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Optimization of engine performance for ethanol consumption

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Abstract:

Ethanol is a fuel obtained from vegetable by-products becoming a promising substitute for gasoline in internal combustion engines. It is obtained by plants, which convert carbon dioxide into oxygen through photosynthesis, what implies that the carbon dioxide cycle is very short, since that the CO₂ released by combustion can be withdrawn from the atmosphere on ethanol production. This is absolutely contrary to the fossil fuels consumption, which introduce carbon dioxide into the atmosphere that will only be taken off in billions of years cycle.

The incentive for the present work had the genesis in the Student Formula team of the Polytechnic Institute of Leiria (FSIPLeia) which has interest in get the advantages and disadvantages of the use of ethanol (E85) as fuel in the development of the next car prototype. The basis of this work is to optimize the engine of the FSIPLeia team to run with ethanol. To attain this objective, it was used software to model the engine and to compare the final result with the experimental tests developed in order to obtain the validation of that model. This allow to find the best engine parameterization in order to get the best of it when he was fueled with E85, a mixture of 85% of ethanol and 15% of petrol.

Taking into account the objectives of the team FSIPLeia, a computational model using Ricardo Wave based on gasoline was developed to simulate the behavior of the engine and later study not only the influence of the ethanol but also other parameters that was necessary in view of the optimization of the engine when fueled by E85. Together with the software modeling, an experimental set-up was established to acquire data from the gsxr-600 engine under study in a chassis dynamometer, in order to validate the developed model and make able to draw conclusions about the use of ethanol as fuel.

It was possible to develop software models with a relative error below 10% of the initial objective. A torque curve with a maximum deviation of 6.2% in the gasoline model and 8.5% in the model E85 was obtained, in relation to the experimental tests.

Regarding the optimization process, it was possible to evaluate the effects of the increased compression ratio and the ignition timing, which revealed that it will be possible to obtain an increase in engine performance with the use of ethanol by correct adjustment of these parameters.

Keywords:

Ethanol, Internal Combustion Engines, Engine Performance, fuel consumption, biofuels, Formula Student.

1. Introduction

Since the beginning of the automobile expansion the dominant fuels have been of fossil origin, whose by-products such as gasoline and diesel dominate the sector, due to the accessibility and financial competitiveness given by these fuels.

However, the fossil fuels present environmental problems and are a non-renewable source of energy which has increasingly force car manufacturers to seek solutions to mitigate these negative aspects. Alternative renewable fuels such as ethanol come into play, which from the theoretical point of view can either be used as an alternative to petrol in positive-ignition engines or used in a small percentage in compression-ignition engines, operating as an agent acting as an improve of fuel properties and consequently increasing the combustion efficiency. These capabilities can even lead these fuels to be used as an alternative energy source in competitions worldwide such as Formula1, FIA World Endurance Championship and FIA World Rally Championship. On the other hand, competitions such as the World Time Attack Challenge have in recent years an increase in the number of participants running with high percentages of ethanol (E85 and E100) to fully exploit some of the characteristics of this renewable fuels, such as higher octane, higher laminar flame velocity and lower latent heat of vaporization.

Even considering the measures already taken to increase energetic efficiency use and to include other energy sources, the perspectives for a crescent need for energy are obvious. As it can be observed in figure 1, there are a clear trend for a growth in fossil fuels as petroleum and natural gas consumption but also in renewables and nuclear. It becomes evident that the renewable fuels can contribute to supply the energetic demands, reducing the needs for fossil fuels and becoming an important agent for decreasing greenhouse gases emissions. According with the EIA data presented in figure 1, renewables are the fastest growing energy source for the next 23 years (from 2017 to 2040).

Energy consumption increases over the projection for all fuels other than coal in the Reference case with renewables being the fastest-growing energy source

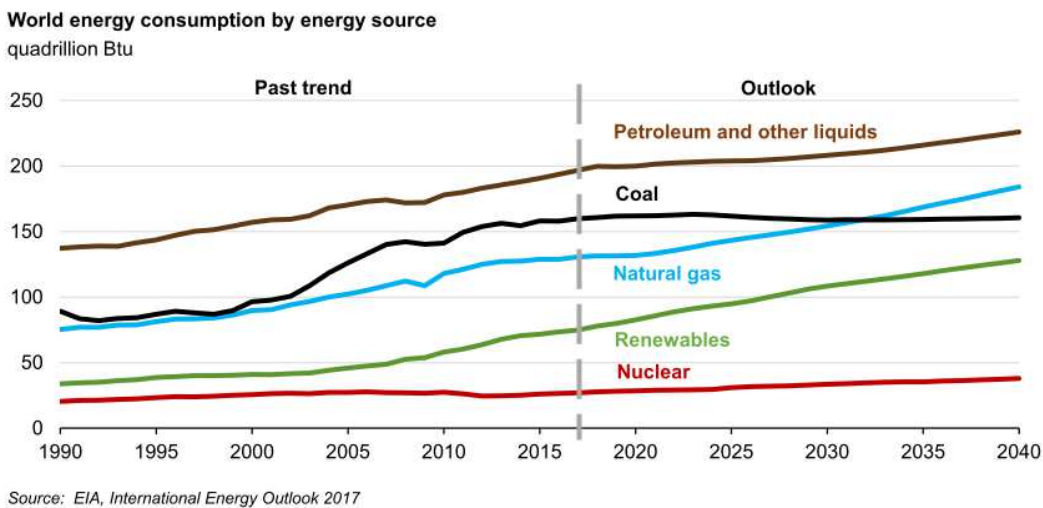


Fig. 1. – World Energy Consumption by Energy Source [1]

1.1. Objectives

The use of renewable energy sources is already taking an important role in electric production with wind and hydraulic revealing interesting results and presenting financial viability, but for vehicles, there are some important constrains and doubts. The purpose of this work was to study the

possibilities that overcome from using ethanol in an engine used for a competition named Formula Student.

