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EMISSION OF VOLATILE ORGANIC COMPOUNDS DURING COMBUSTION PROCESS IN A MINIATURE TURBOJET ENGINE

Aviation is one of the fastest growing modes of transport. Due to the growing number of flights, the consumption of aviation fuels (mainly jet fuels) keeps increasing. The combustion process in the aircraft engine results in harmful exhaust emissions having an adverse impact on the environment. Alternative fuels based on bio-components and biofuels are a way of reducing the harmful exhaust emissions. Analyses and measurements performed on real aircraft engines are complex and expensive. For this reason, increasingly more research and development projects have been carried out on small-scale engines. This paper presents investigations into volatile organic compound emissions from jet fuel combustion in a miniature turbojet engine. Based on chromatography tests, the compositions of exhaust gases produced by the jet engine fed with various fuels were determined, which in turn led to evaluation of its toxicity and harmfulness. Conventional fossil-based fuel Jet A-1 and a blend of Jet A-1 with 25 vol. % of biobutanol were tested at the same fuel flow rates. The engine working parameters such as, e.g., thrust or emission index have been determined with respect to the type of fuel. The test results have been compared and analyzed.

1. INTRODUCTION

The development of industry and transport depends on the continuous supply of energy. Transport is one of the sectors of the economy which consume the most energy and it is a major source of greenhouse gas emissions [1]. Aviation is one of the fastest growing modes of transport. In recent years, the number of aircrafts and the intensity of aviation operations have greatly increased. As a result, more and more jet fuel has been

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burnt and the amount of harmful exhaust emissions, including toxic gases, particulate matters, organic compounds, etc., increases. The pollutants generated by air transport have an adverse effect on the climate [2], air quality [3, 4] and human health [5, 6].

As jet fuel is combusted, variously toxic exhaust gases, particularly highly toxic volatile organic compounds (VOCs) are emitted. Despite the fact that VOCs, especially aromatic hydrocarbons, are highly toxic and hazardous to humans, research aimed at determining their concentration is rarely undertaken. The most hazardous and toxic VOCs are benzene, toluene and xylene (BTX). Benzene is strongly toxic, acting on the central nervous system, causing its damage and bone marrow corruption. Toluene and xylene are moderately toxic compounds having no significant effect unless in high concentration. However, long-term exposure to them can lead to a coma.

In recent years, numerous investigations have been undertaken to improve our understanding of the aircraft emissions of particulate and gas-phase organic species [7–10]. Expensive investigations reported in the above papers were carried out on full-scale turbine engines. Specialized test rigs equipped with miniature jet engines faithfully replicate the processes and phenomena occurring in real jet engines. Small-scale turbojets are particularly useful in the field of alternative fuels [11, 12]. The main advantage of the use of a miniature turbojet engine is that little fuel is needed for tests, whereby the cost of verifying technologies being at an early stage in their development can be greatly reduced.

The paper presents investigations into VOC emissions from jet fuel combustion in a miniature turbojet engine. The tests were conducted using fuel Jet A-1 and a blend of Jet A-1 with 25 vol. % of biobutanol. The engine operating parameters and the VOC emissions are compared for the two fuels.

2. EXPERIMENTAL PROCEDURES

Tests were conducted on the GTM-140 miniature turbojet engine (Fig. 1). The engine is a key component of the MiniJETRig (miniature jet engine test rig) – a laboratory test rig for the research of the aviation fuel combustion process [13] created in the Air Force Institute of Technology.

The most important engine specifications are summarized in Table 1. Engine starting is effected automatically on liquid fuel (JET A-1) by an electric starter. After starting, when the engine has reached its idle speed, it is possible to control the engine by adjusting the fuel flow in the pump (fuel consumption). The fuel throttle valve, and so the engine speed, is controlled by the engine control unit (ECU). The engine is equipped with a strain gauge (a load cell) for measuring thrust, an optical sensor for measuring rotational speed and a type K thermocouple for measuring exhaust gas temperature. During the tests, the above engine parameters are displayed online on the control panel.

