EXPERIMENTAL INVESTIGATION OF SPRAYS' CHARACTERISTICS USING GASOLINE-ETHANOL BLENDS AS FUEL FOR AERONAUTICAL ENGINES

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Abstract. This work presents a proposal of experimental investigation of sprays' characteristics for combustion of aeronautical engines using gasoline-ethanol blends as fuel, in order to reduce general aviation operational costs and damages to the environment. In order to reach this aim it is necessary to study combustion process, mainly the atomization of sprays. The injection process is critical in combustion process because it needs to have high energetic efficiency and control particulate material emissions. Controlling correctly responsible parameters for performance is an effective way to obtain high energetic efficiency and a clean combustion. Here are showed three different methods to analyze the characteristics of sprays and how these characteristics can affect the combustion process. These methods are: Planar Laser Induced Fluoresce, Spread of Drop and Particle Image Velocimetry. In the final step 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. Finally, the conventional gasoline, considering a same thermal efficiency of 30%, presents an ecological efficiency of 0,824 and the alcohol presents an ecological efficiency of 0,895.
Keywords: Aeronautic Combustion Engines, Particle Image Velocimetry, Laser Induced Fluorescence, Ecological Efficiency.

1. INTRODUCTION

Nowadays, the world is realizing the importance of the global warming problem and consequently more and more people are working in order to reduce environment emissions. The world is more worried about the future availability of energy resources. Today is necessary to get new and less pollutant sources like alcohols such as ethanol. Ethanol can be produced from natural source like sugar cane in Brazil and corn in the United States. In Brazil it is already one realistic alternative fuel. There are cars using alcohols in Brazil since 1979.

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. When the piston moves up, it compresses the air-fuel mixture, raising its temperature. If 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. On the other hand, ethanol has the corrosion problem on the mechanical components, especially for components made of copper, brass or aluminum. This is consequence of its complete miscibility with water in all proportions, while the gasoline and water are immiscible. Additionally, alcohol can react with most rubber and create jam in the fuel pipe.

Until now, there is not any bi-fuel aircraft in the world. The main goal of this work is to suggest and show some diagnostics techniques to develop the study to convert an internal combustion engine used in aircrafts in a bi-fuel engine. The Lycoming O-360-A engine will be able to operate with aviation gasoline (Avgas) and alcohol maintaining same configuration.

1.1 Internal Combustion Engine's Characteristics

Preliminary considerations are shown by Pontoppidan et al (2005). The Lycoming O-360-A series engines are horizontally opposed four-cylinder, direct-drive, air-cooled 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 Data Sheet, 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 constant all mechanical characteristics of engine. This means that will be utilized the same configuration of the original gasoline model including compression ratio. Some details like the cold-start procedure, which is critical for ethanol fuel, will be discussed. In current benchmark work is utilized, similar to automobiles, a little gasoline tank for starting the engine. In this work is presented some diagnostics techniques whose goal is to 'zoom' to injection process and the final intention is help with some insights to improvement injections technology.

The injectors that will be used in the FLEX engine's development will be mounted out in order to be tested and studied. Injectors are being developed by Magneti Marelli Brazil.

2. EXPERIMENTAL TECHNIQUES

Understanding of fuel injector sprays by measuring spray cone angle, drop size, fuel velocity, and mass flux will provide combustor designers with information about fuel sprays and fuel-air mixing, enabling designers to place the fuel-air charge in the appropriate region in the combustor for low-emissions and improved combustor performance.

Basically, there are two kinds of diagnostics techniques when it is necessary experimental studies. They are intrusive and non-intrusive diagnostics techniques. In general, intrusive are cheaper and does not demand much expertise regarding non-intrusive techniques. Meanwhile it presents minor temporal and spatial resolution. Non-intrusive techniques have several advantages, but they depend on largely of the quality of the DOE (Design of Experiment), the precise knowledge and control of boundary conditions as well as the physical process to be monitored (Particle sizing, velocimetry, mixture process or combustion). It needs much more financial resources and researchers with a lot of experience.

It is an unquestionable fact that non- intrusive diagnostics techniques are powerful tools to analysis combustion process. In particular, engine stroke process presents a great challenge. There are several simultaneous phenomena which occur in critical conditions.

