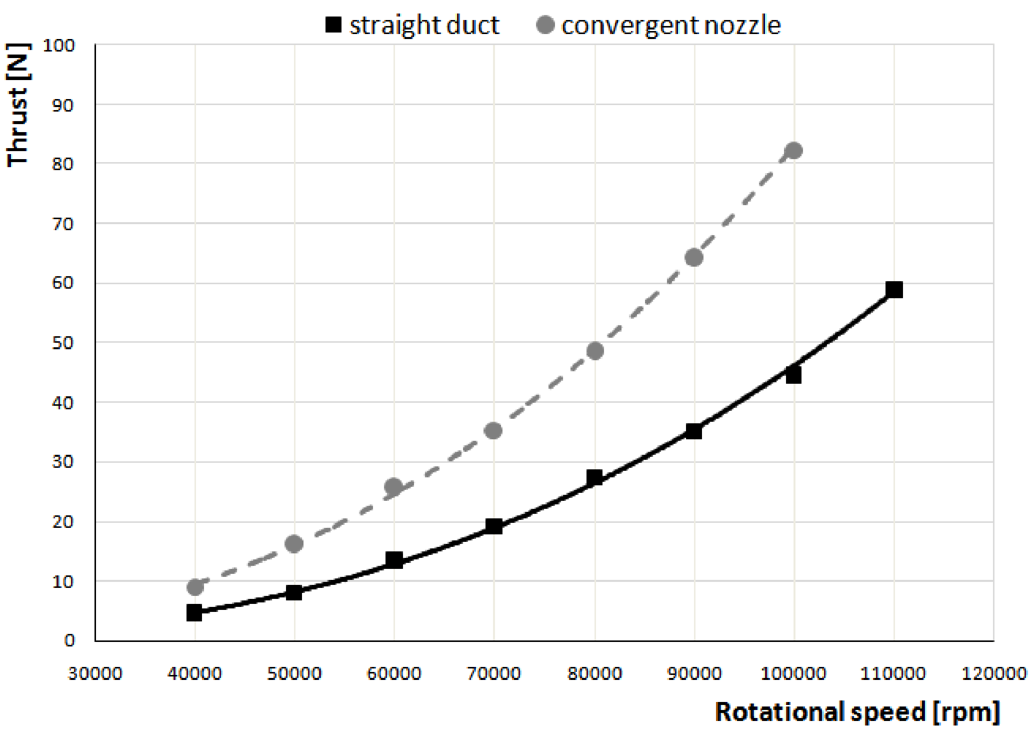


Figure 8: Thrust as a function of engine speed

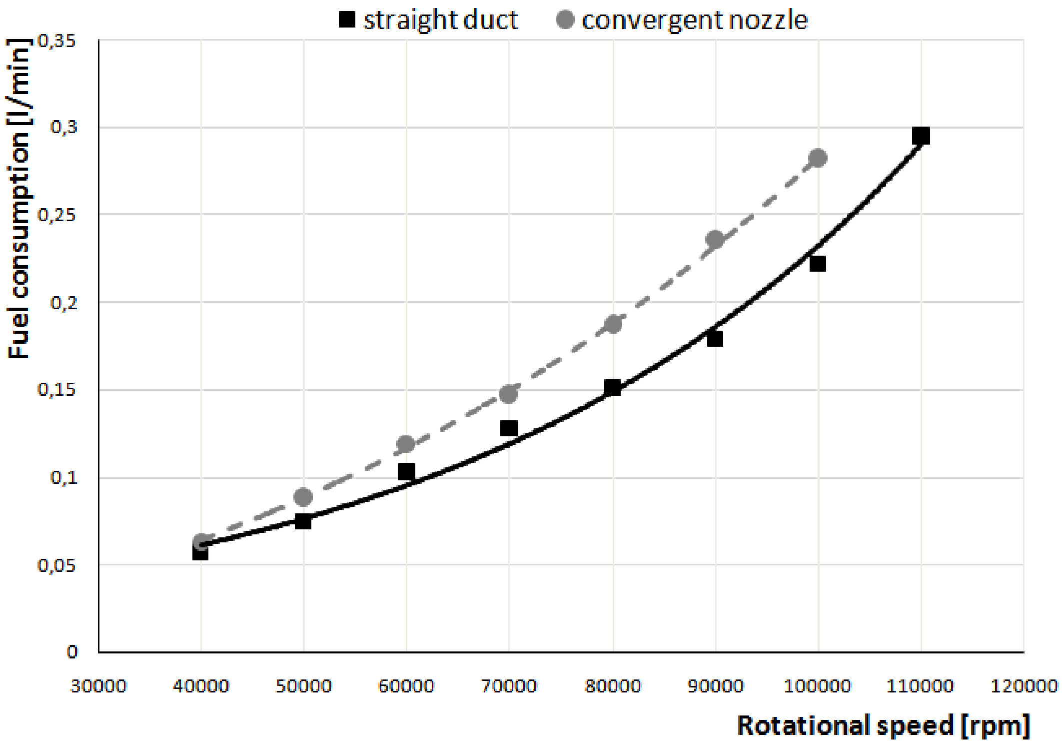


Figure 9: Fuel consumption as a function of engine speed

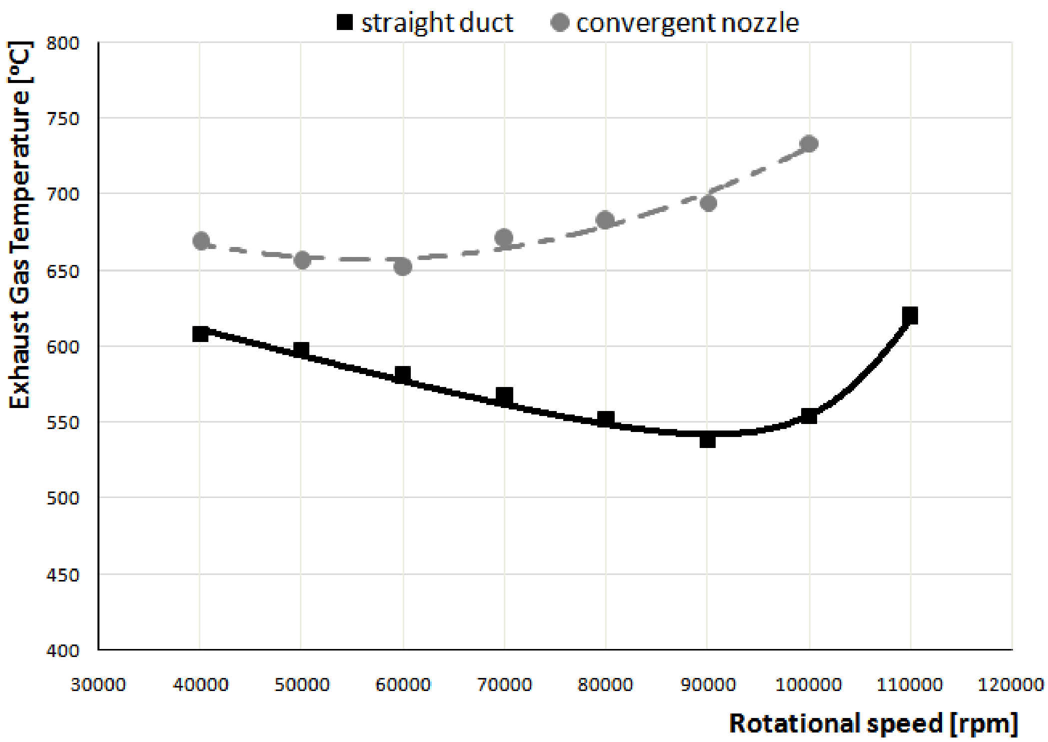


Figure 10: Exhaust Gas Temperature as a function of engine speed

Trends of engine measured parameters are similar to the characteristics obtained on a full scale jet engines [5, 6]. Thrust produced from the engine is proportional to the amount of fuel consumed. Use of convergent nozzle as compared with straight duct gives expected results - parameters: thrust, fuel consumption and exhaust gas temperature are reached higher value.

Selected exhaust gas components concentrations (CO, CO_2 and NO_x) are shown on Fig. 11 – 13. The exhaust gas sample probe was positioned in the center of the exhaust stream:

- at the end of straight duct;
- 10 cm from the convergent nozzle.

