COMPARISON THE PISTON AIR ENGINE PERFORMANCE WITH AVIATION GASOLINE (AVGAS) OR THE E-85 ECOLOGICAL FUEL SUPPLY

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Abstract

The fuel presently used for feeding of aircraft piston engines (petrol including TEL) is characterized by "strong unfriendliness" for environment. Many research centres have been going on fuels investigation, which could substitute Avgas utilized in aviation. This is why are there no being in force for Europe standards defining the allowable emission of pollutions in exhaust gases of aircraft piston engines (equivalent to EURO - standards introduced for traction engines). The mixtures of gasoline and alcohols are tested as "alternative" aircraft fuels for spark ignition engines, and in case of Diesel engines - even jet kerosene.

During the research works on test bed carried out at Institute of Aviation the performance of four-stroke aircraft carburettor piston engine supplied by "classical" aircraft petrol and the E - 85 fuel (mixture of petrol and ethanol) were compared. Except for measuring the functional parameters of engine (rotational speed, torque, specific fuel consumption, pressures and temperatures) the emissions of gaseous pollutants incorporated in exhaust gas were measured and analyzed. The range of modifications of engine supply system - necessary to introduce in case of changing of fuel type within the tested engine was worked up. There are foreseen comparative test of fuelling the engine with mixtures of petrol and alcohols in different proportions in the next phase of research works.

Keywords: *internal combustion engine, piston air engines, ecological fuels, exhaust pollutant.*

1. Introduction

Aspirations for emissions reduce of harmful substances into the atmosphere

Over the past two decades, international organizations have issued a series of documents dedicated to change in the philosophy of the use of the environment. The effect of the conference in Rio de Janeiro ("Earth Summit" 1992) was so-called "The Rio Declaration", titled "Environment and Development" which, as a programmatic document of the UN (Action Program-Agenda 21) discussed issues of sustainable development: social issues and the protection of natural resources, including the atmosphere.

Some specific arrangements are contained in the Kyoto Protocol (December 1997), which came into existence at the United Nations Framework Conference on Climate Change, where the at least 5% reduction of greenhouse gas emissions up to 2012 in comparison to 1990 was postulated. This protocol was ratified by Poland at 13 December 2002. The important document concerning the promotion of biofuels and renewable energy sources is the European Union Parliament's Directive No. 2003/30/EC dated on 28 May 2003.

Recent assumptions of the EU Council dated on March 2007 provide for:

- Reduction of greenhouse gas emissions up to 2020 by 20% compared to 1990,
- An increase in the year 2020 the share of energy from renewable sources by 20%,
- Reduction of energy consumption by 20% compared to forecasts for the year 2020 by increasing the efficiency of the energy receivers,
- An increase in biofuels share in volume of transport fuels by 10%.

Requirements for the traction motors (Euro-standard)

In Europe, all new models of cars are putting to a series of technical tests required by law to ensure, that they will contribute to a cleaner environment by reduction of pollution levels. These attempts include emission standards, which are becoming more rigorous. Emission standards are known as Euro I (since 1992), Euro II (since 1996), Euro III (since 2000) and Euro IV (since 2005). Tab. 1 shows the levels of pollutants emissions allowable by these standards.

Tab. 1. European emission standards for passenger vehicles, [g/km]

	Start of obligatory	SI Engines				Diesel Engines		
		CO	HC+NOx	NOx	PM	CO	HC	NOx
Euro 3	2000	0.64	0.56	0.50	0.05	2.30	0.20	0.15
Euro 4	2005	0.50	0.30	0.25	0.0025	1.0	0.10	0.08

In Poland, during the last decade, specific carbon dioxide emission of passenger cars diminished by an average of 177 gCO_2/km in 1998 to 155gCO_2/km in 2007.

Monitoring of harmful components of exhaust gases emitted by aircraft

Up to now the control of aircraft engines emissions has not been lead in the manner, as it is done in relation to motor vehicles. However, according to allowance for carbon dioxide emissions fixed for each country, “Guidelines for the preparation of the aviation monitoring plans” were developed and wrote down as the Commission Decision at 16 April 2009. This document amended the Decision 2007/589/EC in regards to inclusion of guidelines for monitoring and reporting in relation to emissions and information about ton-kilometre related to aeronautical operations.

