ECOLOGICAL EFICIENCY OF GASOLINE/ETHANOL BLENDS IN A AERONAUTICAL COMBUSTION INTERNAL ENGINE

Adriana Aparecida dos Santos Costa, est-at@ipev.cta.br
Instituto Pesquisa e Ensaios em Voo
Endereço: Praça Marechal Eduardo Gomes, 50 - Vila das Acácias
CEP 12.228-904 – São José dos Campos – SP – Brasil

Cristiane Aparecida Martins, cmartins@ita.br
Instituto Tecnológico de Aeronáutica
Endereço: Praça Marechal Eduardo Gomes, 50 - Vila das Acácias
CEP 12.228-900 – São José dos Campos – SP – Brasil

José Luz Silveira, joseluz@feg.unesp.br
Universidade Estadual Paulista – UNESP – Campus de Guaratinguetá
Endereço: Av. Ariberto Pereira da Cunha, 333 – Pedregulho
CEP.: 12516-410 - Guaratinguetá – SP - Brasil

Abstract. *Today it is necessary to search new and less polluting sources like ethanol in order to slow growth the global warming. In Brazil it is already one alternative fuel. There are cars using alcohols in Brazil since 1979. Beyond the financial advantages, there are technical and strategic advantages. This work presents an experimental pollutant emissions study for aeronautical engine using gasoline-ethanol blends as fuel. Typical four-stroke engine is made up of a number of cylinders, each having a piston which moves up and down inside. This linear motion is converted to rotational motion of the crankshaft by a connecting rod. The fuel is ignited with a spark when the piston is near the cylinder top. Heat released increases the pressure on the piston head, creating in this way a force that pushes the piston downwards and turns the crankshaft. However, there are some limits to this system. If air-fuel mixture temperature became too high, the fuel could be ignited before spark signal and also before piston reaches the top. This phenomenon is called pre-ignition or detonation. This is the reason why the compression ratio of an engine is limited by the fuel properties and this is one of the advantages of ethanol in comparison with gasoline, its antiknock property which improves engine efficiency and yields higher compression ratios and higher heat of vaporization compared to gasoline, which means that more mass can be drawn into the cylinder, increasing the power output. The substances that compose the exhaustion gases can be classified in several groups: nitrogen, oxygen, hydrogen, steam and carbon dioxide belong to not toxic group substances; the toxic group substances include the carbon monoxide (CO), nitrogen oxides* (NO_x)*, hydrocarbons* (C_xH_y)*, aldehydes* (R_xCHO)*, soot, sulphur dioxides* (SO_2)*, sulphydric acid and solid particles. The polyaromatic hydrocarbons (PAH) are carcinogenic substance and form a special group. Until now, there is not any bi-fuel aircraft in the world. The main goal of this work is show the importance of converting in an internal combustion engine used in aircrafts in a bi-fuel engine. For this, we studied the Lycoming IO-540-K1D5 engine environment impact using only aviation gasoline and operating with aviation gasoline and alcohol blends maintaining same configuration. The concept of ecological efficiency concept is applied to evaluate the environmental impact caused by* CO_2, SO_2, NO_x *and particulate material (PM) emissions. The resultant pollution of each one of fuels are analyzed, considering separately the* CO_2, SO_2, NO_x *and particulate material (PM) emissions. We evaluate and quantify the environmental impact from the use of aviation gas in aeronautical internal combustion engines and the advantages of using gasoline-ethanol blends as fuel. This work will give technical support for further research on flexible-fuel aeronautical engines.*

Keywords*: aeronautical internal-combustion engines, aviation gasoline, bi-fuel, ethanol, ecological efficiency.*

1. INTRODUCTION

About 700 million tons of carbon monoxide, 150 million tons of nitrogen oxides, 200 million tons of solid particles, and 200 million tons of sulphur dioxides are released annually in the atmosphere. The majority of these substances are produced by the transportation sector (Patrakhaltsev et al., 1994). Currently, the internal combustion engines (ICE) produce about 85% of the energy consumed in the planet, for which the vehicle engines constitute a large portion. The exhaust gases that contain toxic substances represent the most dangerous risks related to the environment pollution (Coronado et al. 2009).

Until now, there is no blended fuel aircraft in the world. The goal of this work is to present the results of environmental impact tests executed on the Lycoming IO-540 engine used in aircraft as a blended fuel engine. The Lycoming IO-540 engine will be able to operate with blends of aviation gasoline (Avgas) and ethanol maintaining the same configuration. This engine was chosen because it is used in training aircraft on the Brazilian Air Force.