Configuration system design for some experimental studies where is possible to study whole process, including each detail, is very difficult to build. In some cases it is almost impossible and many times it is necessary some approximations.

Three non- intrusive diagnostic techniques will be utilized in this study and the results will be compared with "macro" engine behavior. Macro map include performance and gas emissions measurements which will be obtained in benchmark test. Brief description about this benchmark will be made in another section.

Each one of diagnostics techniques with their goals are described in this work. They are: Particle Image Velocimetry (PIV) data lead to velocity field; Planar Laser Induced Fluorescence (PLIF) of acetone tracers will be used in order to provide additional data about mixing process and Malver Laser which will be utilized in order to obtain droplet profile.

2.1. Particle Image Velocimetry

PIV is used in measuring the velocity field of particles in a plane of the flow. A pulsed laser and suited optics are used to create a planar laser sheet through the flow. There is an example in Figure 1. The seeded flow particles are then illuminated by the high energy laser pulse and a high-speed camera records their position at that time. After a selected amount of time, another laser sheet is produced by a second pulse and the particle's positions are once again recorded by the camera. This allows one to determine the distance and direction that each particle traveled during the time between pulses.

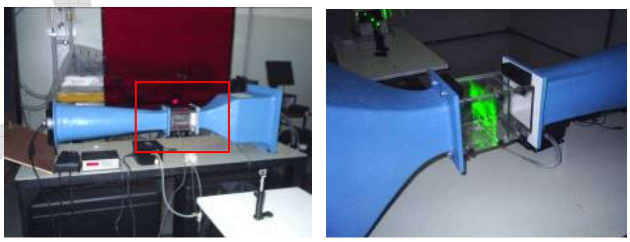

Figure 1- Laser Sheet

This technique is well used for fuel sprays and its limitations are those of spray density and the quality of optical access to the area into which a spray penetrates. The wide windows one each side of the domain associated with the upper and lower narrow windows are well adapted to Particle Image Velocimetry measurements. This non-intrusive technique allows getting instantaneous velocity fields. Nowadays, the digital technology is the most significant way of progress for PIV as well as upgrade in camera acquisition rate, in the dynamic range or in pixels number. The technique used in this study to process the data is cross correlation.

2.2. Planar Laser Induced Fluorescence

Planar Laser Fluoresce (PLIF) will be utilized to provide data about mixing which lead to detection some inhomogeneous distribution of the jet fluid in the chamber. Richie et al (2000) for example utilized PLIF for mixing in coaxial jets. PLIF is suited for measuring mixing due to it yields bi-dimensional images of the flow field. Laser beam at one appropriate wavelength is chosen and optically converted to a thin laser sheet that provokes to fluorescence to certain molecules in the flow field. Resulting fluorescence is proportional to the amount of the absorbing species in the measurement volume. In this technique a seeded gas containing acetone as a tracer fluoresce when laser light shot it, became, in this way, one gas mixture visible for ICCD camera.

A schematic of experimental setup is shown in Figure 2. A Cooke DICAM-PRO intensified charge -couple - device camera will be used with a Sirah pulsed dye-laser pumped by a Quantum-Ray Nd:YAG laser. Light from the Nd:YAG laser at a wavelength of 1064 nm passes through a frequency-doubling crystal producing 532 nm light which pumps the dye laser operated with Rhodamine 6G in ethanol. The camera has 14 bit dynamic range, 1024 x 1248 pixel resolutions.

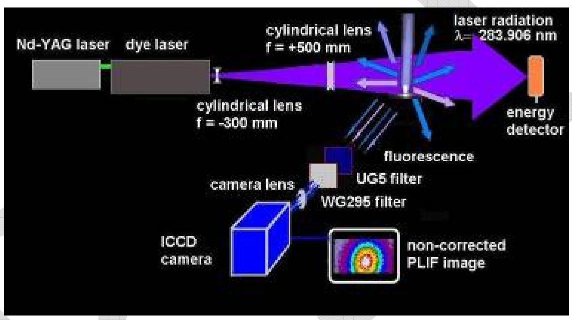

Figure 2 - Experimental Setup for PLIF measurements

Gaseous acetone has been used for the concentration measurement by PLIF to track the mixing process between jet and air during the injection and the compression stroke. The idea is, also, to use acetone. The results of these experiments show relationship between fuel-air.

