2010-01-1563

Emission Measurements of the AI-14RA Aviation Engine in stationary test and under Real Operating Conditions of PZL-104 'Wilga' Plane

Jerzy Merkisz, Jarosław Markowski, Jacek Pielecha and Maciej Babiak
Poznan University of Technology

ABSTRACT

Due to a rapid development of air transportation there is a need for the assessment of real environmental risk related to the aircraft operation. The emission of carbon monoxide and particulate matter is still a serious threat– constituting an obstacle in the development of combustion engines. The applicable regulations related to the influence of the air transportation on the environment introduced by EPA (Environmental Protection Agency), ICAO (International Civil Aviation Organization) contained in JAR 34 (JAA, Joint Aviation Requirements, JAR 34, Aircraft Engine Emissions), FAR 34 (FAA, Federal Aviation Regulations, Part 34, Fuel Venting and Exhaust Emission Requirements for Turbine Engine Powered Airplanes), mostly pertain to the emission of noise and exhaust gas compounds, NO_x in particular. They refer to jet engines and have stationary test procedures depending on the engine operating conditions. The actual standards for the aircraft with the turbine engine emissions assessment are the procedures included in ICAO, FAR 34 regulations [15, 17]. These procedures are stationary and they are provided in the airport area. The said standards do not include aviation piston engines.

Due to the differences in the combustion processes between piston and jet engines it should be assumed that the toxic emissions of a piston combustion engine will be higher than those of a jet engine [5]. A considerable growth in the number of general aviation class aircraft may contribute to an increase in the emissions from piston aviation engines, which may pose a threat to the natural environment. The emission of NO_x in the upper parts of the atmosphere is particularly disadvantageous as it fosters the greenhouse effect [13].

The article presents the results of the exhaust gas emissions research of the small aircraft engine under real operating conditions and the results of the emissions measurements provided during the stationary tests in airport area. The paper presents results of the comparative analysis of the achieved measurements. The analysis enable us to assess the method of the stationary emissions measurements of the toxic gases contained in the exhaust gases of the aviation piston combustion engines.

INTRODUCTION

One of the factors stimulating the technology advancement in all the branches of industry is the necessity to restrict its negative impact on the natural environment. The application of advanced technologies and their further development forces a constant verification of the operating conditions of machines and their impact on the living organisms. Transport is one of the most dynamically advancing branch of economy and its changes are strictly related to the world's economic development. The development of means of transportation is aimed at a reduction of the toxic emissions during operation of all kinds of motor vehicles.

The emission of carbon monoxide and particulate matter is still a serious threat– constituting an obstacle in the development of combustion engines. The applicable regulations related to the influence of the air transportation on the environment introduced by EPA (Environmental Protection Agency), ICAO (International Civil Aviation Organization) contained in JAR 34 (Joint Aviation Requirements), FAR 34 (Fuel Venting and Exhaust Emission Requirements for Turbine Engine Powered Airplanes), mostly pertain to the emission of noise and exhaust gas compounds, NO_x in particular. They refer to jet engines and have stationary test procedures depending on the engine operating conditions. The said standards do not include aviation piston engines.

Due to the differences in the combustion processes between piston and jet engines it should be assumed that the toxic emissions of a piston combustion engine will be higher than those of a jet engine. A considerable growth in the number of general aviation class aircraft may contribute to an increase in the emissions from piston aviation engines, which may pose a threat to the natural environment. The emission of NO_x in the upper parts of the atmosphere is particularly disadvantageous as it fosters the greenhouse effect.

The current level of technology advancement related to the measurement of the toxic emissions enables testing means of transportation under real operating conditions [1–4,6–9,12]. Such investigations allow the determining of the emissions of individual exhaust gas compounds under real traffic conditions. They also allow an assessment of the operating specificity of a means of transportation in terms of time density of engine loads. Such information allows a determining of the operating states of the power train along with their share in the total engine operating time. Such information may then be juxtaposed to the stationary testing procedures which, in the future, may facilitate the optimization of the operating points of engines operated in transportation.

The possibilities of using portable measurement systems are of particular importance in the investigations of small aircraft under real operating conditions. The gross payload of the plane and the cargo space is decisive here – the minimization of the testing equipment is an advantage in the case of portable systems.

2. THE OBJECT OF THE RESEARCH

The investigations of the exhaust emissions of a small plane were carried out on PZL-104 Wilga (fig. 1) fitted with an engine AI-14RA (fig. 2).

Fig. 1. PZL-104 Wilga

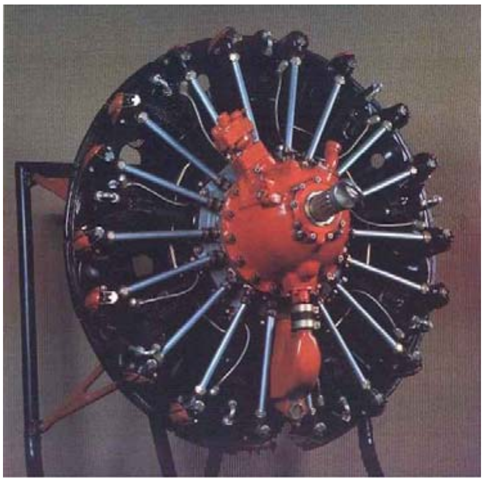

Fig. 2. Engine AI-14RA [15]

Due to the repeatability of the test results important are the pilot's predispositions and piloting style as well as the parameters of the plane. The plane parameters (PZL-104 Wilga) have been shown in table 1.

