# CFR Octane Rating Unit Engine and Dacia Single Cylinder SI Engine with Classical Spark Plug and Laser Ignition: Comparative Findings

Bogdan George DONE, Laszlo BAROTHI, and Ion COPAE

*Abstract*—**Nowadays, research has developed new technologies for a better control of the combustion process. Among the new technologies used for Ignition and combustion control, the LASER Ignition system is defined as an innovative technology which could overcome several limitations of classical spark plug. The purpose of the paper is to present and disseminate the results of the experimental research on the LASER Ignition used in the Spark Ignition engine. Improved performance, ensuring rapid and robust combustion, depends on how the Ignition stage is achieved. It was designed, integrated and built so that it resembled a classical Spark Plug and could be mounted directly on the cylinder of a CFR Octane Rating Unit Engine, as well as on a Dacia Single Cylinder SI Engine, which led to several results among which: indicated, mediated pressures and their wave dispersion and also pollutant emission.**

*Index Terms*—**LASER Ignition, pressures, dispersion, Q-switched, diode LASER**

## I. Introduction

Recently, a large number of engine manufacturers have been directing their efforts towards enhancing the internal combustion engine. Ignition in most engines is produced by the electrical system of the engine at a certain moment of the operating cycle and at a specific position in the combustion chamber where the spark plug is located. Spark plug engine operations still require improvement because of the poor efficiency in the case of low loads, knock tendency in the case of high loads, of nanoparticles emissions and elevated level of the global pollutant emissions. Future combustion technologies applied to heat engine will need to solve the problems of ignitability of lean mixtures and stability of combustion in lean and diluted mixtures i.e. with high EGR, in spark ignited engines [1]. A potentially better technological solution for gasoline injection compression Ignition engines, however, continues to depend on fuel Cetane Number, which should not exceed CN15 [2], thus causing longer Ignition delays. In other words, faster Ignition and combustion over very lean mixtures, have considerable benefits concerning fuel efficiency and emissions, due to the extremely high-power Ignition sources such as LI, and offer several advantages in comparison with classical Spark Plug Ignition [3, 4]. This type of Ignition was tested initially in 1978, when a single-cylinder research engine was ignited by a CO2 LASER [5]. In 2008, advanced Q-switched Nd:YAG LASERs were used to ignite a four-cylinder engine [6] but T. Taira et al. [7] made public the first gasoline engine ignited only by LASER. Following the research, d:YAG/Cr4+:YAG LASERs which were either side pumped or longitudinally pumped and that delivered one beam [8] or multi-beam output [9], proved to be feasible for engines.

The main advantages of LASER ignition are:

- a choice of arbitrary positioning of the ignition plasma in the combustion cylinder;
- absence of quenching effects by the spark plug electrodes;
- ignition of leaner mixtures than with the spark plug, lower combustion temperatures, less NOx emissions;
- no erosion effects as in the case of the spark plugs => lifetime of a LI system expected to be significantly longer than that of a spark plug;
- high load/ignition pressures possible, increase in efficiency, precise ignition timing possible and exact regulation of the ignition energy deposited in the ignition plasma;
- easier possibility of multipoint ignition [8, 9];
- shorter ignition delay time and shorter combustion time [6, 10] and fuel-lean ignition possible.

The disadvantages of LI system are:

- high system costs and proven concept, but no commercial system available yet.

Current research is focusing on the improvement of reliability and miniaturization of LASER Ignition (LI) systems [9], as well as on the influence of delivered energy on a single point [9].

## II. LASER Ignition Process and Mechanisms

The LI process involves the existence of adequate conditions for two basic steps: spark formation (generally limited by breakdown intensity) and subsequent Ignition (generally limited by a minimum ignition), e.g. it is possible either to provide sufficient energy for Ignition, but not enough intensity (i.e. no spark forms), or to form a spark, but lack enough energy for combustion.

LASER-induced sparks are generally smaller in size, shorter in duration and have higher temperatures [10]. Temporal profiles of plasma light emission are formed, a high energy (94mJ) Ignition coil / fine wire spark plug and a focused Nd:YAG LASER beam (10 mJ) [11]. An example of a mechanism by which LASER radiation may ignite fuel

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mixtures is thermal initiation [3, 4], also, non-resonant breakdown which is a well-described LI mechanism. It can be assimilated with classical spark ignition (SI) produced in that plasma which emits light, heat and a shockwave.

