On the assessment of performance and emissions characteristics of a SI engine provided with a laser ignition system

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Abstract. Performance and exhaust emissions of spark ignition engines are strongly dependent on the development of the combustion process. Controlling this process in order to improve the performance and to reduce emissions by ensuring rapid and robust combustion depends on how ignition stage is achieved. An ignition system that seems to be able for providing such an enhanced combustion process is that based on plasma generation using a Q-switched solid state laser that delivers pulses with high peak power (of MW-order level). The laser-spark devices used in the present investigations were realized using compact diffusion-bonded Nd:YAG/Cr\textsuperscript{4+}:YAG ceramic media. The laser igniter was designed, integrated and built to resemble a classical spark plug and therefore it could be mounted directly on the cylinder head of a passenger car engine. In this study are reported the results obtained using such ignition system provided for a K7M 710 engine currently produced by Renault-Dacia, where the standard calibrations were changed towards the lean mixtures combustion zone. Results regarding the performance, the exhaust emissions and the combustion characteristics in optimized spark timing conditions, which demonstrate the potential of such an innovative ignition system, are presented.

1. Introduction
The actual internal combustion engines which have been developed in time either as spark ignition engines, or compression ignition engines will continue to dominate for the next decades not only the transport sector but also some parts of industrial and agricultural domains. Heat in the spark engines is released by expanding as turbulent flames over premixed homogeneous fuel/air mixtures in the case of multipoint fuel injection, or over nonhomogeneous mixtures in the case of gasoline direct injection. In both cases a controlled ignition is produced by the electrical system of the engine at a certain moment of the operating cycle and at a specific location of the combustion chamber where the spark plug is located.
Engines efficiency, performance and emissions will be continuously improved and even small enhancements, perhaps previously not considered worth pursuing, will become now important. In such context, traditional combustion problems as ignition and early flame development will acquire renewed importance. Ignitability of lean mixtures and stability of combustion in lean and diluted (high EGR) mixtures in spark ignited engines will represent the key issues to be solved in the next combustion technologies applied for heat engines [1].

A novel possible technological solution that seems to represent a promise future development of gasoline engines is the gasoline direct injection compression ignition. This idea was initially proposed to improve the problems of other advanced combustion concepts which were associated with the use of different new petroleum based fuels or alternative fuels. In this case, the major challenge is that the fuel must be injected early in the compression stroke when pressure and temperature are low and the suitable conditions for fast and robust ignition are poor. This challenge is associated too with the gasoline’s very low Cetane Number (CN) which is usually estimated to be no higher than about CN15 [2] that implies longer ignition delays.

To overcome these drawbacks many researches have been dedicated in the last decades to the use of enhanced ignition systems like Radio Frequency Ignition or Laser Ignition (LI) systems. For ensure faster flame initiation in the region of the combustion chamber, where the mixtures are within the flammability limits, promoting thus a rapid combustion over very lean mixtures in the whole combustion chamber with substantial benefits on fuel efficiency and emissions, extremely high-power ignition sources have been tested. LI has been demonstrated to offer some advantages in comparison with classical spark plug ignition in terms of improved efficiency and reduced variability [3-5]. For the first time, such kind of ignition was reported in 1978, when a single cylinder internal combustion engine was ignited by a CO2 laser [6]. Advanced Q-switched Nd:YAG lasers were used to ignite a four-cylinder engine in 2008 [7]. In those experiments the laser beams were directed to and then focused into the engine cylinders by common optics (lenses and mirrors).

Consequently to these researches, spark-plug like Nd:YAG/Cr4+:YAG lasers that were side pumped [8] or longitudinally pumped [9-11] and that delivered one beam [8,9] or multi-beam output [10,11] were demonstrated to be viable for use in engines. Finally, as result of many years of research, the world first gasoline engine vehicle that was ignited only by laser igniters was presented in 2013 by T. Taira et al. [12].

All these efforts are nowadays dedicated to the improvement of LI systems in terms of their reliability, miniaturization, and better operation in correlation with combustion chamber architecture, fuel distribution, inner flow field, turbulence intensity which characterize the diverse and variable passenger car engine working conditions [13]. Moreover, new studies concerning the influence of delivered energy on a local or on multiple ignition points, the requirements concerning time and space distribution associated with the use of alternative fuels with low carbon content are under progress [14-18].

The current paper represents an extension of the previous researches that have been performed from some years at INFLPR and RTR concerning the possibility to use of a LI system to an automobile engine [19,20]. It consists in a theoretical and experimental study regarding the influence of the location of ignition point inside combustion chamber and ignition event on operating cycle expressed in terms of engine operating stability and combustion analysis.