Formula Student is one of the largest student sports events in the world and presents itself to many as the best world stage for the application of knowledge of future engineers, counting already with more than 100 thousand teams around the world. It is a competition where students show not only the fastest car but also prove the overall value of their construction, such as performance, sustainability, feasibility, production and market insertion plan. Thus, together with the encouragement of the organization, which heartens creativity in the engineering behind the development of the car, the Formula Student team at the Polytechnic Institute of Leiria was interested in testing the advantages and disadvantages of using ethanol (E85) as fuel in the development of the next prototype.

1.2. Research Procedure

To attain the objectives of this research work, the methodology used was based in a computation model through Ricardo Wave software that will simulate the behavior of the engine considering the use of gasoline. Together with the software modeling, an experimental set-up will be established to acquire data from the HONDA GSXR-600 engine, used in formula student vehicle, under study in a chassis dynamometer, to validate the developed model and be able to use this to draw conclusions regarding the possibilities of using ethanol as fuel.

In a subsequent phase the computer model was also altered to consider the use of ethanol, allowing not only the study about the influence of the fuel, validated through the results obtained in chassis dynamometer tests, but also to change the parameters in the scope of getting an optimization of the engine when fueled by E85.

2. Bibliographic Review

2.1. Biofuels for transport

The production of renewable fuels has been increasing in the last decades, increasing the offer of an alternative supply for the transport sector which dependence from liquid fossil fuels is huge, reaching almost 90% of all fuels used. Even considering this increase in the renewable fuels availability, due to the increase of fuel consumption, the share of energy has been almost stabilized. Considering all the energy consumed in the world, around 20% goes to the transport sector, and the perspectives are to notice an increase of this level, expecting to reach 40% by 2040 [2]. Two major groups of renewable fuels have been presented to the consumers, biodiesel and bio-alcohol. Biodiesel has been used in a great extent in compression ignition engines while bio-alcohols has been majority used in spark ignition engines. The most common bio-alcohols were ethanol and methanol which can be used in pure form or as a blend with conventional fuels, to act as a valid alternative solution for reducing the demand for crude oil.[3]. In particularly, in case of ethanol, it became established as an alternative fuel in 1970 due to the oil crises [3]. Nowadays there are a surge of several alternatives for vehicle propulsion, like hydrogen or electricity, but biofuels still present a valid solution which offers also several other positive impacts in employment and economy in a regional level, on markets that provide bigger incentives or higher production capacity. Even with the emergence of other solutions the use of biofuels in general and of bioethanol in particular, present an overall growing tendency, as can be proven by the expectations in the recent investments in advanced biofuels, due to policy energy mandates and financial de-risking measures for advanced biofuel plant investment, which point to limiting the life-cycle carbon intensity of transportation fuels [4].

2.2. Ethanol use in engines

Tacking in account the characteristics of the bio-alcohol to be used as a fuel for automobiles engines, several detaching properties should contribute for the selection of this type of renewable as energy source to supply vehicles.

First of all, the benefit of being renewable and high density of energy offered by this liquid fuel, which presents the advantage over the gaseous alternatives that need to be pressurized to be transported. Also, the fact that the fuel supply systems of common vehicles it is prepared by the series production for alcohol usage. The regular vehicles produced by the great majority of car manufactories allow to use moderate alcoholic mixtures, and the change for stronger mixtures are not extremely difficult. Additionally, transport and storage security are improved due to a higher auto-inflammation point [5-8]. Ethanol or other short chain alcohols can also be used in racing applications, where the conditions are more demanding [9].

The ethanol blend in gasoline allows the enlargement of the lean burn limit and offers the capability to improve the combustion process. The introduction of ethanol in the fuel endorses a lower combustion duration period and increase cylinder pressure and temperature. The increase of the percentage of ethanol in the blend with gasoline exposes the potential to increase brake power and thermal efficiency of the engines [10].

On weight basis, ethanol may contain about 35% oxygen, which makes it considered as a partially oxygenated fuel [11,12]. The existence of oxygen in the fuel molecule induces a cleaner combustion with lower particle emissions and nitrogen oxides formation, but also implies a lower amount of energy released and low air / fuel ratio when compared to gasoline [12,13]. Physical and chemical properties of ethanol and gasoline are similar but also some evident differences are noticeable, specifically the lower heating value (rounding 65% of the value of gasoline in a volumetric basis) leading to a growth in fuel consumption. Significant differences also of stoichiometric air/fuel ratios appear, once ethanol is 9.0:1 and gasoline 14.5:1, which reveals likewise an increase in fuel consumption, since for similar swept volumes the use of ethanol implies the need to use more fuel [14].