The aircraft operators are supposed to produce two monitoring plans:

a) for monitoring of ton-kilometres, which is prepared on the basis of data applied for the distances between airports as well as the mass of passengers and freight transported on the route,
b) for monitoring the annual emission of CO_2, which is prepared on the basis of data related to the quantity of consumed fuel.

The aircraft operator must determine the actual consumption of fuel during each flight and then compute the volume of emissions using the equation:

$$\textit{Emissions (kg } CO_2\textit{) = fuel consumption (kg) * emission factor (kg}CO_2\textit{/kg fuel)}$$

With relatively small values of the emission (not greater then 50,000 tones CO_2 per year) the uncertainty of fuel consumption measurement by an operator should not exceed 5% and for the operators, whose emission volume surpasses the value of 50,000 tons of CO_2, fuel consumption shall be determined more precisely with a maximum error of 2.5%. Tab. 2 shows emissions factors for different aviation fuels.

Tab. 2. Indicators to calculate emissions for different aviation fuels

Kind of fuel	Emission factor $[kg_{CO_2} / kg_{paliwa}]$
Aviation fuel (Avgas)	3.10
Kerosene (Jet-A1)	3.15
Biofuels	0

ICAO (International Civil Aviation Organization) developed emission standards for gas turbine engines (Engine Exhaust Emissions Data Bank) and procedures for measuring emission values. This method applies to the standard (or representative) cycle LTO (Landing and Take-Off) consisting of the following phases:

- Approach to landing from a height of 3000 feet (914 m) lasting 4 minutes (by 30% of start-up

thrust),
- Landing run on the runway and taxiing lasting 19 minutes (by 7% of start-up thrust),
- Take-off run within 0.7 minutes (by 100% of start-up thrust),
- Climbing to the altitude of 3000 feet during 2.2 minutes (by 85% of start-up thrust).

Tab. 3. Exhaust emission standards for selected aircraft with turbine engines (acc. to ICAO).

Aircraft	Engine	Fuel consumption for LTO, [kg]	CO_2 [kg]	CO [kg]	NO_x [kg]	CH_4 [kg]	SO_2 [kg]
A 320	CFM 56-5	770	2440	6.19	9.01	0.06	0.77
B 737-400	CFM 56-3	780	2480	13.03	7.19	0.08	0.78
B 767-300	GE CF6-80C2	1780	5610	14.47	28.19	0.12	1.77
MD 11	GE CF6-80C2D1F	2310	7290	20.59	35.65	0.24	2.31
ATR72-500	PW 127F	200	620	2.33	1.82	0.03	0.20

The Swiss (Federal Office of Civil Aviation FOCA) caring for natural environment in agreement with the German Aerospace Centre (DLR), such companies as Oil HJELMCO, BRP-ROTAX GmbH & Co., HORIBA Europe GmbH, TSI GmbH, and ALPAIR as well Swiss Air Force developed emission standards guidelines for aircraft powered by reciprocating engines. Like the ICAO for jet engines, so FOCA submitted proposals for the parameters of the standard LTO cycle for piston engines.

According to this proposal the cycle would include the following phases:
- a take-off run in 20 seconds (100% of start-up thrust),
- climbing in 2.5 minutes (85% of start-up thrust),
- approach to landing lasting 3 minutes (45% of start-up thrust),
- landing run and taxiing on the runway, lasting 12 minutes.

The emission of pollutants during a flight with 65% of start-up thrust would be determined on the basis of the recorded time of flight (the cross-country flight in Europe lasts statistically about 20 to 40 min.)

Conventional fuels for piston aircraft engines (high-octane gasoline, leaded gasoline)

The spark ignition aircraft engines are currently supplied with one of the three commercially available fuels of diversified properties, marked respectively with appropriate colour:
- Avgas 80 red unleaded 0.14 g_{Pb}/dm^3
- Avgas 100LL blue low leaded 0.56 g_{Pb}/dm^3 NATO: F18
- Avgas 100 green leaded 1.12 g_{Pb}/dm^3

The fuels above indicate leaded petrol with additive of highly toxic lead tetraethyl. The most widely used aviation gasoline in Poland, 100LL, is manufactured by Research and Development Center of Płock Refinery or imported by the Total firm. It can be used to supply of all types of piston aircraft engines.

