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Performance analyses of a spark-ignition engine firing with gasoline–butanol blends at partial load operation

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ABSTRACT

Biofuels seem to represent one of the most promising means for the limitation of the greenhouse gas emissions coming from traditional energy systems.

In this paper, the performance of a "downsized" spark-ignition engine, fueled by gasoline and bio-butanol blends (20% and 40% butanol mass percentage), has been analyzed.

In the first phase of this activity, the experimental tests have been carried out at operating points ranging from low to medium engine speed and load.

The first investigations were aimed to assess the main differences among the different fuels in terms of output torque, thermal efficiency, combustion duration and optimal spark timing. In order to study the engine behavior in a wide range of fuel mixtures, these parameters have been evaluated for equivalence ratio values ranging from 1.25 to 0.83.

The results obtained in this step show that both the engine torque and thermal efficiency slightly decrease (meanly about 4%) when the blend alcohol content increases. However, butanol increases the burning rate of lean mixtures and an interesting result is that the spark advance does not require adjustments when fueling changes from neat gasoline to bio-butanol/gasoline blends.

Later, the pollutant emissions and the CO_2 emissions, for both rich and lean mixtures of pure gasoline and gasoline bio-butanol blends, have been measured. In general, firing with alcohol blends, NO_x and CO emissions remain quite the same, HC emissions slightly decrease while the CO_2 emissions slightly increase.

At the end, in order to reproduce the real world urban driving cycle, stoichiometric mixtures have been analyzed. In these conditions, the engine thermal efficiency, at given speed and torque, has been evaluated for each kind of fueling. The results obtained in these operating points have shown that the alcohol blend fueling performs an efficiency penalty less than 2 percent.

1. Introduction

The gradual depletion of fossil fuels and the problems related to the climate change have led to an increased interest in the use of the so-called biofuels. In recent years, the transportation sector has rapidly grown with a consequent increase in energy consumptions. In the European Union it is expected that in 2030 the use of energy for transportation will be higher by about 50% compared to that of 2007. Naturally, this circumstance could have negative consequences in terms of environmental impact as announced in the General Plan of Transportation [1]. Among the measures to improve the environment quality, the possibility of replacing traditional fossil fuels with those of biological origin has been considered. The latter usage may be exclusive, in specially designed engines, or they can be added to fossil fuels so that, with appropriate precautions, they could fuel engines normally in circulation.

Bio-alcohols are compounds obtained from specific agricultural productions or from plant residues and organic waste. They have a high interest because: they have very low sulfur content, are biodegradable and are obtained from renewable sources such as biomasses [2]. Everyone knows that biofuels reduce the dependence on fossil fuels, so they represent a source of renewable energy and a means for the CO_2 emission control. Further benefits are:

- decentralization of production so as to eliminate the problem of monopolies, price cartels, control of supplies;
- exploitation of unproductive land;

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- resource utilization as abandoned factories or other facilities adapted for the production of biofuels;
- job creation.

At the end, a widespread use of biofuels could limit those conflicts arising from the ownership and the management of oil fields.

However, the increasing production of biofuels could have a positive or negative impact on the environment depending on the rules that will be introduced in the context of ecology. Using such traditional production methods, as cultivations with fertilizers derived from fossil fuels, then it is possible to get more harm than benefit; emissions of greenhouse gases could even increase rather than decrease [3].

In order to avoid the competition between biofuel production and food production, thanks to the action of the Committee on World Food Security, the European Parliament has placed a limit to the use of first generation biofuels in the European Union. The 'traditional' biofuels should not exceed 6% of final energy consumption by 2020, compared to 10% of the previous legislation, and has received a new target of 2.5%, again for 2020, for second-generation biofuels [4].

Talking about spark ignition engines, the most used biofuel is ethanol: in some countries such as Brazil, it is possible to drive flexible fuel cars, able to run on any blend of ethanol and gasoline, up to neat ethanol (E100) refined from sugar cane and sugar beets; in North America, ethanol is sold in blends up to 85% Ethanol, 15% Gasoline [5]. Now, focus is also addressed to methanol [6], and butanol [7–12]. A lot of countries have the opportunity to produce some kinds of bio-alcohols. As a consequence, a lot of countries have to adapt engines to run on gasoline–alcohol blends.