Other important differences between fuels properties should be noticed. The higher-octane number presented by ethanol and higher laminar flame speed. Both properties offer an improvement in combustion and thermal efficiency of the engine, which can become profitable by making the proper adjustments in engine. In a global perspective, the lower heating value of the fuel offered by the alcohol can be compensated by the amount of fuel and an increase on combustion efficiency which can justify a possible increase in torque and power in engines running with a blend of gasoline and ethanol. The existence of oxygen in the fuel, the higher density and the higher latent heat of vaporization permits to increase the amount of energy provided to the cylinder for each stroke, delivering more energy to the wheels. [15] This was substantiated by Thangavelu et al [16] that observed a significant improvement in engine torque, brake power and brake mean effective pressure with the use of bioethanol. There are clear indications that lower ethanol-gasoline blends could present a slight increase of the fuel consumption with a correspondent increase in torque output [16,18]. However, the costs for these achievements by using ethanol were a brake specific fuel consumption that is more pronounced for higher blends. The electronic control and effective adaptatively capacity offered by today's technology allow to use multi-blend rates of ethanol combined with real time adaptive process obtaining at all instant the optimum brake thermal efficiency for a given engine speed and position of intake throttle position enhancing the performance of engine torque, which is more pronounced at lower engine speed [19].

Resuming, ethanol has a lower calorific value than gasoline, which at first glance might lead one to think that ethanol decreases engine efficiency when replacing gasoline, but there are other attributes that play in favor of ethanol.

The fact that the stoichiometric combustion mixture of ethanol is 9 parts of air to 1 of fuel allows to compensate for the calorific power deficit by injecting more fuel for the same amount of air, in addition, the fact that the latent heat of vaporization is lower in ethanol, although it may cause problems in the cold start, it allows to cool the air during the admission, thus allowing more air to be admitted to the engine, increasing the amount of mechanical energy generated per cycle, by the effect of increasing the volumetric efficiency.

Another advantage of ethanol is its octane ratio, which, being higher than that of conventional gasoline, allows engine to work at higher compression ratios, with higher ignition feed and higher boost pressures.

As evidenced by reduced calorific power, an ethanol-fueled engine tends to consume a greater amount of fuel, however the use of adequate ignition advances, higher compression rates, and higher boost pressures may help to compensate for this effect, and since ethanol production has a positive energy yield and contributes to carbon sequestration, ethanol may prove to be more advantageous from the point of view of energy than gasoline.

The expectation that some improvements in engine performance could be achieved by doing the proper adjustments in the engine that is going to be used in Formula Student IPleiria Team (FSIPL), when fuelled by a mixture of 15%gasoline and 85%ethanol (E85), serves as motivation for the present work.

3. Methodology

The work methodology is based into a computer simulation of the engine of the FSIPL team in software and validation of the obtained results with the experimental tests developed in a chassis dynamometer to be assured about the simulated data and allow to develop the model to achieve the best configuration to get the advantages of using ethanol in the engine.

This permit to test several hypotheses without damaging the engine and to reduce time and costs in the production of several prototypes and respective tests. Through computer simulation it is also possible to study slow processes quickly and the detailed analysis of certain details throughout the simulation. All this offers advantages that save time and money, even if this requires a high initial investment for both the software and the simulation data.

The simulation validation for gasoline and for ethanol, means that the experimental tests also should consider the use of gasoline and the use of E85 in the same conditions, to allow the comparison of the results. After the validation of both modules, the simulation can be then applied for optimization process considering the consumption of the ethanol-gasoline blend.

3.1. Chassis dynamometer tests

The tests were carried out on a chassis dynamometer bench installed in the ESTG automobile engineering laboratory, presented in figure 2. The vehicle FSIPL with the objective of obtaining results of the power and torque curve and fuel consumption of the engine. The MAHA LPS 3000 dynamometer consists in a eddy current brake bench type where it is possible to test vehicles with a maximum power of up to 355 hp or 4-wheel drive vehicles with a maximum power of 710 hp and a maximum speed of 260 km/h [20].

Two types of test were planned, in steady state mode and transient mode. For the steady-state tests the motor rotation range (4000-11000rpm) was chosen with increments of 1000rpm to correspond directly to the points analysed in the software. The transient mode corresponds a one continuous

process of accelerating the vehicle, and the dynamometer respond with an suitable increase in load in order to accommodate the maximum power that the engine is capable to offer.