Attempts to replace the aircraft leaded gasoline by other fuels

Because of the toxicity of lead tetraethyl many scientists studying its properties had suffered (including one of its inventor - T. Midgley), and some of them died. For the same reason the leaded motor gasoline was withdrawn from use (for example the USA at 1976–1986 and in Poland the last batch of E94 gasoline was produced by Orlen in December 2000). The researches made in 1994 showed that thanks this decision the lead content in the blood of U.S. citizens dropped by 78%.

Today other substances, including the increasing addition of ethanol, replace the tetraethyl lead. There are also attempts to introduce such gasoline into service as so-called MOGAS. However, not all manufacturers of piston aircraft engines are giving their consent to use them. The aviation fuel MOGAS-type can be used in several types of aircraft engines, not very exerted, of power not exceeding 100 kW. They have already received relevant certificates. In Germany for instance, these fuels are admitted for feeding of approximately 57% of aircrafts but in the whole world about 53 000 aircrafts are supplied by such fuel.

The idea of a uniform fuel for the aviation industry was revived (supplying of various aircraft turbine and reciprocating engines by the same fuel). The attempts are made to give such status to aviation kerosene (Jet A), formerly applied only to gas turbine engines.

A dozen or so years ago development programs GARA (General Aviation Revitalization Act) and AGATE (Advanced General Aviation Transport Experiment) were initiated by NASA. Their effects in the USA were not very apparent; foremost aircraft engines manufacturers Teledyne Continental Motor and Textron Lycoming contented rather with "cosmetic" changes to their products, while in Europe several unconventional designs came into existence. The engineers team Renault Sport (Formula I) has developed a family of diesel engines fuelled with aviation kerosene, of which SR305-230 with a cylinder capacity of 5 litters and power of 230 HP was certified at April 2001as the propulsion unit of TB-20 Trinidad airplane.

In the similar way the Thielert Company carried out a modification of the Mercedes engines. Coming from OM 668 engine which is a propulsion motor of A 170 CDI (W168) car, the aircraft Diesel engine Centurion 1.7 fed with Jet A fuel was obtained, having power of 101 kW (135 HP). Till the end of 2006 year about 1500 above-mentioned engines were built (performing over a million of flying hours on the aircrafts Cessna 172, Piper Cherokee and Diamond Star DA40-TDI) therewith the production was ceased in favour of Centurions 2.0. Thielert Company went bankrupt in May 2008 (perhaps due to poor servicing network for their products - mainly in the U.S. market), but the Diamond Aircraft took over the production of Centurions. In January 2009 Diesel engine E4 (Centurion 2.0 being present on the market at the same time under the trade name Austria AE300), has been certified by European Aviation Authorities - EASA. The engine has been approved for use in light tourist- and sport aircrafts.

The next type of fuel that could replace conventional aircraft leaded gasoline is ethanol and its blends with unleaded petrol. This fuel has many advantages; therefore, for example, in Brazil this fuel - including the first worlds certified Embraer 202 Ipanema, supplies over 1,000 flying airplanes. Ethanol is there three times cheaper than aviation gasoline.

In the U.S., the Baylor University - a private university in Waco, Texas –is concerned with research works on the use of this fuel in aviation. From 1980Th dr. Maxwell Shauck manages the researches. In 1989 he and his wife Grazia, flew from Waco to Paris (about 6000 miles) by single-engine Velocity SE plane, powered by pure ethanol (this was the first such transatlantic flight).

2. Comparison of 100LL AVGAS and E-85 fuel properties

The calorific value of ethanol is about 21.5 MJ/dm^3, but gasoline about 32 MJ/dm^3. Higher heat of evaporation of ethanol (three times higher than the gasoline's one) results in "cooling" of cylinder charge, improving of charge regulation and increasing of engine power at a slightly heightened fuel consumption in comparison to gasoline. Tab. 4 shows some properties of aviation gasoline and eco-fuel E-85 containing 85% ethanol and 15% unleaded gasoline.