1.1. Internal Combustion Engine Characteristics

The Lycoming IO-540 series engines are horizontally opposed six cylinder, direct-drive, aircooled models. The cylinders are of conventional air-cooled construction with heads made from an aluminum-alloy casting and a fully machined combustion chamber. Table 1 presents engine characteristics.

Table 1. Engine aircraft characteristics (LYCOMING, 2007)

Type	4 Stroke SI
Number of cylinder	2 + 2 boxer
Compression ratio	8.5:1
Stroke (inches)	4.375
Bore (inches)	5.125
Cubic inch displacement	360
Rated horsepower	180 hp @ 2700 rpm

The initial idea is to maintain all mechanical characteristics of the engine constant. This means that the same configuration of the original gasoline model will be utilized, including compression ratio. Tests using only ethanol were repeated with a fuel injector servo changed for ethanol applications. Some details like the cold-start procedure, which is critical for ethanol fuel, will be discussed. Similarly to automobiles, in the current test bench a little gasoline tank is used for starting the engine.

The FLEX aeronautical engine is being developed by Brazilian Air Force and Magneti Marelli Brazil Company. Lycoming IO-540 test bench is shown in Fig. 1.

Figure 1 - Lycoming IO-540 engine mounted in test bench

In the present work, Carbon Dioxide Equivalent and Ecological Efficiency concepts will be applied. Both concepts are briefly described below.

2. CARBON DIOXIDE EQUIVALENT AND ECOLOGICAL EFFICIENCY

The coefficient for the equivalent carbon dioxide $(CO_2)_e$, a hypothetical pollutant concentrations factor, is determined by "Eq. (1)" (Cardu and Baica, 1999). For the calculation of this coefficient, the CO_2 maximum concentration value allowed is divided by the corresponding air quality pattern for NO_x, SO_2 and PM in hour. Thus, the expression for the $(CO_2)_e$ is:

$$(CO_2)_e = (CO_2) + 80\,(SO_2) + 50\,(NO_x) + 67\,(PM). \tag{1}$$

In the "Eq. (1)", $(SO_2)_e = 80\,(SO_2)$ is the sulphuric dioxide equivalent in (CO_2), $(NO_x)_e = 50\,(NO_x)$ is the nitrogen dioxide equivalent in (CO_2) and the particular matter equivalent in (CO_2) is $(PM)_e = 67\,(PM)$. The best fuel from the ecological standpoint is the one which presents a minimum amount of $(CO_2)_e$ equivalent carbon dioxide obtained from its burning. In order to quantify this environmental impact, the "pollutant indicator" ($\prod g$) is defined in "Eq. (2)".

$$\Pi_g = \frac{(CO_2)_e}{Q_i}, \quad (2)$$

where $(CO_2)_e$ in kg/kg (kg per kg of fuel), Q_i in MJ/kg is the LHV (Low Heating Value) and (Π_g) in kg/MJ is the pollution indicator and kg refers to (CO_2)e mass.

Ecological efficiency is defined as an indicator which allows the evaluation of the thermoelectric power plants gas emission environment impact, by comparing the hypothetically integrated pollutant emissions (CO_2 equivalent emissions) to the existing air quality patterns. The conversion efficiency is also considered a determinant factor on the specific emissions, expressed by a fraction number. Using "Eq. (3)" is possible to estimate the ecologic efficiency may (Cardu and Baica, 1999), (Cardu and Baica, 2001), (Villela and Silveira, 2007):

$$\varepsilon = \left[\frac{0{,}204\eta}{\eta + \Pi_g} \ln(135 - \Pi_g) \right]^{0{,}5}, \quad (3)$$

where ε comprises in a single coefficient the aspects that define the thermoelectric unit environment impact intensity, fuel composition, combustion technology, pollutant indicator and conversion efficiency. The value ε is directly proportional to thermoelectric power plant efficiency (η) inversely proportional to (Π_g), pollutant indicator value, and also alternates between 0 and 1, similarly to thermoelectric efficiency. The situation is considered unsatisfactory from the ecological point of view when ε = 0, but when ε = 1 it indicates an ideal situation.