2. Experimental Details

The spark ignition engine was a conventional multipoint fuel injection car engine with 4 cylinders with 1598 cm³ total displaced volume and rated power of 64 kW at 5500 rpm. The engine was provided with open ECU Continental EMS 3132 and connected with an ECU control system ETAS-INCA v2.1. The experimental test bed was correspondingly equipped for the control of the engine operation and the collection of all the relevant parameters characterizing engine’s operating conditions. The engine was coupled with a Froude Consine AG 250-UK eddy current dynamometer for control and the measurement of its torque and speed. Test bed control system is TEXCEL v6 having installed the corresponding software Froude for engine dyno-control and for low speed parameters variation data acquisition on 16 channels. The exhaust emissions (CO2, CO, NOx, THC)
were measured and the relative air/fuel ratio $\lambda$ was calculated by a gas analyzer Horiba Exsa -1500L. The engine fuel consumption was measured with a dynamic fuel meter AVL 733S coupled with a fuel temperature conditioner AVL 753C. A data acquisition system for high speed variation parameters as cylinder pressures, electric discharge parameters, injectors needle lift, type AVL Indimodul 621 for 8 channels was coupled with a micro-IFEM AVL system. Two cylinder-pressure sensors AVL ZF43 were installed in cylinder 1 and 4 and one AVL GU21D in the cylinder 1 by crossing the cylinder head. The crank angle encoder AVL 365 connected to the AVL Indi module was used for generating the marker and trigger signals necessary for data recording (figure 1).

![Figure 1. The experimental test bed.](image)

For each tested operation point, pressure traces for 200 consecutive cycles were registered. The operation condition was light load, at 2000 rpm and 2 bar brake mean effective pressure (BMEP), considered as representative for the city traffic. The load was identified by the pressure existing in the inlet manifold equal to 430 mbar for light load. Final data comparisons concerning the effect of using different ignition systems at various $\lambda$ and engine speed and load, were made for optimized ignition timings (minimum advance for best torque, MBT).

The LI system was developed at the National Institute for Laser, Plasma and Radiation Physics, Magurele, Romania. It consisted of an integrated four-laser sparks device that was triggered by the electronically control unit of the car. In general (or usual operation mode), each laser spark delivered pulses with energy up to $E_p = 4.0$ mJ and pulse duration around 0.8 ns; the repetition rate could be increased from few up to 60 Hz. In addition, by increasing the pump-pulse duration at a defined repetition rate, each laser spark could emit multiple pulses (i.e. two, three or even four pulses), realizing the so-called burst-pulse operation. More information about the design and performances of such a laser spark can be found in Ref. [19].
3. Simulation Details
The numerical model was built using the AVL BOOST 2016 simulation codes to estimate the engine performance, efficiency, combustion characteristics and exhaust gas emissions. The engine calibration parameters and cylinder processes’ simulation were described by using codes v2016 (AVL BOOST Theory and AVL BOOST Users Guide) [21]. Hence, the engine components, such as the intake and exhaust manifolds, cylinder geometry, air filter or the system boundaries and catalyst were implemented in the BOOST interface based on the real values which were taken from the engine installed on the test bed and used in this study. All the engine components are linked together by pipes and its symbolic model is shown figure 2.

![AVL BOOST numerical model.](image)

**Figure 2.** AVL BOOST numerical model.

![Fractal combustion model characteristics.](image)

**Figure 3.** The Fractal combustion model characteristics.

An assessment of the possible influence of the location of ignition point inside the combustion chamber was performed by considering the Fractal combustion model (figure 3) that was selected from the library of the BOOST code. The combustion chamber shape manufactured in the cylinder head is Pentroof, while the flat piston top crown was adopted having the same dimensions to the real combustion chamber and piston. In this model the position (X,Y) of the flame kernel is considered as variable being initially connected for model calibration with the spark plug location. The distance to the combustion chamber center is related to the focal length of the lens that is used to focus the laser.
beam and is calculated based on current values of (X,Y) which were selected in different steps. This distance started with 10 mm equivalent to the original position of the spark plug and goes down to 0 mm, equivalent to the combustion chamber center.

4. Experimental results
The results obtained show a better engine stability when running with LI system, compared with the conventional spark plug ignition system. Reduced coefficients of variability (COV) were obtained for different engine characteristics for combustion as well as for smooth engine operation.

A smaller COV, in terms of maximum in-cylinder pressure for 200 consecutive cycles, was obtained for the LI system. Thus, the COV coefficient was improved by 11% for the LI operation in comparison with that of the ignition by a conventional spark plug (figure 4). In addition, the difference between the COV of these two ignition systems in terms of angle of maximum pressure is 2.2 points of COV (figure 5).