The importance of fuel-air mixture behavior is that poor mixture can be responsible to thermal stratification which is favorable to nitrogen oxides formation or even lead to high level of unburned hydrocarbon emission.

This technique is very well adapted to this type analysis. The main problem is the complex layout of the optical access and because this is necessary to know properly how to use it. In a manifold or a combustion chamber this can often be a complex operation, which requires quite a bit of experience in engine experiments.

2.3. Malver Laser

The Malvern Masteries is a non-intrusive technique designed for measurements of sprays. It uses a Frauenhofer diffraction approach, which through statistical computation indicates probable series of diameter families. When the laser passes throughout a spray many lights and darks circles with the same origin will appear. The distance among the circles depends on the size drops. Malvern basically consists of a laser, a light sheet projector, camera, frame grabber, timing controller, computer, and data acquisition, analysis, and visualization software. This technique can be used to determine parameters such as the Sauter mean diameter (SMD). A Malver Master Size system is showed in Figure 3:

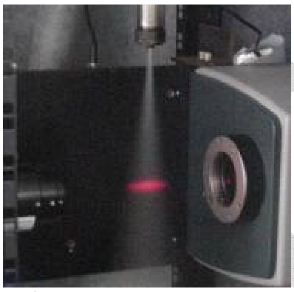

Figure 3 - Malver Master size System

One of the simplest tests to characterize a fuel injector spray is to collect data using the Malvern drop size equipment. Recently, Chin et al. (1996) used a Malvern to characterize the effect of spray performance from dual circuit spray interactions. They found that a beneficial spray interaction could be achieved by careful selection of the atomizer geometry and features. Pilot and main spray interactions can aid in reducing spray SMD values, indicating that Malvern is a useful tool for use in fuel injector characterization and development.

2. PERFORMANCE AND GAS ANALYSIS

In order to complement injection process evaluation, the injectors, already characterized, will be mounted in engine cylinders and will be obtained experimentally the engine performance and pollutant emission data using ethanol–gasoline blended fuels with various blend rates (0%, 25%, 50%, 75%, and 100%).

In this part it is necessary a suitable benchmark which should include gas analyzers, temperature, pressure, torque and engine speed sensors, and so on. With the current benchmark, which is in operation, is possible to obtain cylinder head temperatures, engine speed, fuel consumption and exhaust temperatures. In next months will be implemented torque and gas analysis measurements. Figure 4 presents benchmark with a Lycoming IO-540 engine.

Figure 4 - Lycoming IO-540 engine mounted in test benchmark

Another ethanol advantage is lower engine temperature operation. Aircraft pilots have serious preoccupations about this parameter and one of the methods of controlling the temperature is with mixture control. If some engines run at high performance levels for long periods of time they tend to overheat, which could lead to rough operation or sudden failure. Maximum heat is produced by optimal (stoichiometric) mixture, but in certain situations it is necessary to run with richer mixtures, in order to cool the motor. For ethanol fuel, cylinder head and exhaust gas operation temperatures are usually smaller (or minor) than with gasoline. Cylinder head temperatures should not exceed 260º C (533K), cooling oil temperatures usually become critical at 120º C (~390K) and the exhaust temperature should not exceed 900º C (1173K).

2. PRELIMINARIES RESULTS

It was studied an internal combustion Lycoming IO-540-K1D5 engine model in order to analyze its performance using alcohol and aviation gasoline as fuels [Ewald and Vasconcellos, 2006]. This engine was chosen because it is used in training aircraft in Brazilian Air Force. These results can support the FLEX aeronautic engine's studies.

It was acquired data on performance engine operating with aviation gasoline and further with alcohol. Gasoline engine starting procedures were used because these were the reference. A windmill was used to control the rotation engine and to consume its power. Engine speeds adjusted were 2680, 2550, 2350, 2200, 2000 and 1800 rpm and parameters analyzed were engine speed, cylinder head and exhaust temperatures, fuel consumption and intake manifold pressure. Figure 5 indicates that maximum engine speed is 100 rpm higher with alcohol than with gasoline, keeping higher along the speed range. It means that alcohol supply more power because stabilized rotation is got when engine power has the same value than windmill power.