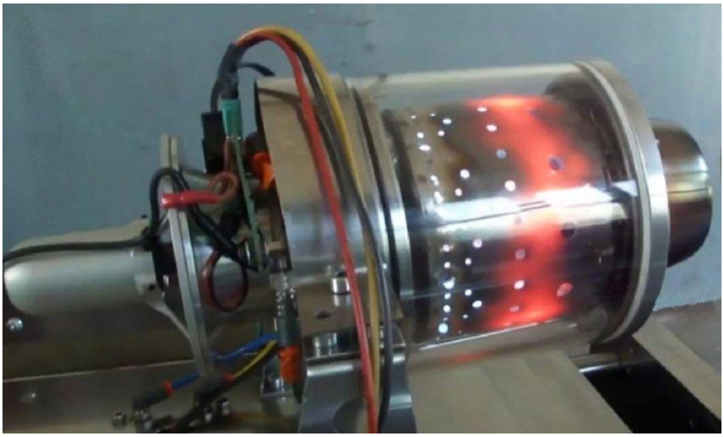

Fig. 1. Miniature turbojet engine GTM-140

Table 1

Main GTM-140 specifications

Engine type	Turbojet – single spool
Compressor	single-stage radial compressor
Combustion chamber	annular combustion chamber
Turbine	single-stage axial flow turbine
Pressure ratio	2.8:1
Minimum rpm	33 000
Maximum rpm	120 000
Thrust at maximum rpm	140 N
Fuel consumption at max. rpm	420 g/min
Mass flow at maximum rpm	350 g/s
Maximum exhaust gas temperature	750 °C

The miniature jet engine is run on the conventional fuel used in the aviation industry, i.e., Jet A-1 with added 3–5% of AeroShell Turbine Oil 560. This volume of oil is recommended by the engine manufacturer for bearing lubrication, but the oil addition adulterates the results of combustion process assessment. The test rig was modified by dividing the fuel supply system into two separate systems: the primary system supplying fuel to the combustion chamber and the secondary system supplying fuel pre-mixed with oil to the bearings. Thanks to this solution, pure jet fuel is supplied to the combustion chamber.

The identification of VOCs is usually performed in three steps: collection of samples, desorption and chemical analysis. In order to identify VOCs and their concentrations, a special probe was placed directly in the exhaust gases, samples of the latter were aspirated and subjected to chromatographic tests.

The aim of the investigations was to identify VOCs and compare their concentrations in the exhaust gases from the combustion of respectively fuel Jet A-1 (the Merox process) and the blend of Jet A-1 with 25 vol. % of biobutanol (*n*-butanol isomer, abbreviated to BIO throughout the paper was used). *n*-Butanol is produced through the fermentation of C5 and C6 sugars from renewable feedstocks, whereby highly pure renewable butanol is obtained. The following test program was adopted. After starting, when engine has reached its idle speed, the rotational speed was increased by increasing the fuel pump voltage to the value specified in Table 2. The same fuel flow rate was assumed for the two fuels. In each engine, the test was running for 20 min. The experiment was repeated twice for each of the fuels. The test rig is schematically shown in Fig. 2.