## III. Experimental Investigation

Experimental investigations were carried out in a research laboratory of the Faculty of Mechanical Engineering and Mechatronics, Department of Thermotechnics, Engines, Thermal Equipments and Refrigeration Installations, within University POLITEHNICA of Bucharest.

The experimental research was developed on an experimental single cylinder SI engine, equipped with LI on two engines. The Dacia Single Cylinder SI Engine (Fig. 1) operating regime was 2800 rev/min, 90% load, and the CFR Octane Rating Unit Engine (Fig. 2) operating regime was 900/min. Both experimental engines were single-cylinder and were mounted on test beds adequately instrumented. The LI used in the experiments was provided by INFLPR, Laboratory of Solid-State Quantum Electronics, Magurele, Romania. A photo of the LASER spark is shown in Fig. 3 [12, 13].


Figure 1. Dacia Single cylinder SI engine equipped with LI


Figure 2. CFR Octane Rating Unite Engine equipped with LI

Figure 3. CFR Octane Rating Unite Engine equipped with LI

## IV. Results and Discussion

Fig. 4 shows the pressure values of the CFR engine for 491 cycles, $n = 400$ rev/min, Ignition advance $\beta = 28.5^{o}$ RAC, and $\lambda = 1.1$ excess air coefficient. The graphs also indicate the external outlines of the 491 cycles, as well as the related maximum values for the classical spark plug (Fig. 4a) and the LI (Fig. 4b). As it can be noticed in the 2 graphs, the maximum pressure values range was 22–26.3 bar in the case of the classical spark plug, while the range for the LI was 22.4–26.9 bar. As seen and expected, Fig. 4 shows the existence of the cyclic dispersion phenomenon. According to the scientific literature, cyclic dispersion is defined, as a rule, by the coefficient of variation (*COV*), which – for a given value *x* – represents the ratio between the standard deviation σx and the average value $m_x$:

$$COV_x = \frac{\sigma_x}{m_x} \quad (1)$$

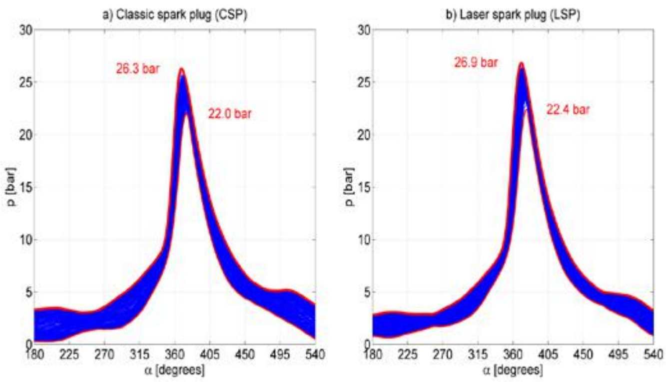

Figure 4. The indicated pressure, instantaneous values and cycle tires the CFR engine for 491 cycles, $n = 400$ rev/min, $\beta = 28.5^{o}$ RAC, and $\lambda = 1.1$

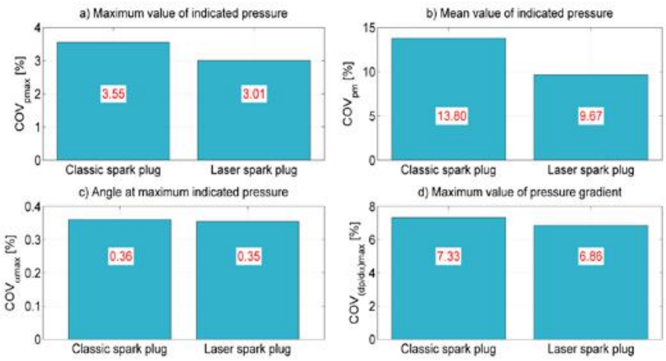

Figure 5. Coefficients of variation for maximum pressure, mean pressure, maximum pressure angle, maximum pressure gradient, CFR engine for: 491 cycles; $n = 900$ rev/min; $\beta = 28.5^{o}$ RAC; $\lambda = 1.1$

Fig. 5 presents the variation coefficient values for the pressure curves in Fig. 4, and for the four values mentioned in the graph: the maximum and average pressure values indicated, the rotation angle of the crankshaft (CAD) related to the maximum pressure and the maximum value of the pressure gradient. As the graphs show, the LI variation coefficient has lower values by comparison with the classical spark plug, for all the four above-mentioned values. Consequently, in this case, based on the variation coefficient, the scale of cyclic dispersion is smaller than in the case of LI.