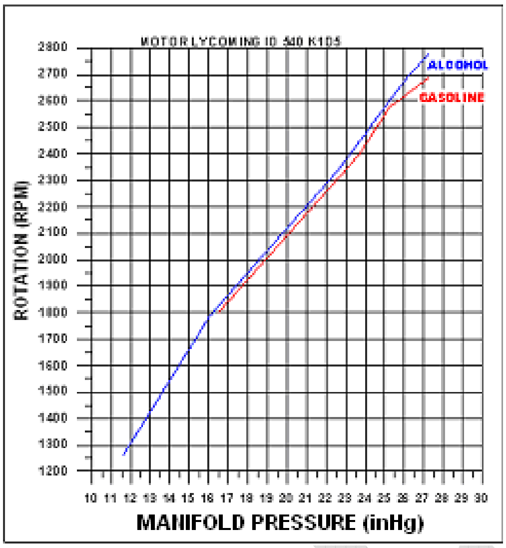

Figure 5 – Rotation versus Manifold Pressure

In Figure 6 is showed engine fuel consumption versus manifold pressure and it is possible to observe that alcohol consumption is higher. This was expected because alcohol has smaller calorific power than gasoline. It was concluded that alcohol has higher efficiency. If alcohol had the same efficiency it would be spent 40% more than gasoline and in plot it is presented only 25% more.

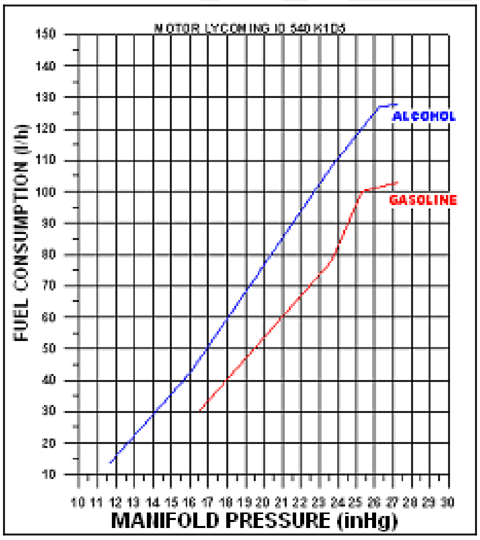

Figure 6 – Fuel Consumption versus Manifold Pressure

Alcohol causes smaller thermal stress to engine than gasoline because the cylinder temperature is 20ºC lowers than gasoline operation. This fact can be confirmed by Figure 7.

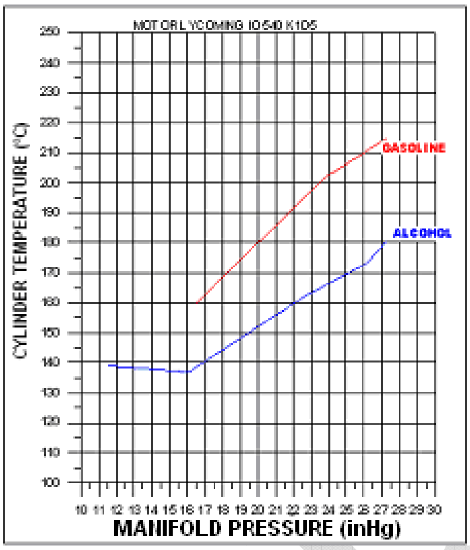

Figure 7 – Cylinder temperature versus Manifold Pressure

It is possible to note in Figure 8 that exhaust temperature, when the engine operates with alcohol, is higher than when it operates with gasoline for higher rotations and higher manifold pressures. Probably, it happened because the engine's ignition timing was not changed and the alcohol's combustion velocity is slower. In this way the combustion time may not have been suitable. Furthermore, the air fuel-ratio may have become near of stoiciometric at these points, without extra fuel for internally cooling the engine. Nevertheless this parameter is less important than critical cylinder temperature.