Table 1. Technical data PZL-104 Wilga

Version	PZL-104 Wilga 35
Wing span	11.12 m
Length	8.10 m
Height	2.94 m
Wing area	15.50 m^2
Kerb weight	900 kg
Payload	400 kg
Gross weight	1300 kg
Engine	PZL AI-14RA
Engine type	9 cylinder radial engine
Cooling system	Air
Bore	105 mm
Stroke	130 mm
Displacement	10.13 dm^3
Compression ratio	5.9
Supercharger	Single stage, single speed, geared centrifugal supercharger
Fuel system	Carburetor
Power (take-off)	194 kW
Power (nominal)	161 kW

The design of an aviation engine, its technology level and workmanship and, most importantly, its condition play a very important role in the aircraft emission tests. The tested plane PZL-104 Wilga was fitted with a 10.16

dm^3 9 cylinder star spark ignition air cooled piston engine AI-14RA. The engine was fitted with a single speed mechanically driven radial blower. The drive of the propeller W530-D11 was based on a planetary transmission of a gear ratio 0.787:1.

For the purpose of the emission tests the exhaust system of the plane was extended by 3 m. This allowed the measurement of the emissions at a spot that ensured a proper fitting of the measuring sensor (fig. 3). Such a long distance was needed to safe exhaust gas probe mounting. Due to elongation of the original exhaust system the exhaust gas temperature at the sample point, which is about 3.5 meters distant from the exhaust valve, reaches approximately 1300K.

Fig. 3. Location of the exhaust gas probe

3. TESTS IN REAL OPERATING CONDITIONS

MEASUREMENT EQUIPMENT

The aim of the performed tests was the evaluation of the toxic emissions under real operating conditions of the aircraft. This task required the application of two measuring systems. The first– exhaust gas analyzer TESTO 360 (fig. 4) – was used for the measurement of the exhaust gas compound concentration in the exhaust (the analyzer measuring data have been shown in table 3). The analysis of the exhaust gas compounds concentration made by TESTO 360 analyser was based on a principle of chemical reactions connected with compounds ionization. The CO_2 concentration mesurements was made with non dispersive method with use of infrared radiation (NDIR) [14]. The other system–data acquisition system LogBook 360 along with the analog input module DBK 214 by IOtech – was used to record the basic operating parameters of the engine i.e. pressure, ambient temperature, ambient humidity, exhaust gas temperature at its sample point as well as the parameters related to the flow of the exhaust gases.

Fig. 4. Exhaust gas analyzer TESTO 360

Table 2. TESTO 360 measuring parameters

Measured quantity	Measurement range	Measurement error
CO	0–10 000 ppm	below 2.0% of the range
CO_2	0–25% vol.	below 1.5% of the range
HC	0–2.5% vol.	below 10% of the range
NO_x	0–3500 ppm	below 3.8% of the range
SO_2	0–5000 ppm	below 2.5% of the range
O_2	0–21% vol.	below 1.2% of the range
Exhaust gas temperature	20–800°C	4°C

The measuring parameters of TESTO 360 enable recording of the measurements of the exhaust gas compound concentration with the frequency of 0,25 Hz. Hence, the measurements of the other parameters– with the use of the data acquisition system LogBook 360 – were recorded with the same frequency. Additionally, the data acquisition system was fitted with a GPS transceiver 18x by Garmin, which enabled the recording of the plane position parameters in a 3dimensional space. Based on the recorded position parameters the plane trajectory was determined.

TEST RESULTS

The measurement of the toxic emissions from the AI-14RA engine fitted in the aircraft PZL-104 Wilga was carried out from taxi until landing. In a standard type of flight we can distinguish several phases. These are: taxi, takeoff, climb, steady flight, approach to landing, landing taxi to apron. Depending on the performed task the time share of the individual phases in the whole flight differs. Most frequently the taxi and takeoff as well as approach to landing do not have a large share in the whole flight. Nevertheless the scope of the investigations comprised all these mentioned phases.

The route was set from the Airstrip of Aeroklub Poznański (Poznań Aeroclub) in Ligowiec near Kobylnica and the town of Wągrowiec of a distance of 45 km from the airstrip. Thus, the total flight distance amounted to approximately 90 km. The actual trajectory was determined based on the recorded parameters of the GPS transceiver (fig. 5).