![Figure 4. The variation of maximum in-cylinder pressure (p_max) [bar] for 200 consecutive cycles at 2000 rpm and 2 bar of BMEP (graph n/n+1).](image1)

![Figure 5. The variation of maximum in-cylinder pressure angle (alpha_p_max) [deg] for 200 consecutive cycles at 2000 rpm and 2 bar of BMEP (graph n/n+1).](image2)

![Figure 6. The variation of Indicated Mean Effective Pressure (IMEP) [bar] for 200 consecutive cycles at 2000 rpm and 2 bar of BMEP (graph n/n+1).](image3)

![Figure 7. The angle when 50% of the total mass fraction is burned (AI50%) [deg] for 200 consecutive cycles at 2000 rpm and 2 bar of BMEP (graph n/n+1).](image4)
Also, the COV calculated for all 200 consecutive cycles in terms of indicated mean effective pressure (IMEP) [bar] was smaller (by 15.8%) for the LI system compared with the conventional one. (figure 6). Another important combustion characteristic analyzed was the variability of the angle where 50% of the total mass fraction was burned (A150%), measured in crank angle degrees. A better stability for LI was measured with a smaller COV by 6.1% compared with the classical ignition system (figure 7).

In all above figures representing the stability of engine operation (figure 4 to figure 7) more disperse point repartition can be seen for the classical spark plug ignition system compared with LI system. These promising results in terms of stability when using a LI system support the extension of investigation in the operating areas of the engine in which the stability coefficients are high.

5. Simulation results
The numerical simulation model offered the base to analyse the variation trend of main characteristics of engine efficiency, combustion and exhaust emissions, when modifying the position of the ignition point inside the combustion chamber. Simulations for five different focal lengths were made for three different spark timings. An analysis for lean mixtures (λ=1.2 [-]) was made, highlighting the more significant advantages of this engine operation zone. We would like to mention that the above mentioned focusing positions can be very easily obtained by changing the lens that is used to focus the laser beam inside the cylinder.

In figure 8, the variation of brake specific fuel consumption (BSFC) [g/kWh] is presented. Higher drops of percentages for BSFC, up to 7.5%, is expected for all spark timings from the leaner mixture (λ=1.2) compared with the stoichiometric engine functioning condition (λ=1) (table 1).

![Figure 8. Brake Specific Fuel Consumption (BSCF) [g/kWh] depending on ignition position for λ=1 and λ=1.2 at 2000 rpm.](image)

The total combustion duration characteristics from figure 9 shows, at λ=1, small variations depending on the ignition position. The most important combustion duration reduction was 35% for λ=1.2 at the 3rd spark advance investigated (av3) (table 1).
Figure 9. Combustion duration [deg] depending on ignition position for $\lambda=1$ and $\lambda=1.2$ at 2000 rpm.

The major disadvantage when changing the ignition position was obtained for the nitrogen oxides emissions (NOx). This increase in NOx occurs as the peak fire temperature rise along with the central position of the flame kernel (figure 10). The greater actual increase was for $\lambda=1$ and the 3rd spark advance (av3), of 2 g/kWh between the initial point and the center of the combustion chamber (table 1). Smaller disadvantages were obtained for $\lambda=1.2$; the biggest increase of 0.9 g/kWh was at the 3rd spark advance (av3). This drawback could be mitigating by using high diluted EGR mixtures together with an enhanced ignition system like LI.

Table 1. Percentages of variation between conventional position (10 mm) and centered position (0 mm) for the main characteristics.

| Spark timing [deg] | av1, $\lambda=1$ | av2, $\lambda=1$ | av3, $\lambda=1$ | av1, $\lambda=1.2$ | av2, $\lambda=1.2$ | av3, $\lambda=1.2$ |
|-------------------|-----------------|-----------------|-----------------|-------------------|-------------------|-------------------|
| BSFC [%]          | -2.2            | -1.7            | -1.1            | -7.5              | -6.4              | -5.3              |
| Combustion Duration [%] | -6.1          | -8.7            | -12.1           | -12.6             | -24.4             | -35.0             |
| NOx [%]           | +31.1           | +29.9           | +28.7           | +25.0             | +25.1             | +31.0             |
6. Conclusions
A petrol multipoint fuel injection engine equipped successively with a spark ignition and a LI system was operated for a specified condition of speed 2000 rpm and 2 bar brake mean effective pressure. In the same time, a set of simulations were performed for the same engine and same condition but with different locations of ignition point inside the combustion chamber. It was made an analysis in terms of performance, efficiency and combustion characteristics for which the main findings can be summarized as follows:

- Theoretical investigations shown the possibility to improve efficiency by 2% when changing the ignition point location from the actual position of the spark plug to the center of the combustion chamber;
- This evolution seems to be similar when the stoichiometric mixture that is characteristic for the normal operation of the engine is replaced by lean mixture;
- The theoretical results obtained for stoichiometric mixture were in good agreement with an overall accuracy of 3% by the experimental data measured on the test bed;
- The extension towards the lean mixture associated with the use of an enhanced ignition system as LI can improve efficiency and engine operation stability by reducing cycle-by-cycle variability.

These investigations will continue for lean mixtures but covering also other engine operating conditions.

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