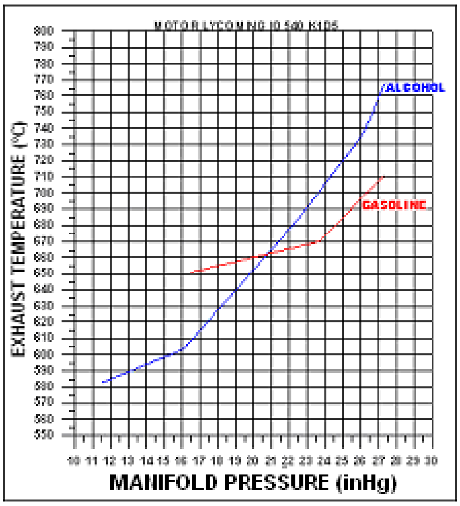

Figure 8 – Exhaust temperature versus Manifold Pressure

3. THE CARBON DIOXIDE EQUIVALENT

The coefficient for the equivalent carbon dioxide $(CO_2)_e$ hypothetical pollutant concentrations calculation is determined [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 NOx, SO_2 and PM in hour. Thus, the expression for the $(CO_2)_e$ is:

$(CO_2)_e = (CO_2) + 80\ (SO_2) + 50\ (NOx) + 67\ (PM).$ (1)

In the Eq. (1), $(SO_2)_e$ = 80(SO_2) is the sulphuric dioxide equivalent in (CO_2), (NOx)e= 50(NOx) 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 as it follows.

$$\prod_g = \frac{(CO_2)_e}{Q_i} \qquad (2)$$

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

4. ECOLOGICAL EFFICIENCY

Ecological efficiency is defined as an indicator which allows the evaluation of the thermoelectric power plants gaseous 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. According to [Cardu and Baica, 1999] and [Villela and Silveira, 2007], the ecologic efficiency may be estimated as:

$$\varepsilon = \left[\frac{0{,}204\, n}{n + \prod_g} Ln\left(135 - \prod_g\right)\right]^{0{,}5} \qquad (3)$$

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. Value ε is directly proportional to thermoelectric power plant efficiency (η) inversely proportional to ($\prod_g$), pollutant indicator value, and also alternates between 0 and 1, similarly to thermoelectric efficiency. The situation is considered unsatisfactory of the ecological point of view when ε = 0, but when ε = 1 indicates an ideal situation.

6.1. Gasoline and Alcohol

The gasoline is a fuel constituted basically by hydrocarbons and, in fewer amounts by oxygenized products. These hydrocarbons are, in general, less heavy fuels than those that composes the diesel fuel formed by molecules of small carbonic chains (normally has 4 the 12 carbon atoms). Beyond the hydrocarbons and the oxygenized ones, the gasoline contains sulphur composites, nitrogen composites and metallic composites, all these with low concentrations. [Brazilian Petrol, 2007].

The chemical formula of the aviation gasoline used in this work is approximately 65% of Iso-octane, 20% of iso-pentane and 0,15 of toluene; its density is 740 kg/m^3 [Brazilian Energetic Balance, 2006]. The equation for normalized air excess α follows.

$0{,}65C_8H_{18} + 0{,}2C_7H_8 + 0{,}15C_5H_{12} + 12{,}5\alpha O_2 + 47\alpha\ N_2 \rightarrow\ 8CO_2 + 9H_2O + 47\alpha\ N_2 + 12{,}5(\alpha-1)O_2$ (4)

By adopting the gasoline burning, with 100% air excess, after the stoichiometric balance, a percentage in mass of each compound resulting from this reaction is: 9.263% CO_2, 3.893% H_2O, 75.387% N_2 and 11.457% O_2.[Coronado *et al*, 2007].

Making reference to Resolution nº 35 of the ANP - Brazil, the alcohol ethylic in anhydrous state, is miscible in 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 alcohol is C_2H_5OH and its density is 0.79 t/m^3 , from its stoichiometric combustion reaction, the result is: 88g CO_2 for 46g alcohol, in consequence: 1.511 ton of CO_2 for m^3 of alcohol.

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

By adopting the alcohol burning, with 100% air excess, after the stoichiometric balance, a percentage in mass of each compound resulting from this reaction is: 10.12% CO_2, 6.21% H_2O, 72.63% N_2 and 11.04% O_2 [Coronado *et al*, 2007]

7. TOXICITY IN INTERNAL COMBUSTION ENGINES (Gasoline and Alcohol)

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 (NOx), hydrocarbons (CxHy), aldehydes (RxCHO), 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 2,8kg/h CO. In general, when 1kg of gasoline is burnt, it release between 300 and 310 toxic components, specifically: 225g of CO, 55g NOx, 20g of HC, 1,5 to 2g of SO, 0,8 to 1g of aldehydes, 1 to 1,5g of soot [Patrakhaltsev at al, 1994]. According to [Carvalho and Lacava, 2003] the PM emissions of gasoline fuel for internal combustion engines is 1,44 kg/m^3. 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 NOx according to CETESB (Environmental Cleaning up Technology Brazilian Company) is approximately 0,8 kg/m^3.