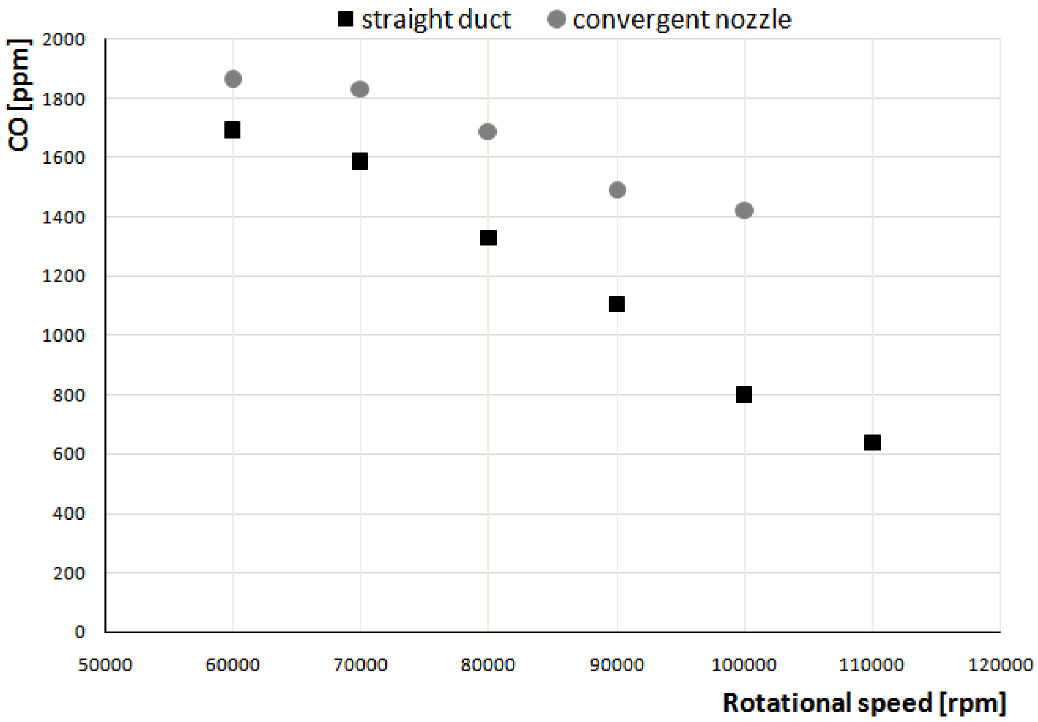


Figure 11: CO emission as a function of engine speed

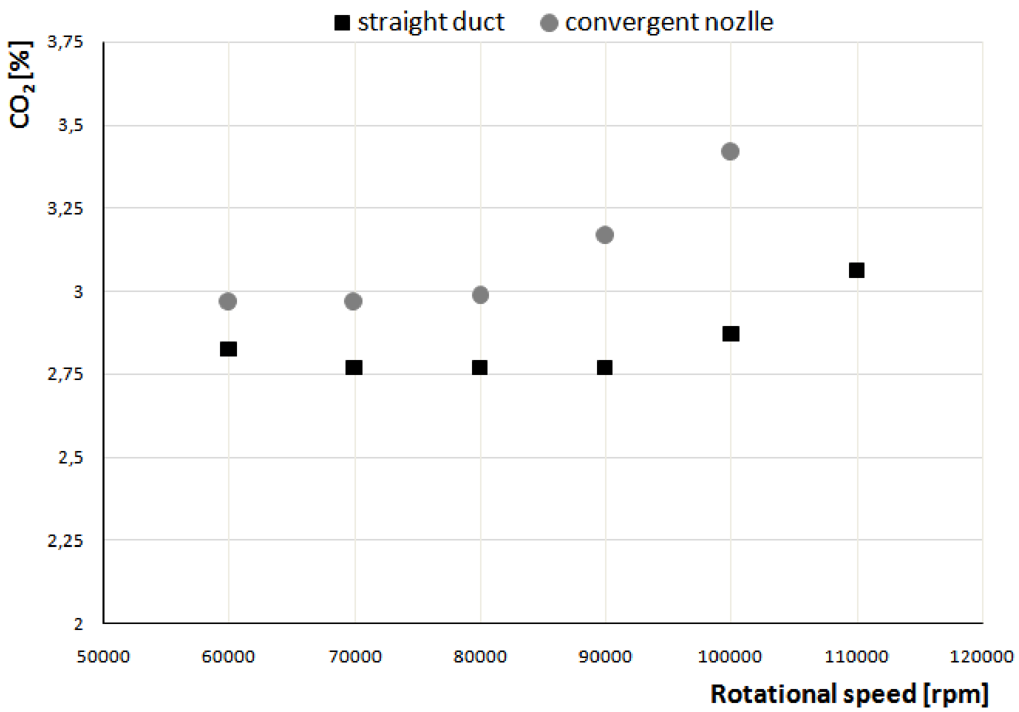


Figure 12: CO_2 emission as a function of engine speed

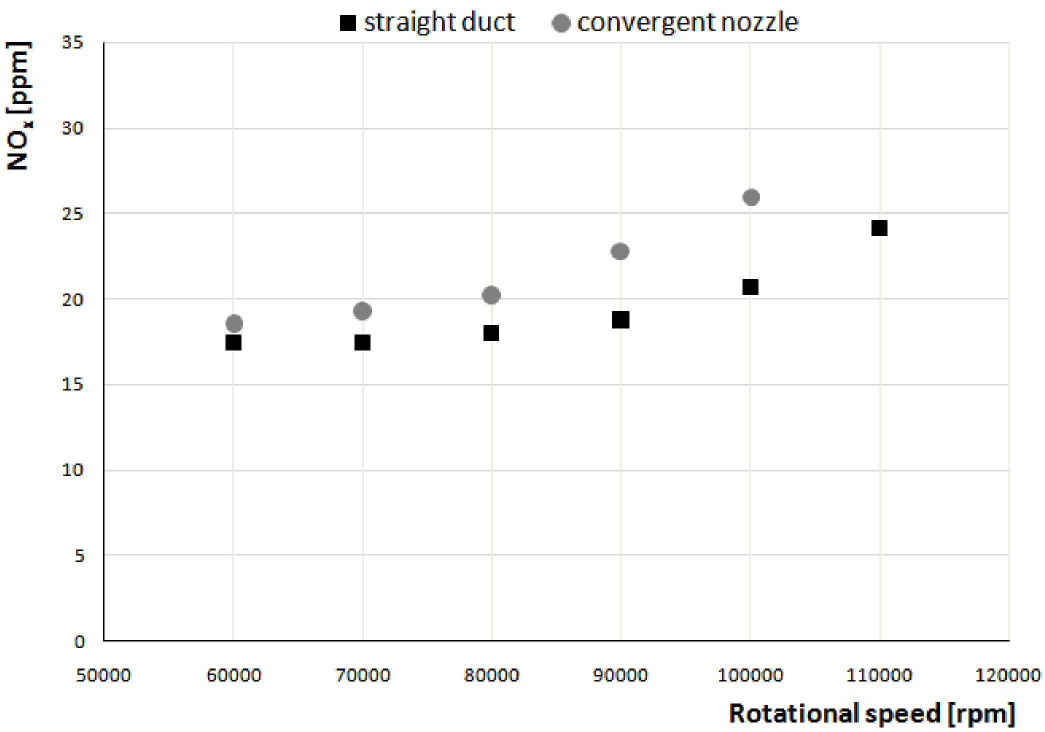


Figure 13: NO_x emission as a function of engine speed

General trend for CO emissions is that they are highest at low power conditions, and decrease with increasing power output. The CO data (Fig. 11) follow this trend in presented range of rotational speed. Fig. 13 shows that NO_x emission increased as engine speed increased. This follows the trend found in the literature [7].
Fig. 14 – 16 show comparative research results of emission, between MiniJETRig and turbofan engine CFM56 [8], which is used for commercial aircraft propulsion. Trends of emission selected exhaust components: CO, CO_2, NO_x on a laboratory test rig is similar to the characteristics obtained on a full scale jet engine. It is seen, that ranges of reached values for CO_2 emission are similar.