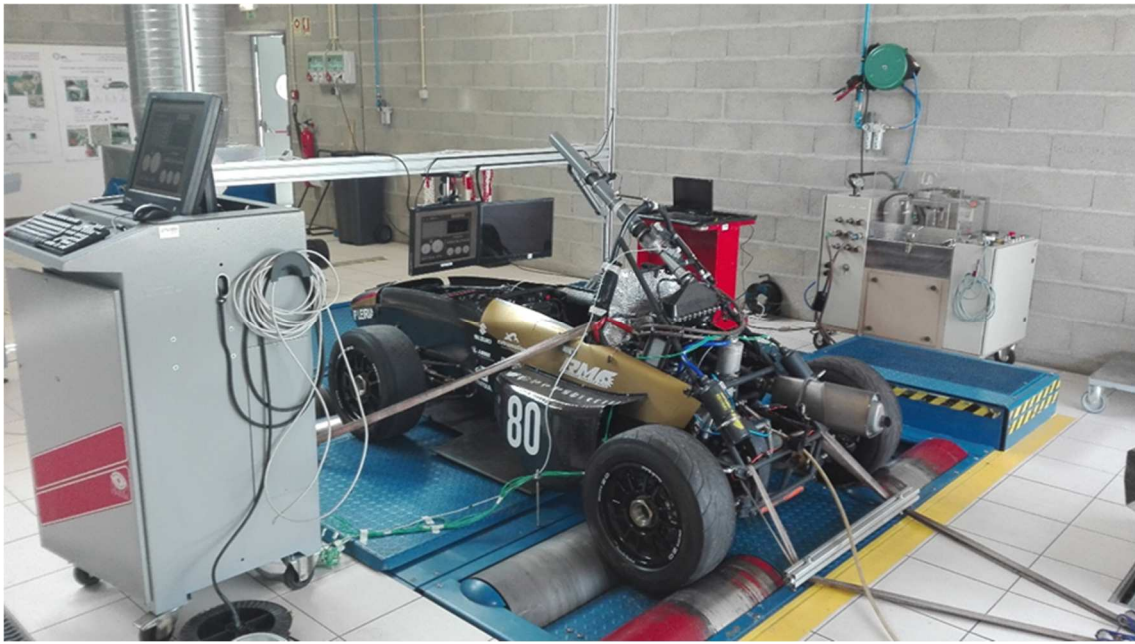


Fig. 2. – Chassis dynamometer bench test with the vehicle to be tested

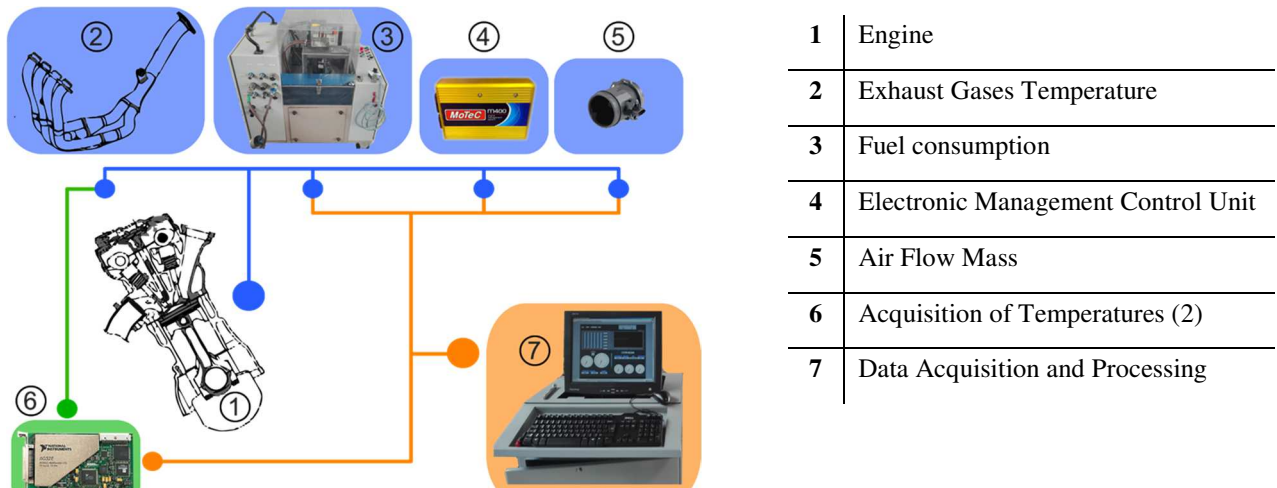


Fig. 3. – Data Acquisition System representation

Table 1. Table .format in ECOS: Template for manuscripts

Sensor	Reference	Scale	Accuracy	Acquisition
Lambda sensor	Bosch LSU 4.2	0.65 - ∞	± 0.007	MOTEC
Crankshaft rotation	Original	≤ 15 kHz	± 1°	MOTEC
MAF	Bosch 0280217123	8 – 370 kg/h	≤ 3%	MOTEC
Intake Admission Temperature	Bosch 0280217123	-40 – 120 °C	± 1.4°C	MOTEC
Engine Temperature	Original	-40 – 130 °C	± 1.4°C	MOTEC
Exhaust Temperature	Termopar tipo K	0 – 1100 °C	± 2°C	LABVIEW
Fuel Consumption Measurement	Mettler FS7001 - F	0 – 7600g	± 0.1g	LABVIEW

A data acquisition system was developed, using the LABVIEW software, in order to obtain all the data used in the electronic management of the engine through the Motec control unit, as well as information on exhaust gas temperatures, admitted air mass, admitted air temperature and consumption of fuel. Also collected are values obtained from the test bench relative to the atmospheric conditions and the power and torque developed by the engine under study that was measured in the dynamometer. This system is represented in figure 3.

3.2. Computer Simulation

To start the development of the computational model it was used RICARDO Wave software, which allows, in a simple and explanatory way, to set different functionalities of the program from scratch, starting with defining as well the combustion and geometric parameters of the engine passing through the increase from the complexity of the model to the intake and exhaust system and a final version with all components implemented.

In addition to the introduction of the geometric parameters relative to the engine SUZUKI GSXR 600, it was also necessary to define initial conditions related to temperatures, which were inserted in the form of a table to fit the conditions of the future simulations. It was also possible to choose sub-models of analysis relating to combustion, heat transfer, turbulence and flow, from which only the combustion and heat transfer sub-models will be used, which were defined using the already proposed methods.