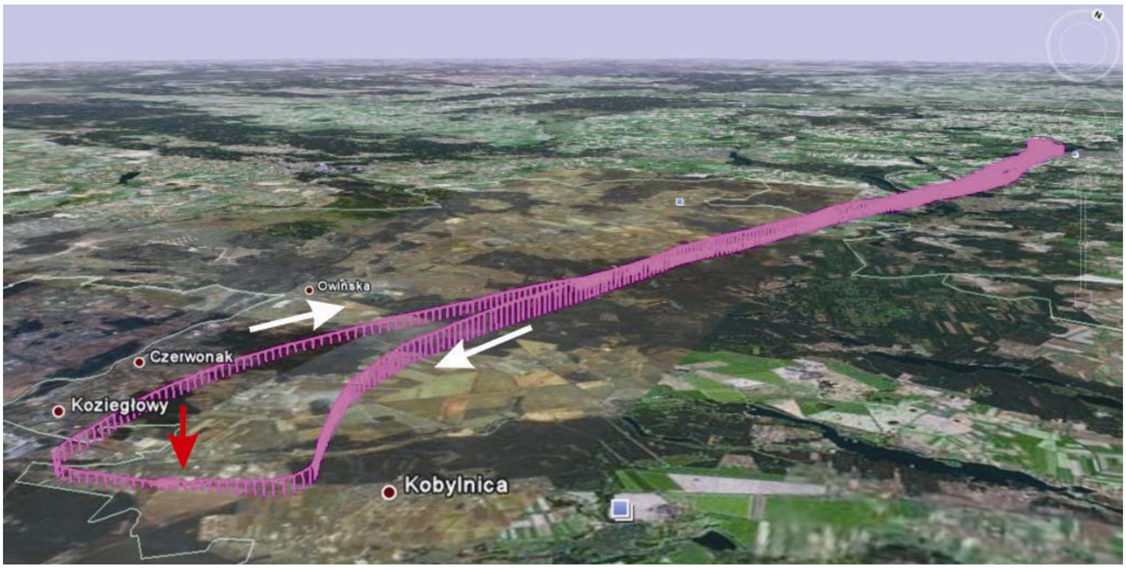

Fig. 5. Flight path during the test flight (red arrow place of the takeoff, white arrows – flight directions)

During the flight the concentrations of the exhaust gas compounds in the exhaust were recorded with the use of the TESTO 360 analyzer. Due to the exceeded maximum values of the measuring range of the analyzer the measurement of the hydrocarbon and CO was not possible. Hence, only the concentrations of the NO_x and SO_2 were measured, which enabled determining their correlation with the engine speed, cruising altitude or exhaust temperature at its sample point. The shown courses enable a detailed determining of the individual phases of the flight.

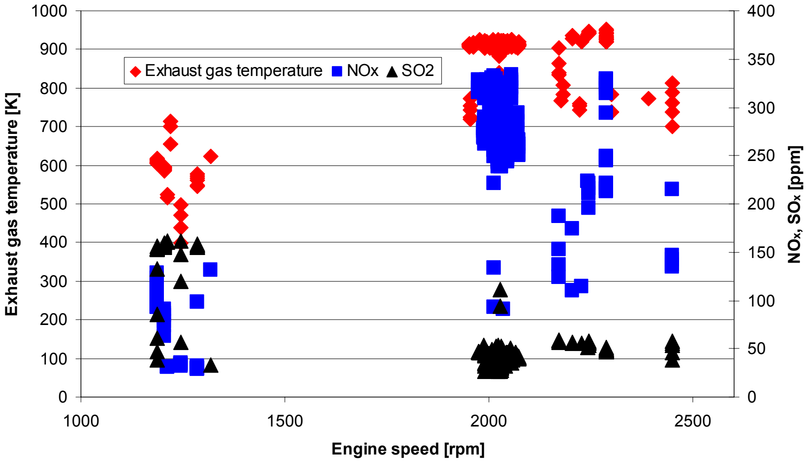

Fig. 6. The exhaust gas temperature, NO_x, SO_2 courses related to the engine speed

The visualization of the distribution of the NO_x and SO_2 concentration in the takeoff and landing phases have been shown in figs. 6. The obtained results indicate a tight correlation of the engine speed with the changes in the exhaust temperature values and the NO_x concentration (fig. 6). This dependency is related to a fixed setting of the rotor blade generating the effect of the engine load. While analyzing the changes in the instantaneous SO_2 emission we need to take into account that it is a consequence of combustion of aviation fuel that contain sulfur compounds. We can thus assume that the values of instantaneous concentration of SO_2 well reflect the instantaneous fuel consumption, which depends on the engine load and air fuel mixture composition.