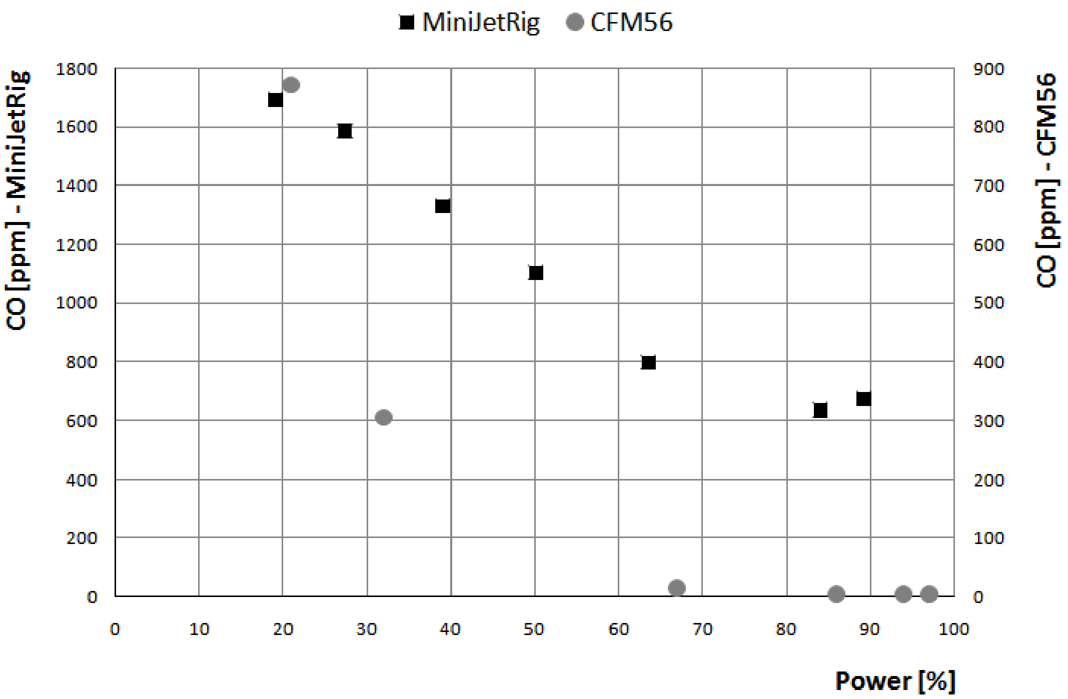


Figure 14: CO emission for MiniJETRig and CFM56 [8]

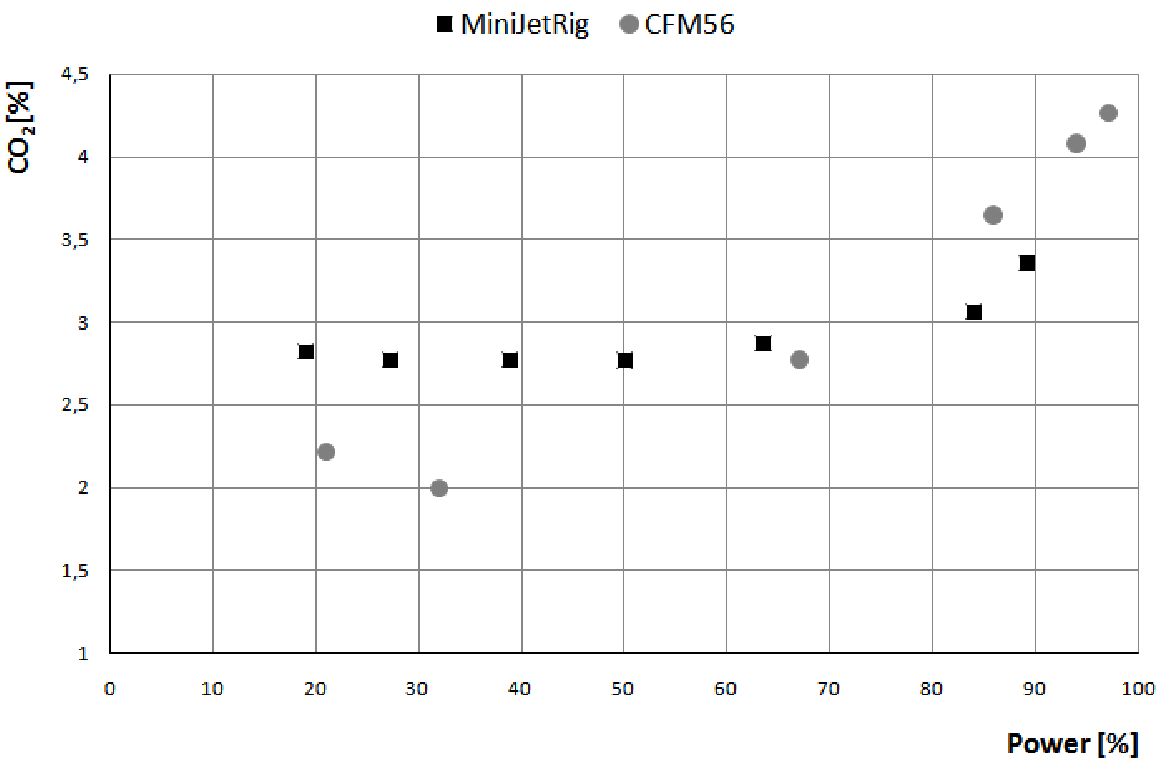


Figure 15: CO_2 emission for MiniJETRig and CFM56 [8]