In this simulation scenario, the data convergence was analyzed with a limit of 1% variation for pressures and speed defined by the software. Two cycles of convergence were also followed to consider the result as stable, and only the values for the 10000 and 11000 RPM did not reach the convergence parameters after the maximum limit of 1000 iterations, nevertheless it was considered that since they remained below the 3% variation, were accepted as valid.

4. Results

Regarding the collected data, its selection was chosen based on the criteria of stabilization of the exhaust gas temperatures. Thus, after analyzing the temperatures of some preliminary tests, it was concluded that after 30s from the start of the tests at any regime, the exhaust temperatures were already stabilized.

When analyzing the test data, the values for the first 30s in which the stabilization took place were discarded, and an average of the power values was made around the next 10s (Figure 4) developed the torque curve represented in Figure 5.

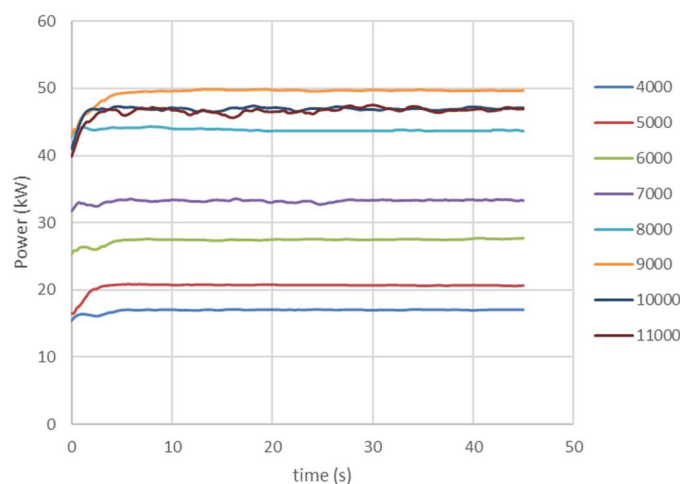


Fig. 4. – Temperature results obtained for different tests, assuring stabilization.

4.1. Analysis between simulation and experimental results

The analysis of the results presented in figures 5 and 6 shows that the torque curves obtained in the simulation and experimentally, are very similar when considering the use of gasoline and when considering the use of E85. The existing variations between the two curves in both situations are perfectly acceptable, once the maximum error between experimental and calculated values are bellow 10%. In fact, it is possible to detect a difference in gasoline case that reaches 6% maximum for 6000rpm and 11000rpm, and for E85 the maximum difference reaches 8% for 7000rpm. Considering the expectable errors to completely simulate the real working operation of the engine, the observed differences are completely tolerable.

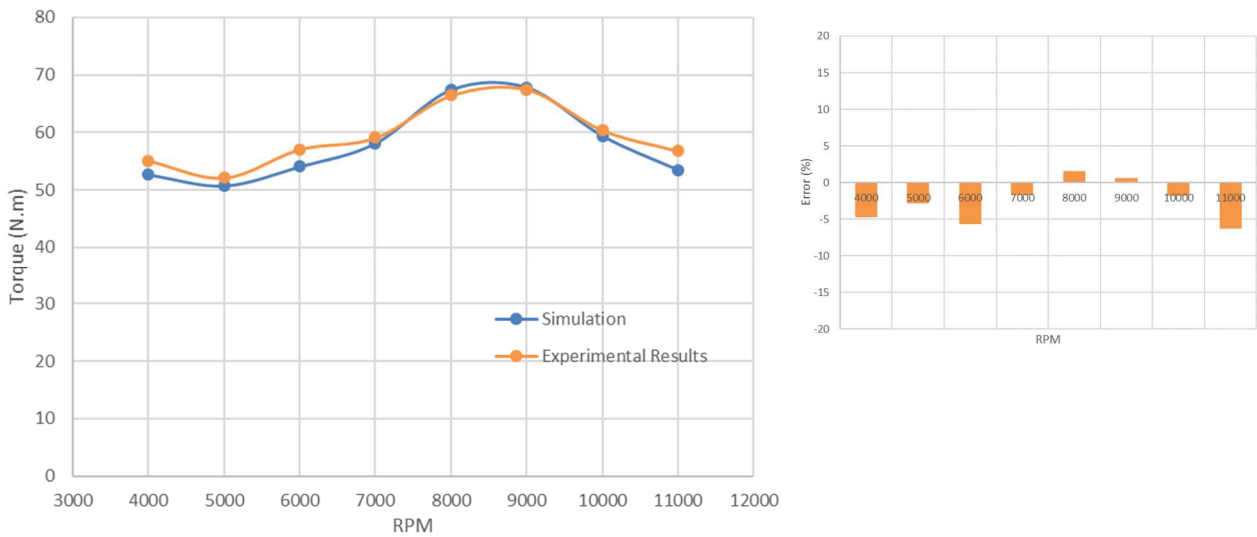


Fig. 5. – Torque curve obtained with simulation and experimental tests for gasoline fuel.