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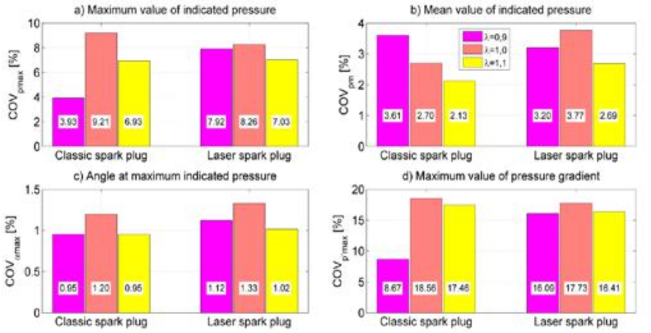


Figure 6. Coefficients of variation for maximum pressure, mean pressure, maximum pressure angle, pressure gradient, Dacia mono cylinder for: 50 cycles; $n = 2800\ \text{rev/min}$; $\kappa = 90\%$; $\lambda = [0.9;1.0;1.1]$

Similarly, Fig. 6 presents the variation coefficient values in the case of the indicated pressure curves of the Dacia mono cylinder engine, for three values of the excess air coefficient λ as well as for the same four before-mentioned values. As the graphs show, this time the variation coefficient does not always have lower values in the case of the LI by comparison with the classical spark plug, for all the four values mentioned and for all the excess air coefficient values. With reference to the above statements, one particular aspect related to the variation coefficient should be mentioned. As resulting from (1), this coefficient represents a ratio of two values: standard deviation and average value. Consequently, *COV* can be higher in both the case of a high standard deviation and the case of a low average value. As a result, estimating cyclic dispersion by means of the variation coefficient proves not to be the best solution. In this sense, estimating cyclic dispersion based only on dispersion (square of standard deviation) is ultimately a better solution.

In conclusion, it is recommended to estimate cyclic dispersion by dispersing the curves at each angle of the crankshaft rotation, in other words based on the distance between the external outlines of the curves. This type of estimation is closer to the cyclic dispersion concept and gives a better evaluation of the phenomenon [11, 12]. For example, Fig. 6 indicates the distance between the external outlines of the curves, which constitutes their dispersal, for the pressures of the CFR engine presented in Fig. 3. As the graphs show, the dispersal of curves is higher in the case of the classical spark plug at narrow and wide β angles and increases in the case of the LI up to a value of $\beta = 364^{\text{o}}\text{CAD}$. Detail A in Fig. 6 shows that the maximum values reached by the curves are 363$^{\text{o}}$CAD for the classical spark plug and 364$^{\text{o}}$CAD for the LI. Detail B highlights the fact that at a $\beta = 357.7^{\text{o}}\text{CAD}$, the curve of the LI is above that of the classical spark plug. Thus, Fig. 7 presents the pressure curves indicated for the $\lambda = 0.9$ classical spark plug case, while Fig. 8b, for the LI, for all the 50 measured cycles; Fig. 7c presents the distances between the external outlines of the curves, at each crankshaft rotation angle. As Fig. 7c shows, cyclic dispersion is higher for narrow angles in the case of classical spark plugs, and higher for wider angles in the case of LI. Moreover, the classical spark plug registers the maximum value (33.1 bar).

In exchange, Fig. 9, shows that in the case of $\lambda = 1.0$, cyclic LI have a higher cyclic dispersion in the case of narrow angles, while classical spark plugs have a higher cyclic dispersion in the case of wider angles. Furthermore, LI registers the maximum value (32.2 bar).

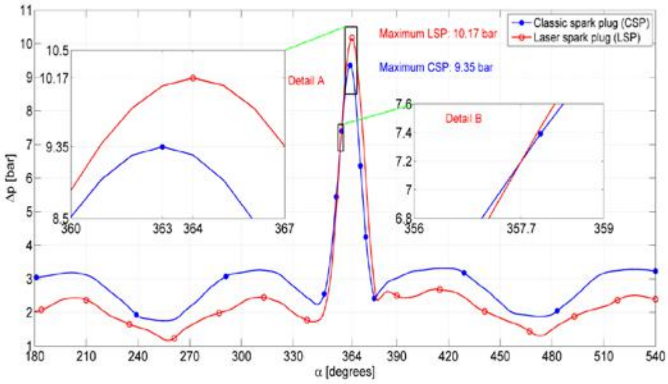


Figure 7. Dispersion of the cycle pressure curves for the classic spark plug and LI, $\beta = 28.5^{\text{o}}\text{CAD}$, $\lambda = 1.1$