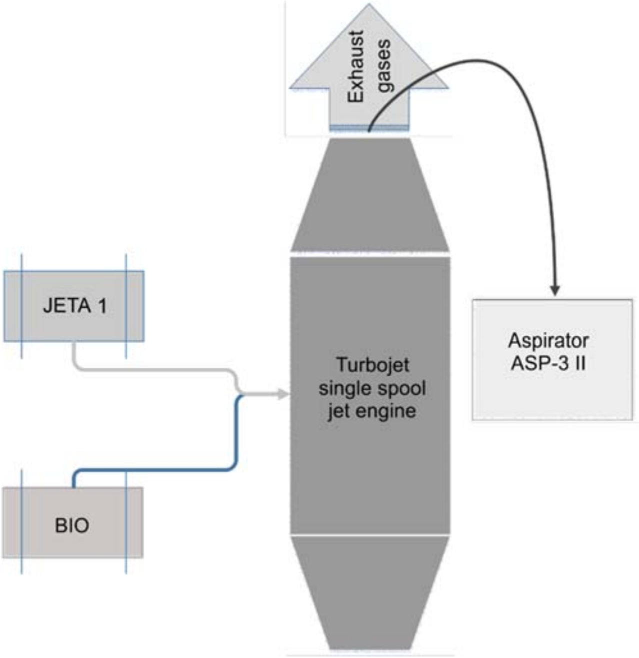

Fig. 2. Schematic of the test rig

The samples collected using the above test rig were subsequently subjected to chemical analysis. Volatile organic compounds in the samples were determined by gas chromatography according to the Emission Research Laboratory Test Procedure No. 1/2010, using a Varian 450-GC gas chromatograph with a flame ionization detector (FID), and a column Varian VF-WAXms 30 m×0.25 mm ID, DF 0.25 um. The analysis was performed at the set temperatures of the column – 373 K, the dispenser – 523 K and the detectors – 423 K. An ASP-3 II YEARS aspirator with the flow rate adjusted to 30 dm^3/h and the amount of collected gas of 10 dm^3 was used for collecting samples. The gas was adsorbed on active carbon Anasorb® SKC CSC. The activated carbon was put into a glass tube in a volume of 5 cm^3 and submerged to 2 cm^3 of carbon disulphide. The glass tube was sealed with a stopper. Extraction proceeded for 20 min. Every few minutes the contents of the bottle was shaken in order to ensure adequate mixing of the material. Then 5 μl of the solution was drawn from above the carbon layer. The collected sample was injected into the chromatograph. The concentration of the compounds designated as “residuals” was converted to a concentration corresponding to *n*-pentatonic acid. In other words, the residuals were present in the gas mixtures, but were not identified by the chromatograph. The total relative error of the method was estimated at 20% (according to PN-EN ISO16017-1:2006).

Additionally, the formaldehyde concentration was determined. As recommended by the spectrophotometric method, formaldehyde was collected from water scrubbers. A scrubber containing 100 cm^3 of distilled water was placed in front of each of the samplers with activated carbon. Analyses were performed using the spectrophotometric cuvette test.

The measured values of the exhaust gases were converted into emission indices (*EI*), in grams of compound per kilogram of fuel (g X/kg fuel). *EI* allow one to refer to each analysed component of exhaust gases relative to CO_2 emission, emitted as a result of the combustion of fuels in the gas turbine engine. The *EI* for each exhaust component (EI_X) can be calculated from [8]:

$$EI_{\mathrm{X}} = \frac{[\mathrm{X}]}{[\mathrm{CO_2}]} \times \frac{M_{\mathrm{X}}}{M_{\mathrm{CO_2}}} \times 3160$$

where [X], $[CO_2]$ are the concentration of the component X, and of CO_2, both in the same units, measured at the exhaust. M_X and M_{CO_2} are the molar masses (g·mol^{-1}) of X and CO_2, respectively, 3160 is a constant value of the emission index based on complete combustion in g CO_2·kg^{-1} fuel.

3. RESULTS AND DISCUSSION

3.1. ENGINE PARAMETERS

The experimentally determined engine parameters for the two fuels are shown in Table 2. Averaged test results for each of the fuels are shown in Table 3.

The rotational speed and thrust values measured at the same fuel flow rate differed between the two fuels due to a lower specific energy of butanol with respect to that of the Jet A-1 fuel. This means that if the miniature jet engine is powered by Jet A-1 and BIO at the same fuel flow rate, engine thrust will reach lower values for the BIO than for Jet A-1. Thus the specific fuel consumption in the case of BIO will be higher than in the case of Jet A-1.