From an engineering point of view, the adaptation of an engine to run on mixtures of alcohol–gasoline requires efforts on both the design and development to achieve a satisfactory durability and a robust calibration. Since standard fuel system components of gasoline engines are not designed to resist alcohol's corrosive properties, some particular components must be appositely designed. Furthermore, their thermochemical properties differ from those of gasoline so an enhanced calibration strategy could be necessary to run the engine under the best possible conditions.

Taking this into account, butanol seems to have a very interesting potential because its properties are very similar to those of gasoline. This can reduce the efforts that Original Equipment Manufacturers are doing to adapt their current range of vehicles to be able to run on gasoline/bio-alcohol blends.

In the following, the performance, emissions and combustion modes of a spark-ignition engine fueled by butanol/gasoline blends are deeply investigated.

2. Biobutanol

The Biobutanol is chemically produced by the fermentation of various biomasses through many microorganisms of the genus Clostridium. The raw material is just the same used for the production of other biofuels, namely beets, wheat and corn in temperate climates, sugar cane and manioc roots in tropical climates. Also straw, hay and residues of agricultural production can be used [13].

The process currently used has some defects related to the characteristics of the Clostridium used. These microorganisms are obligate anaerobes and cause the inability to inject air into the bioreactor from the outside. They produce butanol during the phase of sporification where their vital functions are temporarily suspended. This is caused just by the presence of the butanol. Therefore these microorganisms are not able to support an industrial production. Some researchers have thought of introducing this metabolic pathway in other organisms most known and industrially used, such as Escherichia coli, using genetic engineering techniques, and metabolic proteins. Thus, the genes encoding the enzymes involved in the synthesis of biobutanol were transferred to new more efficient microorganisms. However, also in this case the production is very low. In recent years, a process (Environmental Energy, Inc.) has been developed, in which two bacteria in series (Clostridium-Acetobutilicum and Clostridium-Tirobutiricum) [14] are used with the effect of doubling the productivity of biobutanol. From one m^3 of corn are obtained 260–270 liters of biobutanol (equal to about 30% by weight) more or less as for bioethanol. The cost of production of biobutanol process of the Environmental Energy, Inc. is slightly lower than that of bioethanol. This cost can be further lowered considering that the process is accomplished together with the formation of such byproducts as hydrogen and ethanol [15–17].

Butanol's chemical formula is C_4H_9OH. It occurs in four isometric structures: from a straight-chain primary alcohol to a branched-chain tertiary alcohol. Generally, the simple term butanol refers to the isomer with a linear chain in which the OH functional group is terminal with respect to the straight-chain primary alcohol. This isomeric form is known as *n*-butanol or 1-butanol. In the following, using the unmodified term butanol we intend to refer to the *n*-butanol.

3. Fuel properties of biobutanol

Table 1 compares the main properties of gasoline and some alcohols. Among alcohols, butanol has a higher energy contents both per mass unit and per volume unit. The heat released per volume unit by a stoichiometric air to fuel mixture is quite similar

Table 1
Comparison of fuel properties. Some properties have been derived from Ref. [18,19]. Both the energy released per mixture volume unit and the carbon dioxide produced per heat unit have been calculated considering the complete oxidation of a stoichiometric air–fuel mixture.

		Gasoline	Methanol	Ethanol	Butanol
Lower heating value	(MJ/kg)	43.5	19.7	26.8	32
Density ($T = 20$ °C)	(kg/dm^3)	0.720–0.750	0.790	0.800	0.810
Latent heat of vaporization	(kJ/dm^3)	223	932	723	474
Air to fuel ratio	(kg/kg)	14.6	6.4	9	11.1
Octane Number	(–)	91–99	106	107	96
Stoichiometric laminar flame speed at $p = 1.01$ bar; $T = 25$ °C	(cm/s)	28.9	40.4	35.7	32.7
Solubility in water	(% vol)	About 0.0	100	100	7.7
Vapor pressure	(bar)	0.55–1.03	0.32	0.16	0.01–0.05
Explosive limits	(% vol)	1.4–7.6	7.3–36	4.3–19	1.4–11.3
Energetic density	(MJ/m^3)	32,000	16,000	19,600	29,200
CO_2 producer per heat released unit	(kg/kJ)	7.28E–05	6.97E–05	7.13E–5	6.60E–05
Energy per volume unit of air/fuel mixture ($p = 1.01$ bar; $T = 25$ °C)	(MJ/m^3)	3.5	3.16	3.30	3.27