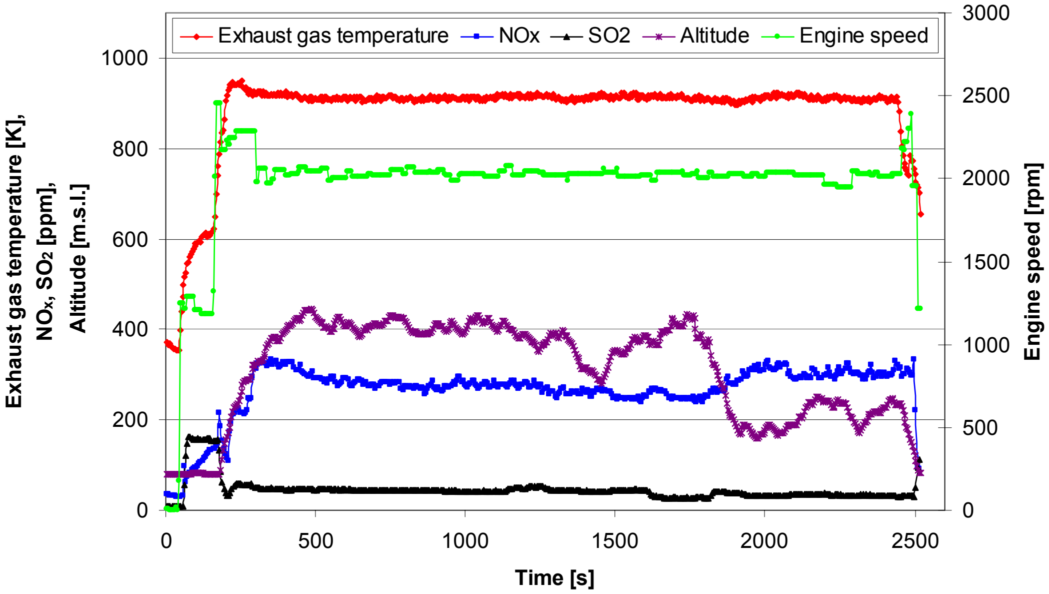

Fig. 7. Instantaneous concentration values of selected exhaust gas compounds, engine speed, flight altitude and exhaust gas temperature referred to flight time

In figure 7 we can distinguish the takeoff, climb and landing phases. In takeoff and climb phases the highest engine load occurs. Also in the same phases the engine is fuelled with a rich air fuel mixture in order to boost the certainty of proper mixture firing. Rich mixture, due to a low excess air number, contributes to the lowering of the maximum combustion temperature. This results in a relatively low value of NO_x (approximately 200 ppm) and a significantly high concentration of SO_2 (approximately 170 ppm). The recorded exhaust gas temperature was approximately 600K.

In the steady phase of the flight the value of the exhaust gas temperature amounts to approximately 900K and the concentrations of the individual regulated emission compounds stabilize and are approx. 300 ppm for NO_x and 50 ppm for SO_2. The steady character of the concentrations of the exhaust gas compounds does not change during the return phase (fig. 7). In all the flight phases the values of the hydrocarbons and CO concentration exceeded the maximum measuring capacity of the analyzer. These values according to the manufacturer specifications are: for HC – 2,5% vol., for CO – 10 000 ppm. It needs to be stated that the emission of these compounds is not determined but is higher than the maximum range of the analyzer.

4. TESTS IN STATIONARY OPERATING CONDITIONS

MEASUREMENT EQUIPMENT

The aim of made tests was the estimation of exhaust gas emission during aircraft standstill on the apron in operating conditions closed as much as possible to the actual working conditions of the aircraft that occur during flight. To the emission measurements the exhaust gas analyzer SEMTECH DS from SENSOR was used (fig. 8, fig. 9) [19].

Fig. 8. The view on the exhaust gas analyzer

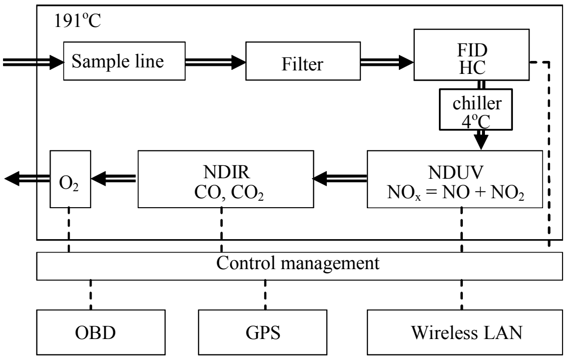

Fig. 9. A diagram of a mobile analyzer SEMTECH DS; exhaust gas flow channels (===) and electrical connections circled (– – –).

Fig. 10. The exhaust gas mass flow probe

The exhaust gas analyzer made possible measuring the concentration of the exhaust compounds (table 4) with simultaneous measuring of total mass flow rate of the exhaust gas with proper measuring probe applied (fig. 10). The exhaust gas is let in to the analyzer by the measuring probe that keeps the temperature at 191 degrees Celsius level. Next the exhaust gas is filtrated of the particulate matter (in CI engine case) and the hydrocarbons concentration in flame ionization detector (FID) is being measured. In the following step the exhaust gas is cooled to 4 degrees Celsius and measurement of NO_x (non dispersive method with use of ultraviolet radiation that allows simultaneous measurements - NDUV - of nitric oxide and nitrogen dioxide), CO (non dispersive method with use infrared radiation - NDIR) and O_2 (electrochemical analyzer) are made in turn. Findings from the vehicle OBD system and GPS system can be added to the central processing unit of gas analyzer, but it was not necessary during experiment.

Meeting the needs of exhaust gas compounds concentrations measurements the exhaust system was elongated by 3 meters. As a consequence the exhaust emission measurements were taken in place that allowed free assembling of the measurement probe and locating the analyzer in safe distance (fig. 11).