Tab. 4. Comparison of aviation gasoline, ethanol and eco-fuel E-85 properties

Parameter	Unit	Avgas 100LL	Ethanol	E-85
Density	[kg/m^3]	720	789	773
Heating value	[MJ/kg]	44.2	27.2	34.6
Octane number	[MON]	100	112	106
Heat of vaporization	[MJ/kg]	0.35	0.92	
Pollution	[kg_{CO2}/kg_{pal}]	3.3	1.91	2.6
Lubricity	[μm]	851		701

Comparing to aviation gasoline, E-85 fuel has a higher octane number and better lubricity (as measured by the High Frequency Reciprocating Rig – a ball of 6 mm diameter loaded by 200 g weight put during 75 minutes to the transverse 50 Hz - vibrations of 1 mm amplitude imprints the trace on steel plate flooded with tested fuel).

3. The method of measurement. Test bench

The research works were run on the aircraft engine's test bench in Institute of Aviation. The test bench was equipped with:

- Eddy-current dynamometer AMX 200,
- Engine's cooling system (automatically controlled airflow from the fan),
- Fuel supply system (AVGAS or E-85),
- Air intake system with an compensation volume and Lemniscate's measurement unit,
- Measuring system with continuous registration of engine parameters (using the ATM-QAR register),
- An exhaust gas analyzer SIGNAL.

As the research object a four-stroke, four-cylinder (opposed-cylinder) SI aircraft piston engine Franklin 4A-235 was used. Air-cooled engine had a take-off power of 80 kW (110 HP) at 2,800 rpm. The tests relied on recording of steady-states engine parameters for the chosen crank shaft speeds according to the propeller curve. After stabilization of speed air-fuel mixture ratio was changed. The study was performed by feeding of engine by aircraft gasoline at first and next was repeated using E-85 fuel. The admission system consisted of an adapted for AVGAS gasoline carburettor, factory- adjusted, modified by enlarging of nozzle diameter - suitable for ethanol fuel- and low-pressure injection system.