3. GASOLINE AND ETHANOL

The gasoline is a fuel constituted basically by hydrocarbons and, in fewer amounts, by oxygenated products. These hydrocarbons are, in general, less heavy fuels than those that compose the diesel fuel formed by molecules of small carbonic chains (normally has 4 to 12 carbon atoms). Besides the hydrocarbons and the oxygenated ones, the gasoline contains sulphur composites, nitrogen composites and metallic composites, all these with low concentrations (PETROBRÁS, 2007). The chemical formula of the aviation gasoline used in this work is approximately 65% of Iso-octane, 15% of iso-pentane and 20% of toluene; its density is 740 kg/m^3 (ENERGY AND MINES MINISTRY, 2006). The equation for normalized air excess α follows.

$$0.65\, C_8H_{18} + 0.2\, C_7H_8 + 0.15 C_5H_{12} + 11.13\alpha O_2 + 41.83\alpha N_2 = 7.35 CO_2 + 7.65 H_2O + 41.83\alpha N_2 + 11.13(\alpha - 1)O_2 \quad (4)$$

Making reference to Resolution nº 35 of the ANP – Brazil (National Petroleum Agency), the ethanol ethylic in anhydrous state is miscible with the gasoline, which allows the use a blend in automobiles that reduces the gasoline consumption and excuses the use of antiknock agent; the percentage has varied along of the years between 20 and 25% in volumetric base (Carvalho and Mcquay, 2007). Thus, the chemical formula for ethyl ethanol is C_2H_5OH and its density is 790 kg/m^3, from its stoichiometric combustion reaction, the result is: 88 g CO_2 for 46 g ethanol, in consequence: 1.511 ton of CO_2 per m^3 of ethanol.

$$1C_2H_5OH + 3\alpha O_2 + 11{,}28\alpha N_2 \rightarrow 2CO_2 + 3H_2O + 11{,}28\, \alpha N_2 + 3(\alpha - 1)O_2 \quad (5)$$

3.1. Toxicity in internal combustion engines (gasoline and ethanol)

The substances that compose the exhaustion gases can be classified in several groups: nitrogen, oxygen, hydrogen, steam and carbon dioxide belong to not toxic group substances; the toxic group substances include the carbon monoxide (CO), nitrogen oxides (NO_x), hydrocarbons (C_xH_y), aldehydes (R_xCHO), soot, sulphur dioxides (SO_2), sulphydric acid and solid particles. The polyaromatic hydrocarbons (PAH) are carcinogenic substance and form a special group (Lizarraga, 1994).

As reference, a small vehicle releases to the atmosphere in average between 0.6 to 1.7 kg/h of CO; a truck releases between 1.5 and 2.8 kg/h of CO. In general, when 1kg of gasoline is burnt, it release between 300 and 310 toxic components, specifically: 225 g of CO, 55 g of NO_x, 20 g of HC, 1.5 to 2 g of SO, 0.8 to 1g of aldehydes, 1 to 1.5 g of soot (Patrakhaltsev et al., 1994). The PM emissions of gasoline fuel for internal combustion engines is 1.44 kg/m^3 (Carvalho and Mcquay, 2007). In the internal combustion engines run with pure ethanol, sulphur emissions was eliminated which to represent a advantage with respect to the gasoline, on the other hand, emissions of particulate material (PM) from internal combustion engines, run with pure ethanol is insignificant and will not be take account in the calculations. Finally the emissions of NO_x according to CETESB (Environmental Cleaning up Technology Brazilian Company) is approximately 0.8 kg/m^3.

4. METHODOLOGY

In this part, a suitable test bench is necessary, which should include gas analyzers, temperature, pressure, torque and engine speed sensors, and so on. With the current test bench, which is in operation, is possible to obtain cylinder head temperatures, engine speed, fuel consumption, exhaust temperatures and torque. Besides the performance parameters, concentration of CO, CO_2, O_2 and UHC were measured, and an orifice plate was used in order to obtain mass air flow. The schematic of the experimental apparatus is shown in Fig. 2.