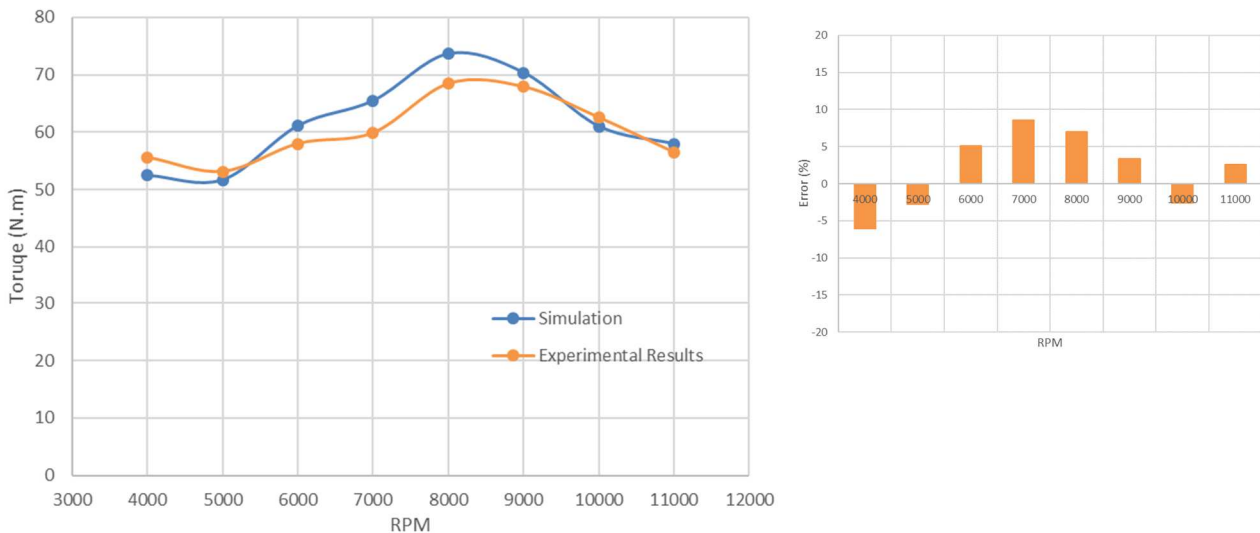


Fig. 6. – Torque curve obtained with simulation and experimental tests for E85 fuel.

The analysis made also consider the specific fuel consumption and the air fuel flow for both simulated and experimental results. It was also possible to detect some acceptable differences in both situations, and a considerable similarity in the curves, which allow to validate the simulation.

Considering the comparison of the experimental results obtained with gasoline and E85, it is possible to verify that the torque value is not significantly affected by the use of different fuels. The use of E85 is characterized by a slight increase in the torque developed by the engine with oscillations ranging from -0.6% at 11000rpm to 3 can be stated that there is a tendency of a very compared with the use of gasoline, as can be visual

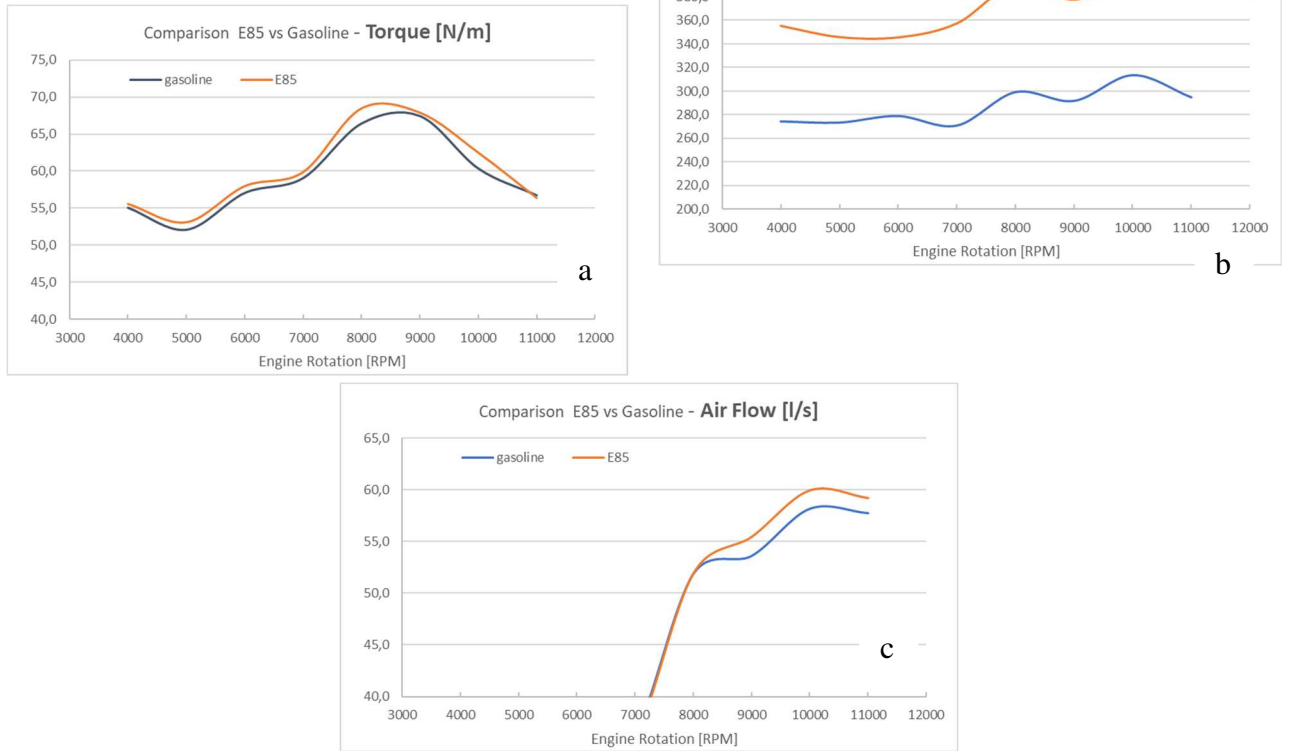


Fig. 7. – Comparison of experimental results obtained for gasoline and E85. a) Torque; b) Specific Fuel Consumptions; c) Air Flow.