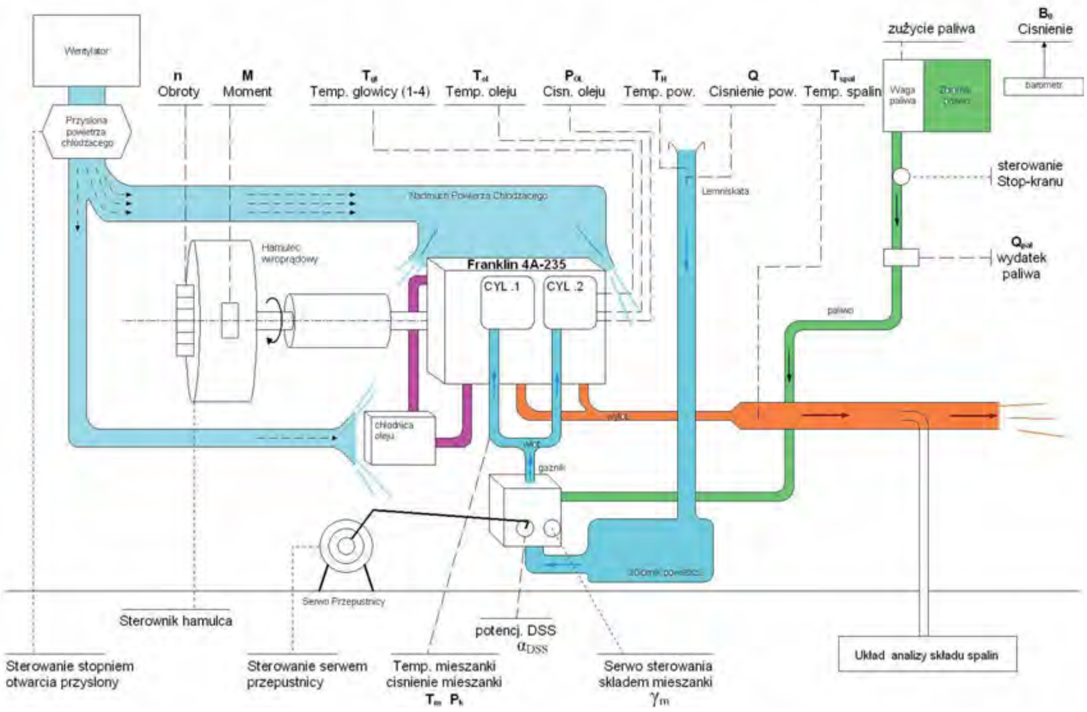

Fig. 1. General arrangement of test bench

4. The need for changes in the supply system

The carburettor principle of operation says that the air-fuel ratio is measured out by volume. The changes of flow cross-aeries in the carburettor should therefore compensate for the change in ethanol fuel density with relation to gasoline in the way that would enable to obtain blends of a ratio similar to stoichiometric. In this case the diameter of the throat, the fuel level in the float chamber and the fuel nozzle diameter were chosen in the manner to enable the suction of 1 kg of fuel (that is 1.38 litters) from float chamber by intake of 14.7 kg of air through the throat of carburettor. After change of the fuel to E-85, 1 kg of this fuel should be sucked in by the airflow of 10.2 kg that is by the intake airflow of 14.7 kg the fuel nozzle should pass the 1.44 kg (or 1.86 litter) of E-85. The cross-section of the fuel nozzle should be then increased in the ratio of 1.86 to 1.38 i.e. about 35% (assuming the similar loss of pressure in the nozzle). Thus, the diameter of the nozzle should be changed from the previous 2.5 mm to 2.9 mm.

At the temperature of +21°C, gasoline dissolves about 150 ppm of water but alcohol – 6000 ppm. During cooling down of mixture the phase separation can occur: alcohol-free gasoline will remain in the top layer while in the bottom - water along with ethanol. It can cause the corrosion of supply system elements. In order to remedy this effect the existing installation, adapted for aviation gasoline, was equipped with stainless tank and fuel filters for E-85 blend. All fuel pipes were replaced with stainless ones. Additionally the appropriate switch-over fuel valves were installed.

In the final phase of research works the carburettor was replaced by low-pressure multi-point injection system Silver Hawk EX-5VA1.

5. The effects of test bed researches

A simple exchange of fuel art from aviation gasoline to E-85 (without undertaking the optimization process, for example, ignition advance angle, compression ratio, etc) caused for test engine fed using carburettor a slight decrease of maximum power by 3 to 4% and increase in specific fuel consumption by 17% due to lower heating value of ethanol fuel E-85.

Tab. 5. Magnitude of power obtained for the take-off phase [kW]

Feeding system	Fuel =>	Avgas 100LL	E-85
Carburettor	"factory"	80.3	77.5
Carburettor	modified		83.9
Injection	"factory"	83.7	82.0

Better results were obtained replacing the carburettor by low-pressure injection system, because maximum power of engine supplied in such way by E-85 fuel was higher by about 4.5% than of the engine fed by the carburettor. An additional advantage is the possibility to permit this engine to aerobatic flights (carburettors engines are susceptible to inclination).

The curves shown in Fig. 2 point out a significant drop of HC and CO concentration in the exhaust gas and a small increase in NOx at their generally low levels of emission.

One should to note that the feeding of test engine with E-85 fuel (unleaded) via injection system would allow the control of the fuel charge by utilization of the oxygen sensor in the exhaust gas (Lambda sensor), which can not be used if the fumes contain lead compounds (the sensor is "poisoned" by them).

6. Conclusions

- These branches of aviation, which operate IC piston engines, continue to use "non-ecological" fuels, i.e. high-octane leaded petrol. It has to be changed because it is contrary to the trends of environmental protection.
- The changes concerning the aircraft piston propulsion take place very slowly: one try to apply Diesel-, two-stroke and Wankel engines. Alternative fuels to aviation gasoline are being examined, such as aviation kerosene Jet A and fuels with a substantial fraction of bio-additives. Among