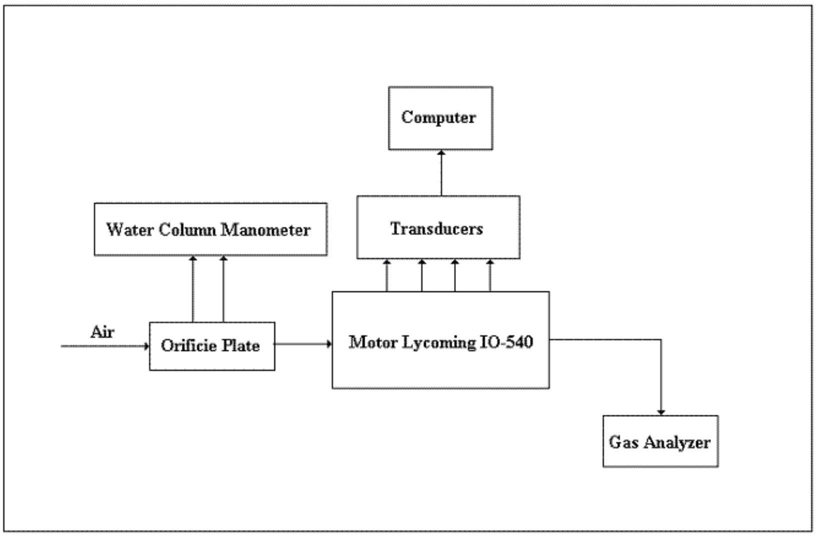

Figure 2 - Schematic of the Experimental Apparatus

In order to evaluate and quantify pollutant emission and ecological efficiency, the engine was tested with several blend rates according to Tab. 2.

Table 2 - Blends tested

Fuel Injector Servo	% Aviation Gas	% Ethanol
Gasoline	100	0
Gasoline	95	5
Gasoline	90	10
Gasoline	85	15
Gasoline	80	20
Gasoline	60	40
Gasoline	50	50
Gasoline	40	60
Gasoline	20	80
Gasoline	0	100
Ethanol	0	100

The tests have been performed in two flight conditions: takeoff and cruise at 10,000 ft. For the takeoff condition, the engine is set at fully rich mixture and maximum speed (2700 RPM).

In order to obtain representative data for the condition of the 10000 ft cruise, the procedure adopted by the T-25 "Universal" aircraft's flight manual (AEROMOT, 1984) has been used. The procedure is to reduce the throttle until reaching 2450 RPM rotation with the mixture lever at maximum rich. Then, one should reduce the mixture lever until the engine exhaust temperature (EGT) reaches its peak. Finally, the mixture should be increased again until the EGT decreases to a multiple of 25ºF. The manifold pressure was checked against the value for the 10,000 ft condition, according to the flight manual. Another way to obtain the conditions of the 10,000 ft cruise is calculating the suction pressure across the table from the engine power control IO-540 series K, L, M 300 HP also found in the flight manual T-25 (AEROMOT, 1984).

5. RESULTS

Ecological efficiency values for aeronautical internal combustion engines have been calculated for different blends of aviation gasoline and ethanol. The chemical composition of reactants and products have been used to analyze the fuels. The stoichiometric air-to-fuel ratio is 14.78 for aviation gasoline and 8.95 for ethanol. However, the stoichiometric ratio is not the best situation for aircraft engines. They always operate in full rich mixture conditions at takeoff and near-stoichiometry in the cruise condition. They do not work properly in the lean burn condition (Gomes et al.,2005).

In Fig. 3, it showed the engine fuel consumption versus manifold pressure. It is possible to observe that ethanol consumption is higher, mainly due to the smaller calorific power of ethanol compared to gasoline. But if ethanol had the same efficiency, 40% more fuel would have been spent, instead of the 25% more shown in the plot considering manifold pressure greater than or equal 25 inHg (typical values in flight condition). Therefore, it can conclude that ethanol has higher efficiency on the test conditions.