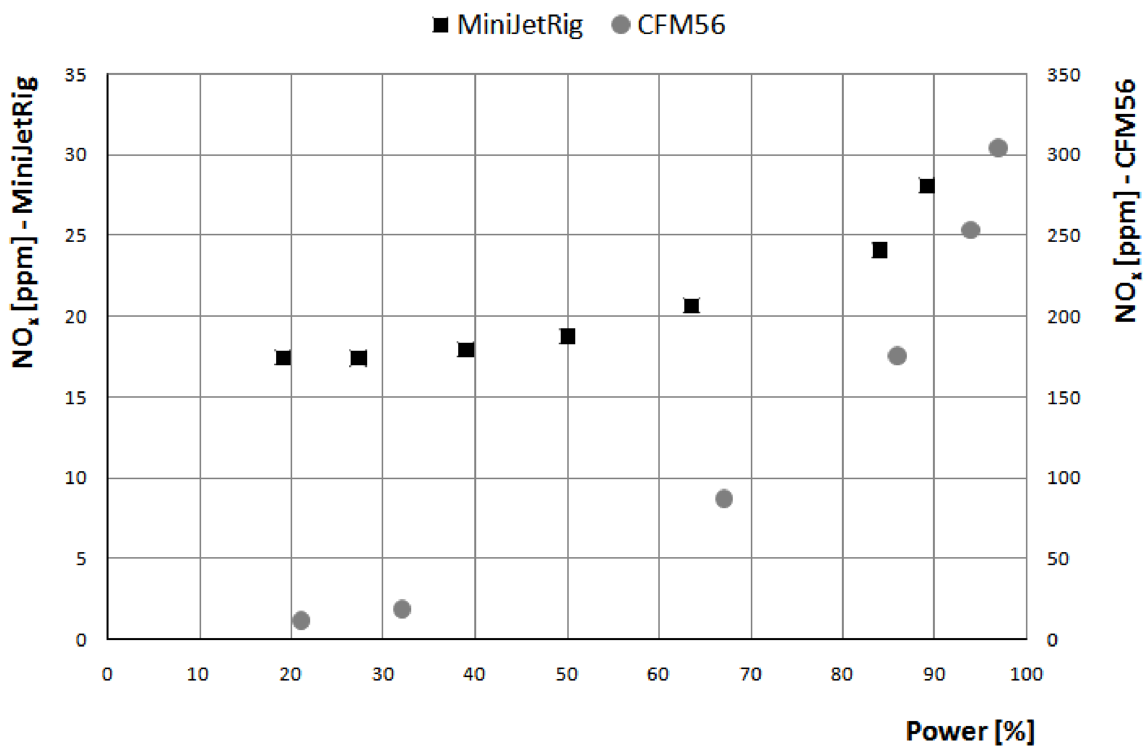


Figure 16: NO_x emission for MiniJETRig and CFM56 [8]

4. Conclusion

Review of the working papers did not reveal such equipped laboratory test rig based on turbojet engine. The most important advantage of presented test rig is fact, that it is a link between laboratory tests of fuels/biofuels (where relatively small quantity of fuels are necessary) and real jet engine tests (where large volume of tested fuel must be delivered). Thus, especially in case of biofuels and biocomponents from experimental production plants or experimental processes, presented equipment may be extremely interesting.
The test rig consists of modules. Thus additional equipment can be designed and mounted, which allows to easily adapt it to research and verification of different technologies for aviation, i.e.:

- alternative fuels and biocomponents;
- innovative materials and coatings;
- advanced construction solutions;
- diagnostic systems and sensors.

Trends of measured parameters on a laboratory test rig are similar to the characteristics obtained on a full scale jet engines. The above confirms, that test run of miniature turbojet engine reflects the processes and phenomena in a real jet engines.
Because biofuels for aviation are an attractive alternate energy source, Department of Fuels and Lubricants currently carries out tests of different biofuels/biocomponents with presented test rig. The results will be presented in forthcoming papers.

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