Observing the specific consumption values shown in figure 7b, it becomes clear that for the engine to ensure the torque result when supplied by E85, which has a much lower calorific value than gasoline, it must compensate for this lower available energy with an increase in fuel consumption. The increase in specific fuel consumption reaches a mean value of 28%, which is consistent with the decrease in energetic availability offered by the fuel. This analysis is also consistent with the decrease in the air / fuel ratio, which for a similar air flow, can inject a higher amount of fuel. In fact, the air flow is constrained by the restrictor that as to be mounted in the intake pipe for regulatory reasons and the air flow present similar values. However, when the engine rotation is higher, some increase in the volumetric efficiency is noticed which allows to have a small growth in air flow when E85 is used, which allows to have a very slight increase in Torque for higher regimes.

4.2. Optimization using E85

This chapter will focus on the validity of the developed model and study a small set of optimizations that intend to explore the potentialities of the E85 as fuel.

The parameters that will be optimized are associated to the characteristics of ethanol that can offer more advantages to combustion from a performance point of view, such as higher-octane number which allow higher compression ratio, higher laminar velocity of flame which will point to an adjustment of ignition point, and higher ignition temperature.

4.2.1 Compression Ratio

As previously mentioned, some of the properties of ethanol, such as higher-octane number and higher latent heat of vaporization, allow the use of higher compression rates in the engines, and according to other authors, it can be expected efficiency gains between 7 to 10% [21].

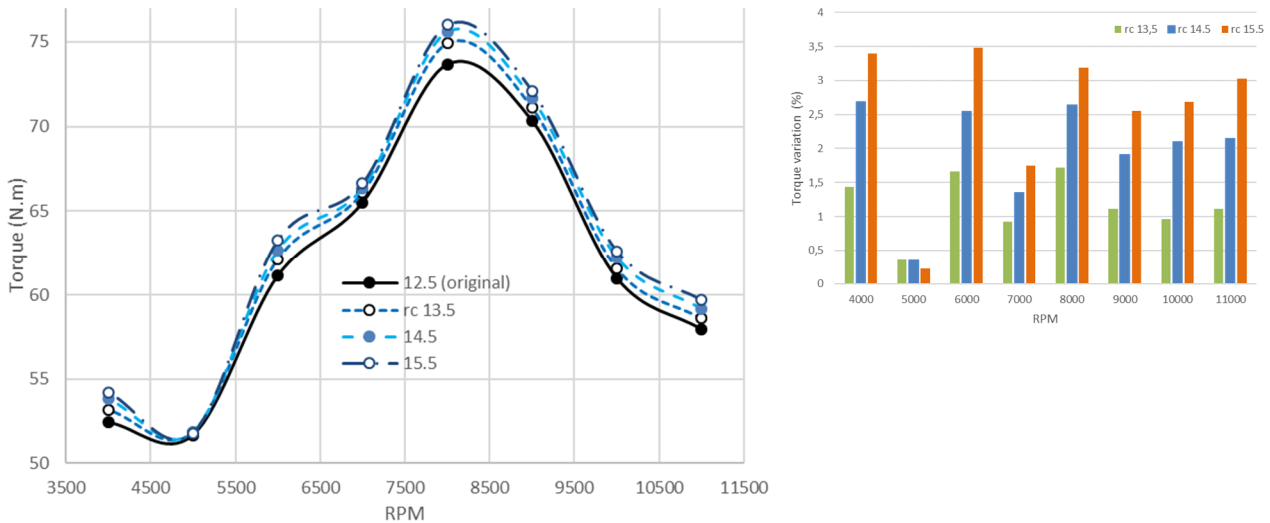


Fig. 8. – Comparison of the results for different compression ratios

As can be seen from the graph of figure 8, it is confirmed that the increase in the compression ratio causes a rise in the torque produced by the engine, however, this higher torque results stays lower than expected. In fact, with an increase in compression ratio of 12.5 to 13.5, 14.5 and even 15.5, a significant torque increase of the order of at least 10% would be expected, as indicated in other studies. It was found, however, that the maximum torque increase in average terms was around 3% for the compression ratio situation of 15.5. Even so, there are a clear raise in the performance of the engine with this optimization for the use of ethanol. This limitation in torque increase is probably caused by the restrictor located in the intake pipe, which limits the air flow, limiting the torque developed by the engine.

4.2.2 Injection advance

As for the ignition advance, considering that the average value used in the simulations was 40° of advance, decrements from 4° to a maximum of 20° of advance were analyzed, once again to try to detect the trend of the changes made in the torque of the engine when fueled by E85.

It is possible to identify in the graph of figure 9 that the decrease in advance of the promoted ignition introduces improvements in the torque produced by the engine. Once again, these variations are not very significant, but they can still reach values of around 4% with the ignition advance reduction from 40° to 24° . It were also analyzed that the effects of the advance vary a little more, but these effects were not notorious.