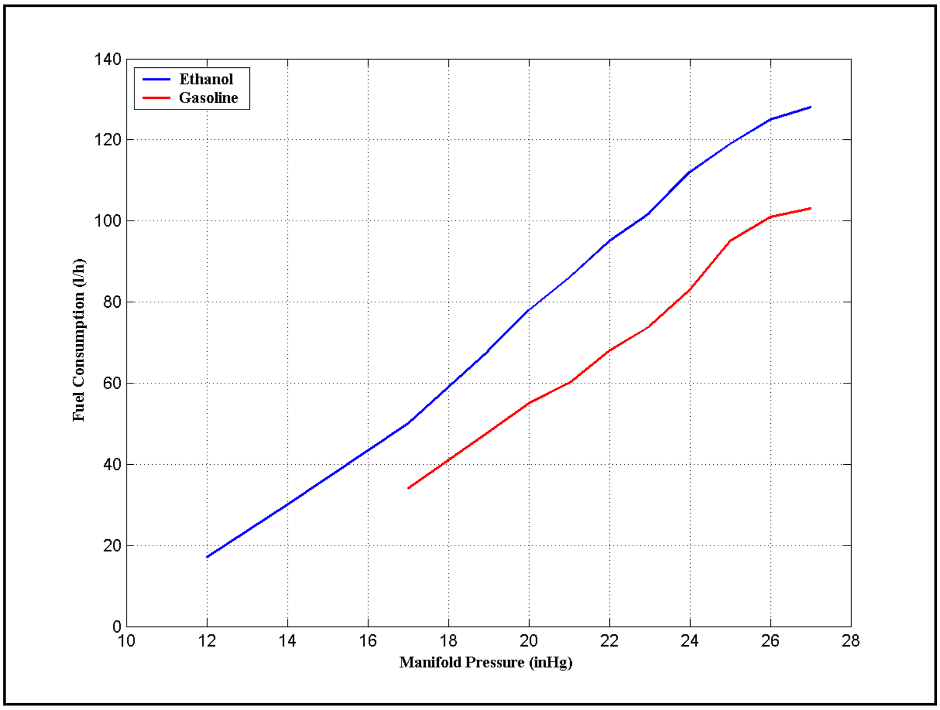

Figure 3 - Fuel Consumption versus Manifold Pressure (Costa et al., 2007)

Figure 4 shows the ecological efficiency values for different blends of aviation gasoline and ethanol for the takeoff condition. It is conclude that the ecological efficiency increases with increasing concentration of ethanol in the mixture, because the ethanol increases thermal efficiency and improves the combustion process. Furthermore, ethanol does not produce sulphur dioxides for burning and theoretically it produces less nitrogen dioxide because engine operates at lower temperatures.

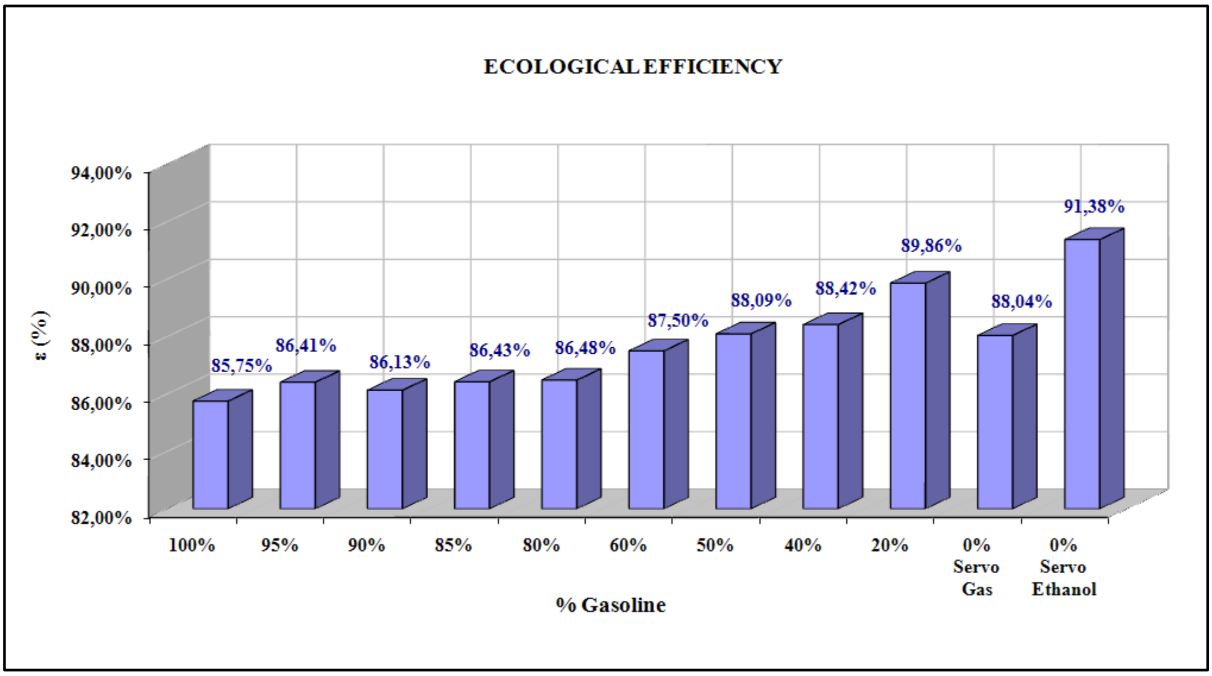

Figure 4 - Ecological efficiency for takeoff condition

Figure 5 shows ecological efficient for cruise flight condition. Like on the takeoff condition, the ecological efficiency increases when aviation gasoline concentration decreases. It can also be noted that ecological efficiency with 100% of ethanol is higher in both conditions with the fuel injector servo changed for ethanol application, because the injector servo for ethanol allows increasing the fuel quantity and consequently it is possible to get richer burns. When the engine was operated with 100% of ethanol with the original fuel injector servo it worked in the combustion limits.