Table 2

Averaged tests results for Jet A-1 and BIO

Engine parameter	JetA-1_1	BIO_1
Fuel pump voltage, V	1.71	1.70
Rotational speed, rpm	78 360.0	75 600.0
Thrust, N	73.5	67.7
Exhaust gas temperature, °C	501.5	503.0

Table 3

Averaged test results for Jet A-1and BIO

Fuel	Fuel pump voltage [V]	Rotational speed [rpm]	Thrust [N]	Exhaust gas temperature [°C]
Jet A-1	1.71	78 360	73.5	502
BIO	1.70	75 600	67.7	503

3.2. VOLATILE ORGANIC COMPOUNDS

The identified VOC concentrations differed between the two investigated fuels. Concentrations of all the VOCs identified in the exhaust gases are presented in Table 4.

Table 4

Volatile organic compounds identified in exhaust gases emitted by engine powered by Jet A-1 and BIO [mg/m^3]

Hydrocarbon	Jet A-1			BIO		
	Test 1	Test 2	Average	1 rep.	2 rep.	Average
n-Pentane	32.4	33.7	33.0	16.0	18.4	17.2
2-Propanol	21.4	41.3	31.3	19.4	27.2	23.3
Benzene	2.2	8.3	5.2	2.1	2.8	2.4
2-Butanol	0.5	6.1	3.3	0.5	1.1	0.8
Toluene	0.4	1.4	0.9	0.5	0.6	0.5
p-Cymene	0.2	0.2	0.2	0.2	0.2	0.2
Ethylbenzene	not detected	0.4	0.2	not detected		
m-Xylene		0.7	0.4			
Cumene		0.1	0.1			
o-Xylene		0.3	0.1			

What is clearly visible is the smaller number of VOCs detected in Jet A-1 mixed with biobutanol. Furthermore, the VOC concentration in the neat Jet A-1 fuel is generally higher (exceeding 30 mg/m^3 in the case of the predominant *n*-pentane) than in the BIO fuel with predominating 2-propanol. But the most important finding is that the concentrations of benzene, toluene and xylene – aromatic hydrocarbons representing high VOC emissivity and being most hazardous to health – in the BIO fuel are much lower. Therefore one can say that the blend of Jet A-1 with biobutanol is less hazardous to human health. Average concentrations of volatile organic compound identified in the two tested fuels are shown in Fig. 3. As can be seen, VOC concentrations are significantly higher in the case of Jet A-1. The concentrations of all the detected organic compounds are approximately twice lower in the case of BIO.