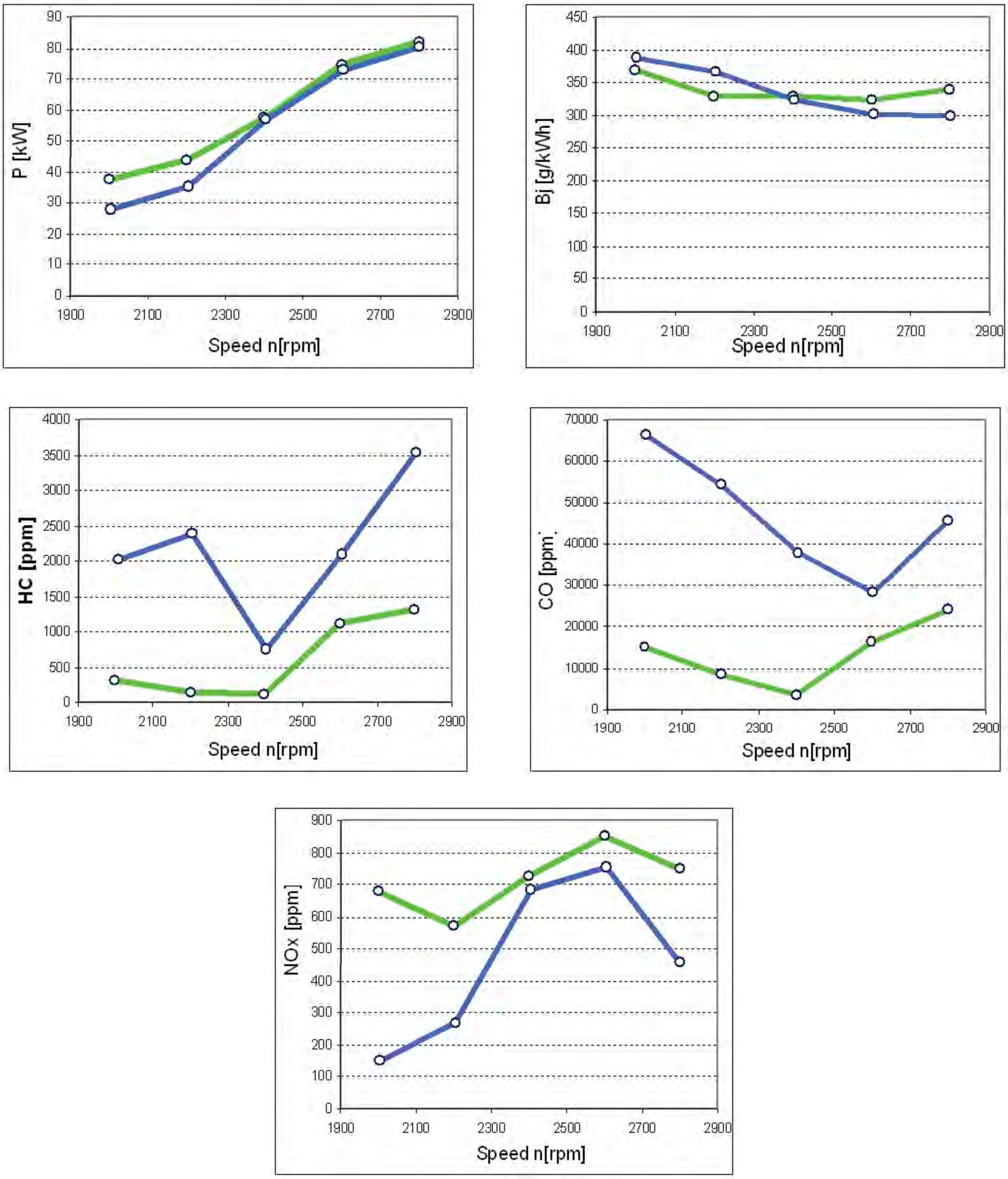

Fig. 2. Comparison of engine parameters and gaseous toxins concentration (CO, HC and NOx) in exhaust gas while running according to propeller curve versus engine speed (n): carburettor feeding with AVGAS 100LL (darker line), injection supply with ethanol E-85 (lighter line)

them, some kind of standard becomes a mixture of 15% unleaded gasoline and 85% of ethanol (being present under the name E-85 in Europe, AGE-85 in the USA, or AEHC in Brazil).

- The change of fuel causes not the necessity of the modifications presented in section 4 only, but also requires further adaptation of the ignition and powering systems. The injection system under test, which settings were not subject to modifications, allowed, when running on E-85, obtaining at low engine speed rich air-fuel mixtures only ($\lambda = 0.8 \dots 1$), and lean mixtures ($\lambda = 1.05 \dots 1.56$) at high engine speed. This implies higher combustion process temperature and higher content of nitrogen oxides in the exhaust.

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