Fig. 11. Location of the exhaust gas probe and analyzer

Table 4. Characteristics of the mobile exhaust gas analyzer SEMTECH DS

Parameter	Measurement method, range	Accuracy
1. Compound concentration in the exhaust gas		
CO	NDIR – non dispersive (infrared), range: 0–10%	±10ppm
HC	FID – flame ionization detector, range: 0–10 000 ppm	±10ppm
$NO_x = (NO + NO_2)$	NDUV – non dispersive (ultraviolet), range 0–3000 ppm	±5ppm
CO2	NDIR – non dispersive (infrared), range: 0–20%	±0.1%
O2	Electrochemical - range 0–20%	±0.1%
Sampling frequency	1–4 Hz	
2. Exhaust gas flow	mass flow rate - measurement range varies on the diameter of used flowmeter which is changeable depending on the engine size T_{max} up to 700°C	±2.5% of the range ±1% of the range
3. Heating time of the heated line before beginning of the measurements	15 min	
4. Response time	T90 < 1 s	
5. Cooperating OBD diagnostic systems	SAEJ1850/SAEJ1979 (LDV) SAEJ1708/SAEJ1587 (HDV) CAN J1939/J2284	

The measurements of exhaust gas compounds emission of AI-14RA engine, that drives PZL-104 „Wilga" airplane, were made on the apron in stationary test. During standard flight of the aircraft a few phases can be specified. These are: taxi to the airstrip, take-off, climb, steady flight, approach, landing, taxi to the stand place. Depending on the completing task participation of particular phases in total flight is different. Three phases were taken into consideration during realization of researches: I - taxi, II - take-off, III - flight, in which settings of the engine controllers and airscrew pitch met the same values like during actual operation in the air. It was possible because all these settings could be set manually from the cockpit. Additionally measurements of toxic exhaust gas compounds emission in cold start phase of the engine were made. Obtained results are presented in table 5 and illustrated on graphs (fig 12-15).

Tab. 5. Emission test results of the AI-14RA engine

Parameter	Simulated operational phase			
	Starting and heating of the engine	Taxiing	Take-off	Flight
Engine speed [rpm]	Variable 500-1500	1200	2500	2000
Phase time [s]	212	372	90	112
Mean concentration				
CO [%]	6	7.2	6.1	2.2
HC [ppm]	4300	6100	3800	2900
NO_x [ppm]	360	570	650	400
CO_2 [%]	3.6	3.9	7	8.2
Emission [g]				
CO	1223	2196	1151	951
HC	48.2	144.0	29.0	15.6
NO_x	5.4	17.1	6.9	3.8
CO_2	1308	1820	1990	1173
Hour emission [g/h]				
CO	20 771	21 255	46 040	30 570

HC	818	1394	1606	502
NO_x	92.2	165.5	276.6	121.6
CO_2	22 210	17 611	79 586	37 711

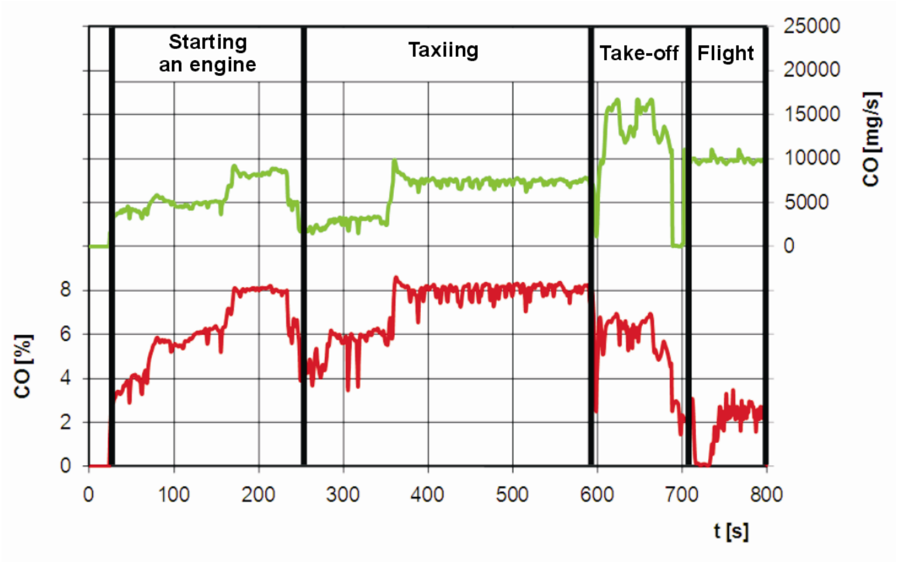

Fig. 12. Carbon monoxide emission in particular operational phases as a function of time