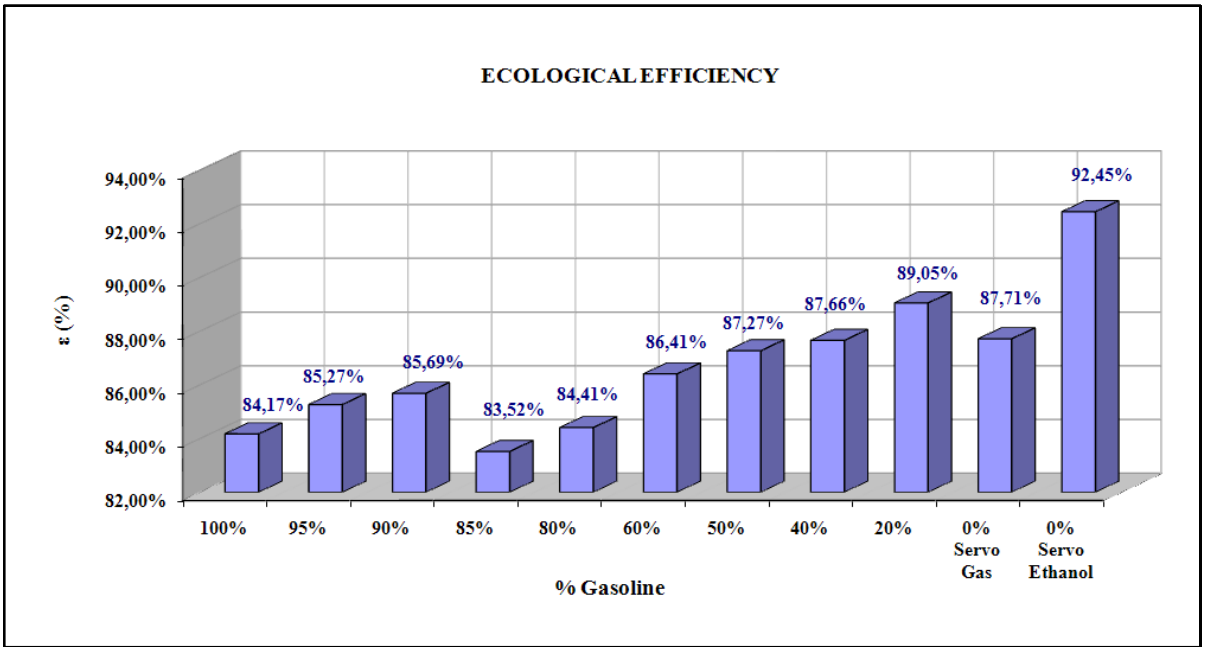

Figure 5 - Ecological efficiency for 10,000 ft cruise flight condition

Another important point about ethanol use is the carbon cycle, which in this case is negative; it means that ethanol absorbs more CO_2 from atmosphere than produces. This fact decreases the environmental problems as greenhouse effect (GHG) about 90%, while the USA ethanol decreases about 30% (BALL STATE UNIVERSITY, 2010). If carbon cycle is considered the ethanol ecological efficiency will be increased.

6. CONCLUSIONS

The main conclusions of this work are listed below.

1. This work shows that it is possible to evaluate the environmental impact by aeronautical internal combustion engines through experiments using ecological efficiency parameters. The influence of aviation gasoline and ethanol blends in the environment is studied, concluding that the use of ethanol or its blend with aviation gasoline represents an excellent option from the ecological point of view.

2. Ethanol combustion is more efficient than gasoline. For the same power output, the engine running on ethanol consumed only 25% more fuel than when running on gasoline. Due to ethanol lower calorific value (about 40% lesser), one could expect such increase in fuel consumption.

3. The need for more energy and rising greenhouse gases poses a dual challenge to global prosperity. Ethanol produces lesser emissions and this fact makes the process less harmful to the environment.

4. In terms of ecological efficiencies, according to the analyzed fuels, gasoline and ethanol have respectively 91.4% and 85.8% efficiency in takeoff condition and 84.2% and 92.4% in cruise flight condition. The study shows that the use of ethanol as alternative fuel, from an ecological point of view, is better than gasoline, showing the highest values of ecological efficiency.

This work did not consider the carbon life cycle. Certainly, ecological efficiency will be increased if considering this aspect.

7. ACKNOWLEDGEMENT

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