The highest sensitivity rotation to the ignition advance is in the range of 6000rpm to 8000rpm, with variations that average around 4%, but when the tested range (4000rpm to 11000rpm) is verified, the average change is about 3 % increase for 24° ignition point.

Like in the case of compression ratio, the variations are not very significative, but these study reveals a clear trend for the increase in Torque developed by the engine. When the two factors could be aggregated, it is expected an interesting increase in the performance of the engine.

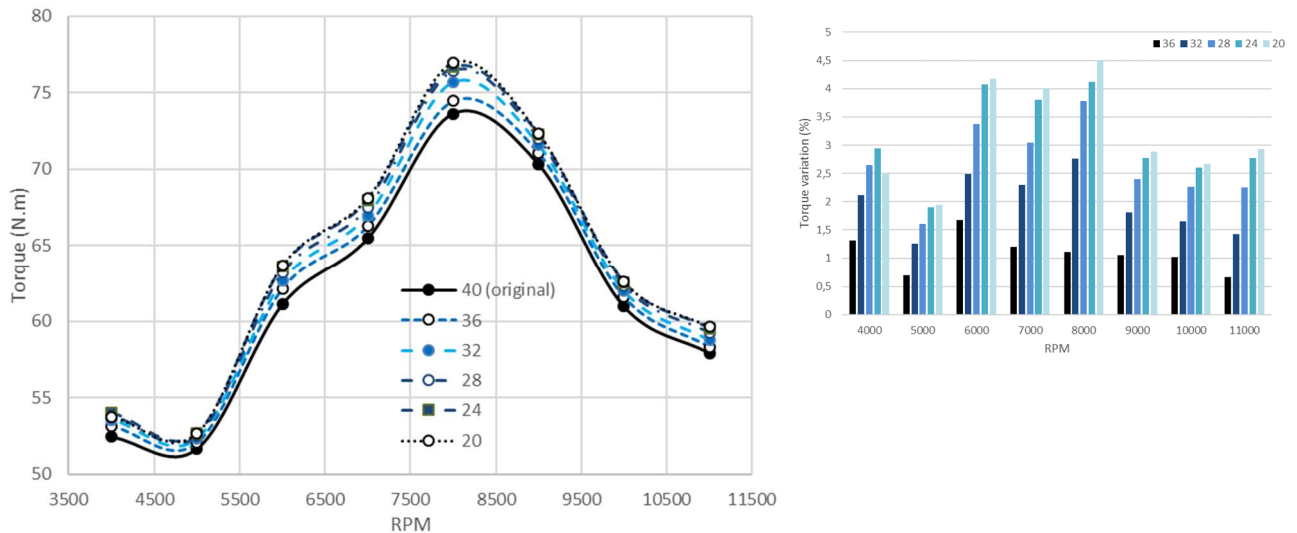


Fig. 9. – Comparison of the results for different injection advance.

5. Conclusions

Ethanol as a fuel is the result of the fermentation of sugars or starch present in vegetable matter, being therefore a source of renewable fuel and consequently cleaner than fossil fuels. The ethanol presents also a set of interesting characteristics from the point of view of the combustion that is why it can become a viable alternative to diminish the dependence on petroleum derivatives and presenting suitable possibilities to increase the performance of engines used in competition.

On the other hand, other properties of ethanol can cause problems in transportation, distribution and use, so to expand its use, a very large investment will be required to prepare supply and transportation infrastructures for the transition to ethanol to be totally safe and to perform enough studies to undertake the sufficient knowledge of how to use properly the potentialities offered by this renewable fuel.

Nevertheless, the adaptation of the vehicles themselves is relatively easy, and it is only necessary to ensure that the fuel system has the capability to withstand corrosion and to deliver the necessary flow to maintain desired performance levels, which implies higher costs in older vehicles, but lower on more modern vehicles whose materials have the necessary properties to handle Ethanol.

Another hypothesis is that in the future, engines will be developed from scratch to operate with high concentrations of ethanol (eg E85), where it may be possible to develop engines with the same performance as a gasoline engine, but with a reduced size, following the trend of downsizing and turbocharging that has been verified in the automotive panorama in recent years.

As for the development of the computational model, it includes the use of the software Ricardo Wave where the introduction of the characteristics of the engine was made considering the use of the two different fuels, gasoline and E85.

Nevertheless, it was possible to develop models with a relative error below 10% of the initial objective, and a torque curve with a maximum deviation of 6.2% in the gasoline model and 8.5% in the E85 figure was obtained, in relation to the experimental tests. This provides a solid basis for the development of future work.

The following step was successfully completed with the optimization of the engine for the consumption of ethanol, by increasing the compression ratio and decreasing the ignition advance. These changes were studied and the compression ratio variation from the original 12,5 to 15,5 allow to have an average increment on Torque of 3%. In other hand, the decrease in the ignition advance from 40° to 24° allow to observe an increase in Torque rounding 4% for the engine rotation scale

6000-8000rpm, and an average of 3% in all tested scale. These values are lower than what was initially expected, but these small variations are probably due to the limit on the air flow imposed by the restriction in the intake pipe. This should now be tested in experimental work.

The great value of the present work is the development of a efficient tool to discover the potentialities of using ethanol in engines, which allow to save time in the detection about the optimization adjustments to get out the best potentialities of ethanol.

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