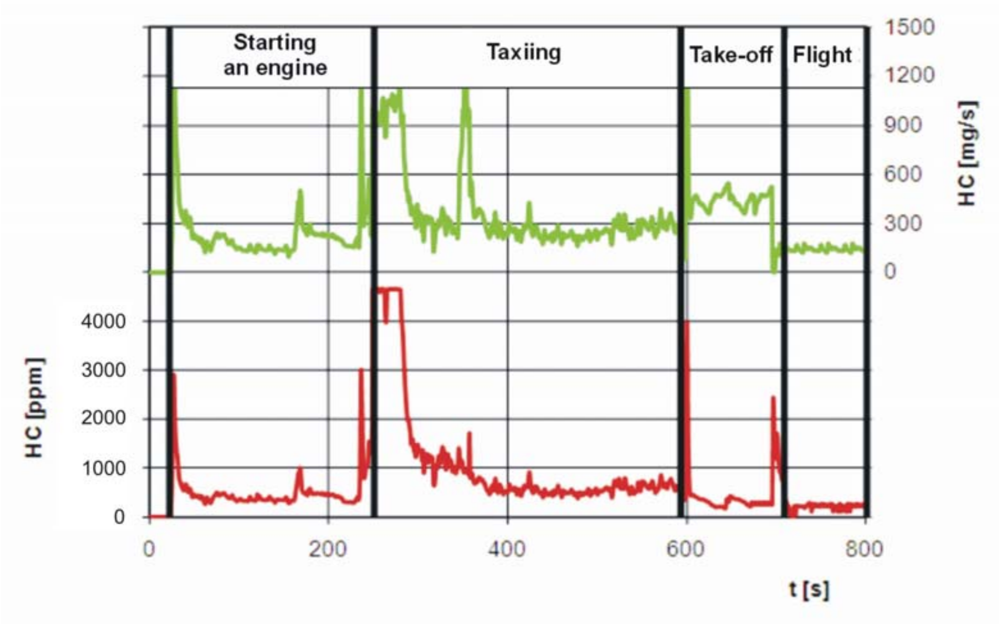

Fig. 13. Hydrocarbon emission in particular operational phases as a function of time

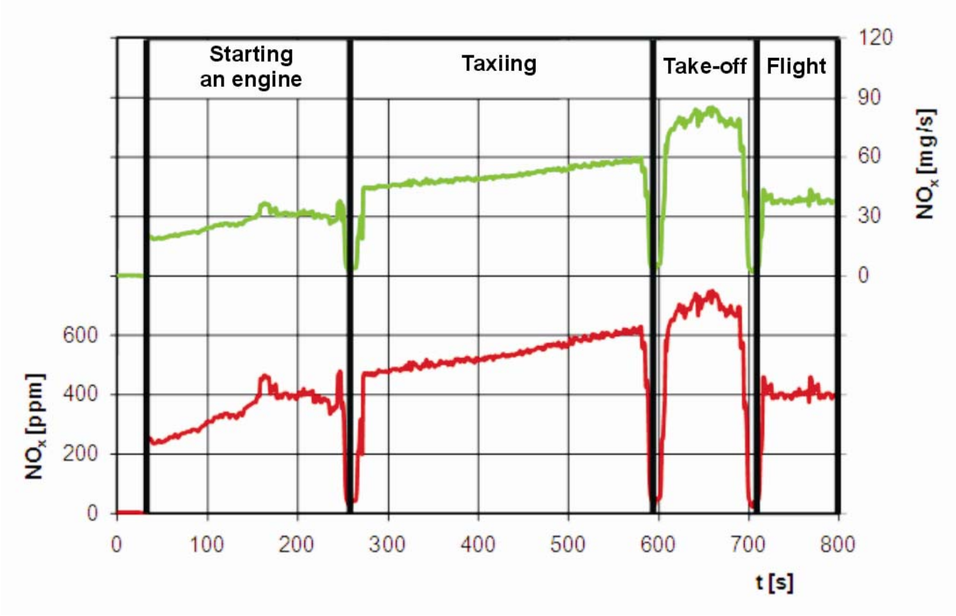

Fig. 14. Nitrogen oxide emission in particular operational phases as a function of time

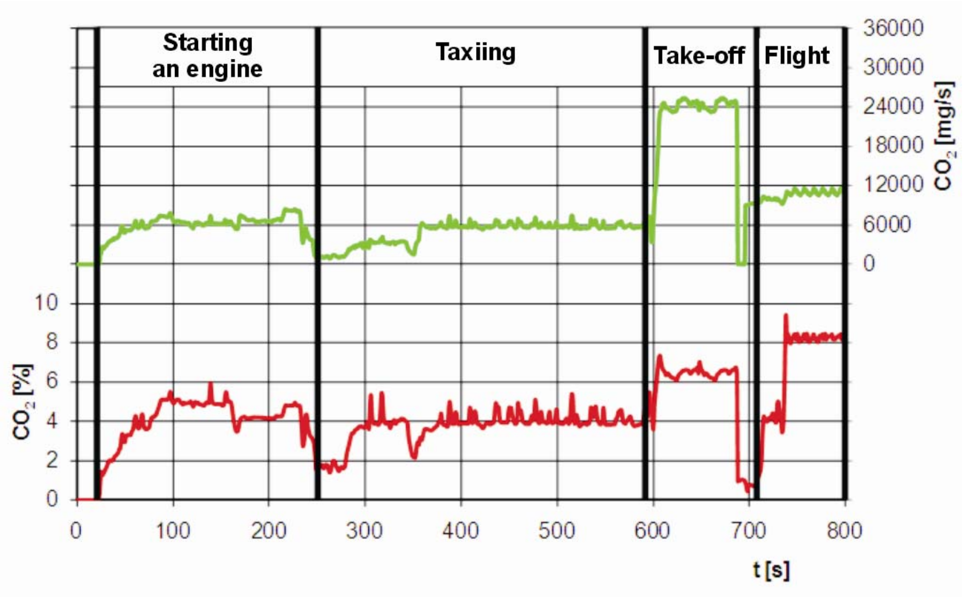

Fig. 15. Carbon dioxide emission in particular operational phases as a function of time