8. ECOLOGICAL EFFICIENT CALCULATION

Table 2 shows a comparison between the gasoline and alcohol for internal combustion engines. Then Figure 9 show the ecological efficient values for the two fuels analyzed and finally, Figure 10 shows the ecological efficient values

Table 2 - Comparison of the results of pollutant emissions between the fuels analysed in internal combustion engines

Pollutant emission Kg/kg of fuel	Aviation Gasoline	Alcohol	Gasoline / Alcohol
CO_{2e}	6,1710	1,9688	3,13 times
PM	$1,945.10^{-3}$	-	-
NOx	55.10^{-3}	$1,1163.10^{-3}$	49,27 times

SO_2	2.10^{-3}	-	-
CO_2	3,1306	1,9130	1,63 times
Total (kg/kg of fuel.)	3,1876	1,9141	1,66 times
Ecological Efficiency (%)	82,43	89,51	-

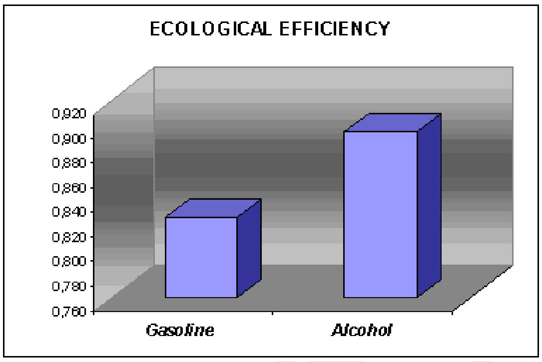

Figure 9 - Gasoline and alcohol ecological efficiency

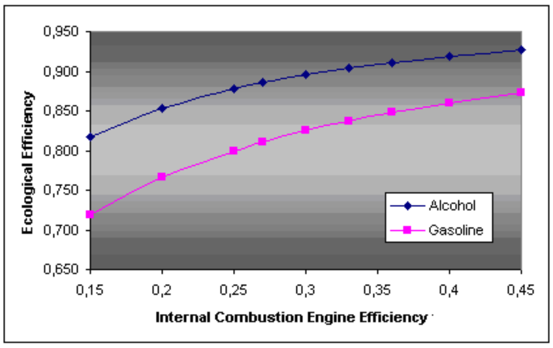

Figure 10 - Ecological efficiency variation in function of internal combustion engines efficiency.

9. CONCLUSIONS

The preliminary studies showed many advantages in fueling internal combustion engines with alcohols. These advantages support the bi-fuel aeronautic engines' researches. They are:

- Alcohol engines are more efficient than gasolines ones. For the same power output, the engine running on alcohol consumed only 25% more fuel than when running on gasoline. Due to alcohol lower calorific value (about 40% lesser), one could expect such increase in fuel consumption.
- Engines will operate more distant of their temperatures limits and this fact will reduce the temperature stress in cylinder heads. The temperature in cylinder heads is a critical operation parameter in this kind of motor.
- The need for more energy and rising greenhouse gases pose a dual challenge to global prosperity. Alcohol produces lesser emissions and this fact makes the process more harmless to the environment.
- The diagnostic techniques showed allow studying the fuel injection process properly aiding designers to obtain the most feasibility project.

- In terms about ecological efficiencies, according to the analyzed fuels; gasoline and alcohol are respectively 82,43 % and 89,51 %. The studies show that the alcohol use as alternative fuel, from an ecological point of view, is better that gasoline fuel, showing the highest values of ecological efficiency. Another evaluation will be presented in another paper because it depends on a new experimental test that is in execution.

In this way, this work will give technical support for flexible-fuel aeronautic engine researches and will be able to aid to design the engine injectors in the correct way. It means to improve its design and performance.

10. COPYRIGHTS

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