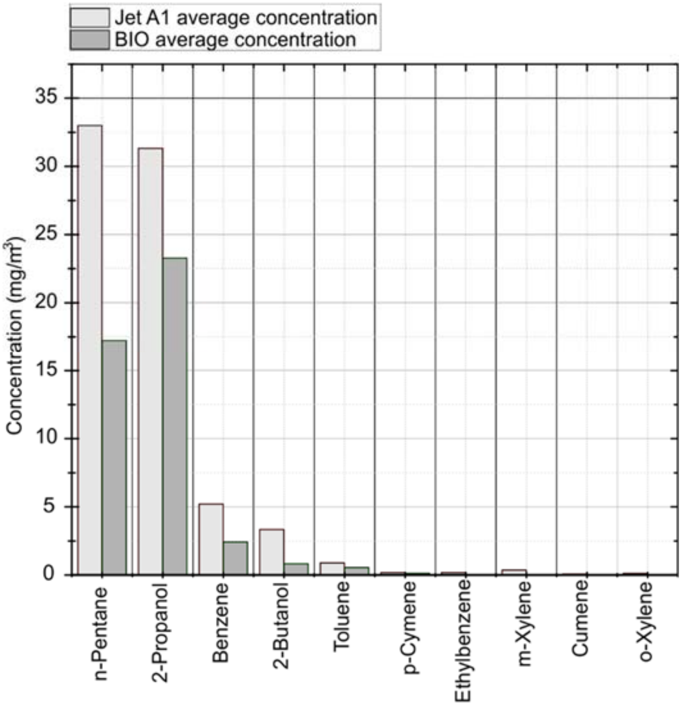

Fig. 3. Average VOC concentrations for Jet A1 and BIO

The two fuels significantly differed in the number of VOCs. BIO is free from several of the organic compounds (including xylene and ethylbenzene) detected in Jet A-1. Most importantly, the aromatic hydrocarbons which are most hazardous to human health were found to be present in much lower concentrations in BIO. Except for xylene, which was not detected in BIO, the percentage difference between the two fuels as regards benzene and toluene amounted to 54% and 44%, respectively, Hence it can be stated that BIO represents lower toxicity and so is less hazardous to humans.

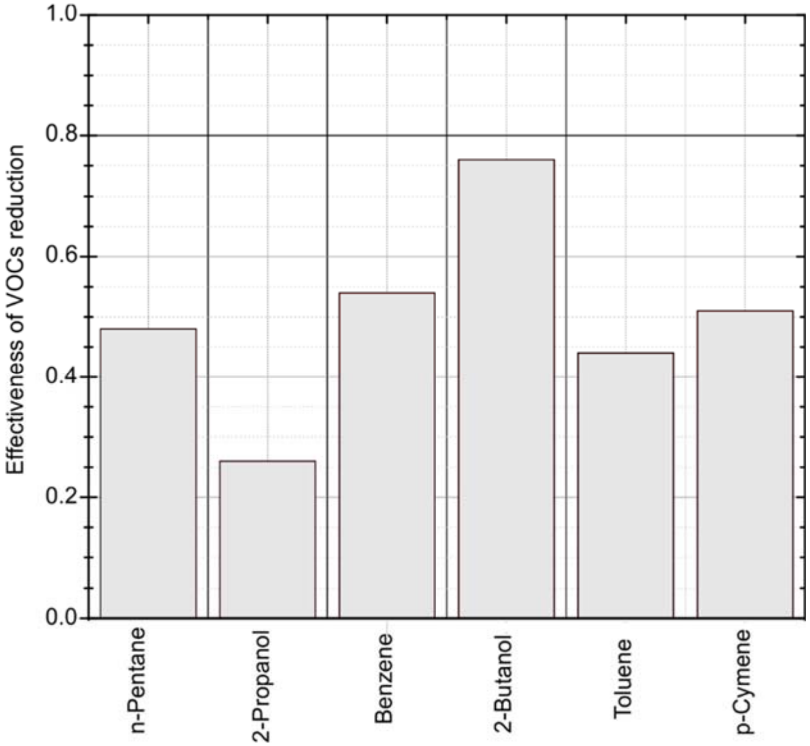

Fig. 4. Reduction in VOCs in exhaust gases from BIO combustion with respect to the Jet A1

Considering the Jet A1 as a reference the percentage reduction of VOC in the case of BIO is shown in Fig. 4.

The figure contains only the compounds detected in the case of both tested fuels. The compounds present in the exhaust gases from the combustion of only one of the tested fuels are not included. Additionally, the formaldehyde concentration was determined. The results of the analyses are presented in Table 5.

Table 5

Formaldehyde concentration in tested fuels

Fuel	Formaldehyde concentration [mg/m^3]
Jet A-1	7.52
BIO	15.09

The formaldehyde concentration should be added to the total VOC concentration (Fig. 5). Considering the total concentration of VOCs, one can say that BIO is less toxic. Moreover, the results indicate that the combustion reaction was stable.