Presented results exemplify courses of exhaust gas compounds emission of AI-14RA engine exhaust gas as a function of time. The measurements of particular exhaust gas compounds were made in conditions of stationary test. For selected test points the same engine controllers settings as during actual engine operation were realized. Values of particular exhaust gas compounds indicate on the nature of the combustion process that is realized in presented engine. Excessive hydrocarbon and carbon monoxide emissions testify of burning reach fuel-air mixture. It is also confirmed by comparatively low emission of nitrogen oxide which indicates low temperature character of combustion process. Moreover high emission of mentioned exhaust gas compounds shows not ecological character of radial engine construction. In that case starting an engine is saddled with excessive emission of hydrocarbons which come from the lubricating oil. The researches were made in one measuring series and particular operational phases were separated from each other by short time when engine was idling, which for the aircraft engine means the minimum engine speed. Measurement results for these operating points were similar during whole research procedure and are characterized by high emission of hydrocarbons and relatively low emission of nitrogen oxide emission. It is interesting to compare mean hour exhaust gas compounds emission for each phases (fig.16). This comparison points a high similarity of starting an engine and taxi phases, especially mean carbon monoxide and carbon dioxide (fuel consumption) emission while values of mean hydrocarbon and nitrogen oxide emissions are higher for the taxi phase. It can be linked with thermal state of the engine. Interesting results were obtained when take-off and flight phases were compared. Mean emission of showed exhaust gas compounds keeps similar character for both phases. When comparing mean emission of the same exhaust gas compounds in particular phases it can be found that the aircraft during taking-off consumes twice as much fuel than in steady flight. The conditions of engine load foster the increased emission of carbon monoxide by 50%, hydrocarbon by 220% and nitrogen oxide by 130%.

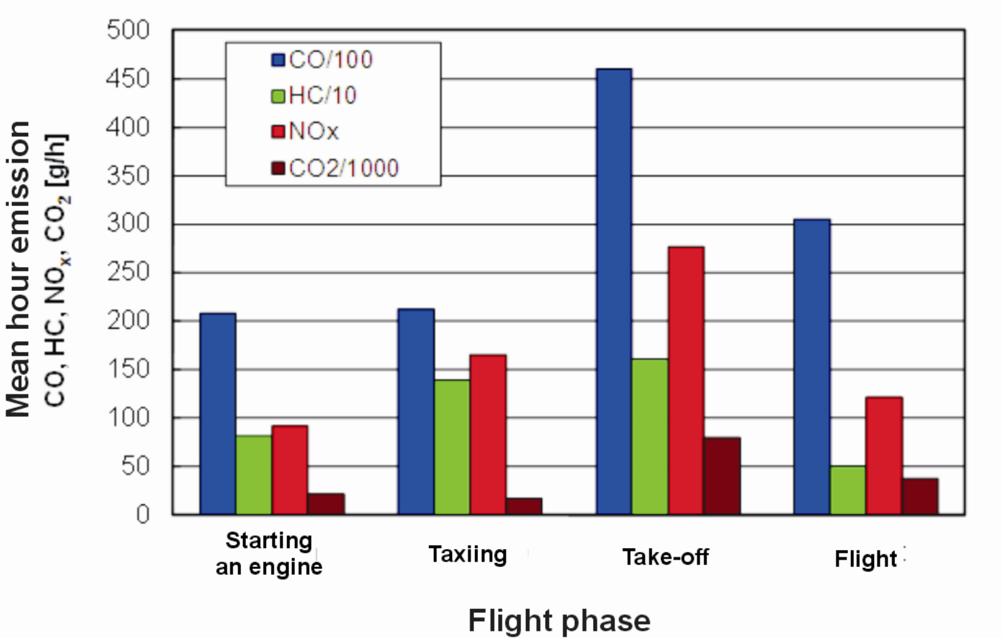

Fig. 16. The statement of regulated emission compounds mean hour emission in particular operational phases

5. CONCLUSIONS

The performed tests and the analysis of the obtained results confirm how significantly impactful many flight specific parameters are. The paper confirms a considerable dependency of the exhaust gas compound concentration on the aircraft operating conditions. The tests have confirmed the significance of the dynamics of the individual flight phases (climb phase in particular) on the concentration of the exhaust gas compounds.