The results of the measurements of the VOC concentrations were compared with the results of tests carried out on different full-size turbine engines [8, 14]. In both cases, the same compounds: *n*-pentane, benzene, toluene, ethylbenzene, *m*-xylene, *o*-xylene and formaldehyde were found to be present in the exhaust gases. It is noteworthy that the concentrations of the individual components depend on the operating modes of turbine engine as well as on its design and type. The emission index for benzene and toluene decreases with increasing engine power and reaches the highest value at the low (idle) operating mode.

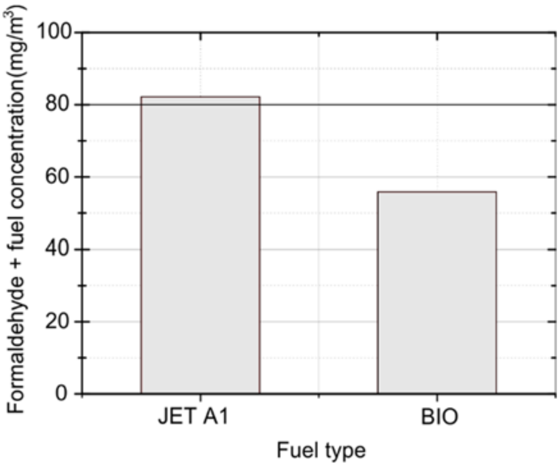

Fig. 5. Average total volatile organic compounds and formaldehyde in tested fuels

Table 6

Data for benzene and toluene emitted
by miniature jet engine GTM 140 fueled by Jet A-1

Component	Concentration		Emission index EI_X [g/kg fuel]
	[mg/m^3]	[ppmv]	
Benzene	5.2	1.6	0.333
Toluene	0.9	0.2	0.058

The concentrations of benzene and toluene determined for fuel Jet A-1 at ca. 50% of engine thrust are given in Table 6 in mg/m^3 and ppmv. The reference temperature was 15 °C. Then the emission index for each of the VOCs was calculated based on [8]. Benzene and toluene emissions for different turbine engines are given in Table 7. Due to the fact that presented data refer to different engine operating modes: for a miniature engine ca. 50% of engine thrust (cruise), for full scale turbine engines 7% and 30% of engine thrust (taxi and approach, respectively), direct comparison between different engines is difficult.

Table 7

Benzene and toluene emission data for different turbine engines

Engine	Type	Power [%]	Emission index EI_X [g/kg fuel]	
			Benzene	Toluene
PW 4158 [8]	turbofan	7	0.147	0.101
RB 211 [8]		7	0.006	~0.008
AE 3007 [8]		30	~0.003	~0.004
T63 Allison [14]	turboshaft	idle	~0.83	~0.45
GTM 140	miniature turbojet	~50	0.333	0.058

4. CONCLUSION

The search for alternative fuels for aviation is extremely important mainly due to environmental issues. Harmful emissions can be reduced through the use of various biocomponents and biofuels. Having this in mind, two types of fuel: conventional kerosene Jet A-1 and a blend of Jet A-1 with 25% biobutanol (BIO) were compared through the same experiment.

It was found that at the same flow rate the miniature jet engine reached higher values of rotational speed and thrust when running on Jet A-1 than on BIO. The exhaust gas temperatures were similar in the two cases.

For the same fuel flow rates the exhaust gases from the combustion of the two fuels contained different numbers of VOCs in significantly different concentrations. In both cases, the highest concentrations were those of *n*-pentane and 2-propanol. The other VOCs occurred in much lower concentrations. The most hazardous to humans are BTX compounds, whose concentrations were found to be higher in the Jet A-1 fuel. The benzene and toluene concentrations in the exhaust gases from the combustion of Jet A-1 were 54% and 44%, respectively, higher than in the case of BIO. Moreover, xylene was found only in Jet A-1 exhaust gases. Thus it can be concluded that the BIO fuel is less toxic. The higher toxicity of the exhaust gases from the combustion of the Jet A-1 fuel was corroborated by the results of the formaldehyde concentration cuvette tests.

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