The performed tests are to be treated as introductory and preliminary. The analysis of the obtained results pointed to a significant problem of an elevated concentration of CO and HC in the whole range of the engine operation. These results should be correlated with the results for the same aircraft fitted with a modern engine.

The information about emission value of toxic exhaust gas compounds from the aircraft engine can be used to verification and development of research procedures for small planes, which do not have sufficient load capacity to install all special full dimension testing equipment. Finally realization of this kind of researches can contribute to define universal research procedures that will determine emissivity of small aircrafts and its impact on the natural environment.

REFERENCES

1. Gao, Y., and Checkel, M.D., "Emission Factors Analysis for Multiple Vehicles Using an On-Board, In-Use Emissions Measurement System," SAE Technical Paper 2007-01-1327, 2007.
2. Khair, M., Khalek, I., and Guy, J., "Portable Emissions Measurement for Retrofit Applications – The Beijing Bus Retrofit Experience," SAE Technical Paper 2008-01-1825, 2008.
3. Khalek, I., "Status Update on the PM-PEMS Measurement Allowance Project," Sensors 6th Annual SUN (SEMTECH User Network) Conference, USA 2008, September 24-25, 2008.
4. Korniski, T., Gierczak, C., and Wallington, T., "Laboratory Evaluation of the 2.5 Inch Diameter SEMTECH® Exhaust Flow Meter with Gasoline Fueled Vehicles," Sensors 4th Annual SUN (SEMTECH User Network) Conference, USA 2007, October 22-23, 2007.
5. Kotlarz W., Turbinowe zespoły napędowe źródłem skażeń powietrza na lotniskach wojskowych, Wyższa Szkoła Oficerska Sił Powietrznych, Dęblin 2003.
6. Merkisz, J., Pielecha, J., and Gis, W., "Gasoline and LPG Vehicle Emission Factors in a Road Test," SAE Technical Paper 2009-01-0937, 2009.
7. Pielecha, J., and Merkisz, J., "On-Board Emissions Measurement from Light Duty Diesel Vehicles," presented at 12 EAEC 2009, European Automotive Congress Bratislava. Europe in the Second Century of Auto-Mobility, Bratislava 2009, June 29-Juli 1, 2009.
8. Pielecha, J., Merkisz, J., and Markowski, J., "Emission tests of the AI-14RA aircraft under real operating conditions of PZL-104 'Wilga' plane," Combustion Engines 3/2009.
9. Quan, H., "ARB's Stockton Heavy-Duty Vehicle Laboratory and Portable Emission Monitoring System (PEMS) Activities," presented at Sensors 5th Annual SUN (SEMTECH User Network) Conference, USA 2008, September 24-25, 2008.
10. Shahinian, V. D., SENSOR tech-ct Update Application Software for SEMTECH Mobile Emission Analyzers, Sensors 4th Annual SUN (SEMTECH User Network) Conference, 22.10.2007.
11. Sharp, C. A., Feist, M., Results of the HDIUT Gaseous PEMS Measurement Allowance Program and Update on PM Program Status, Sensors 4th Annual SUN (SEMTECH User Network) Conference, 22.10.2007.
12. Tsinoglou, D.N., Koltsakis, G.C., and Samaras, Z.S., "Performance of OBD Systems for Euro 4 Level Vehicles and Implications for the Future OBD Legislation," in Onboard-Diagnose II edited by O. Predelli, Expert Verlag, 2007.
13. Uherek E., Lower Atmosphere Basics: Nitrogen Oxides - Formation and Relevance, Max Planck Institute for Chemistry Department of Atmospheric Chemistry, Mainz 2004
14. Manual Instruction - TESTO 360, Testo AG, www.testo.com
15. www.flightsimaviation.com
16. www.garmin.com.pl
17. www.icaodsu.openface.ca
18. www.iotech.com
19. www.sensors-inc.com
20. www.wsk1.kalisz.pl/index_p.htm

CONTACT INFORMATION

Prof. **Jerzy MERKISZ**, M.Eng., Ph.D., D.Sc.
Poznan University of Technology, Institute of Combustion Engines and Transport
3 Piotrowo Street, 60-965 Poznan, Poland
Phone: +48 61 6652207, Fax: +48 61 6652204, e-mail: jerzy.merkisz@put.poznan.pl

Jaroslaw MARKOWSKI, M.Eng.
Poznan University of Technology, Institute of Combustion Engines and Transport
3 Piotrowo Street, 60-965 Poznan, Poland
Phone: +48 61 6652705, Fax: +48 61 6652204, e-mail: jaroslaw.markowski@put.poznan.pl

Jacek Pielecha, M.Eng.
Poznan University of Technology, Institute of Combustion Engines and Transport
3 Piotrowo Street, 60-965 Poznan, Poland
Phone: +48 61 6652208, Fax: +48 61 6652204, e-mail: jacek.pielecha@put.poznan.pl

Maciej Babiak, M.Eng.
Poznan University of Technology, Institute of Combustion Engines and Transport
3 Piotrowo Street, 60-965 Poznan, Poland
Phone: +48 61 6652208, Fax: +48 61 6652204, e-mail: maciej.babiak@put.poznan.pl