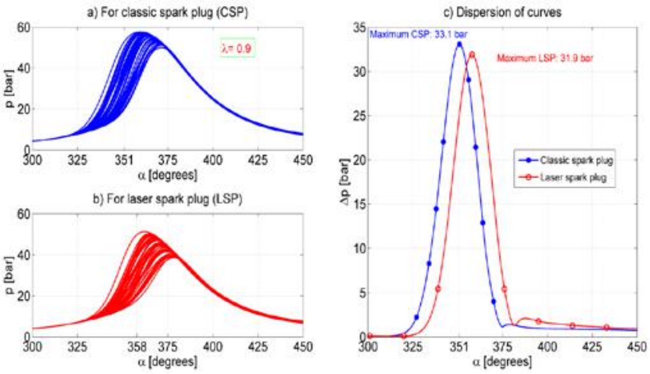


Figure 8. The indicated pressures and the dispersion of their curves (details), Dacia mono cylinder, for: 50 cycles; $n = 2800\ \text{rpm}$; $\kappa = 90\%$; $\lambda = 0.9$

Moreover, the classical spark plug registers the maximum value (33.1 bar). In exchange, Fig. 9 shows that in the case of $\lambda = 1.0$, cyclic LI have a higher cyclic dispersion in the case of narrow angles, while classical spark plugs have a higher cyclic dispersion in the case of wider angles. Furthermore, LI register the maximum value (32.2 bar). The analysis of both engines has resulted therefore, in families of curves for the indicated pressure, related to a given number of functional cycles. Based on them, obviously, it is possible to establish the median pressure curve, through mathematical calculation of the average value for each crankshaft angle.

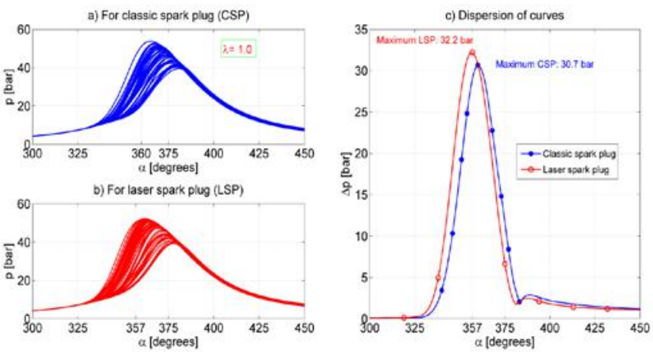


Figure 9. The indicated pressures and the dispersion of their curves (details), Dacia mono cylinder, for: 50 cycles; $n = 2800\ \text{rpm}$; $\kappa = 90\%$; $\lambda = 1.0$

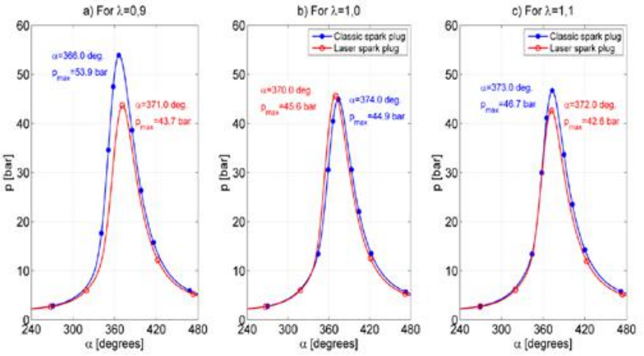

Figure 10. The indicated pressure for the Dacia single-cylinder curve for: 50 cycles; $n = 2800$ rpm ; $\kappa = 90\%$ ; $\lambda = [0.9;1.0;1.1]$

For example, Fig. 10 indicates the median pressure curves for the Dacia mono-cylinder engine, for three values of the excess air coefficient $\lambda$. The graphs also show the maximum pressure values $p_{\max}$ , as well as the rotation angle $\beta$ related to them. Also noticeable in Fig. 10, in the case of the stoichiometric mix ( $\lambda = 1.0$ ), the maximum pressure values indicated are the closest to the two types of spark plugs (44.9 bar and 45.6 bar respectively). Also, for this excess air coefficient value, the maximum pressure value is obtained in the case of the LI. In regard to the above, however, it should be specified that the operation based only on the median pressure of cycles represents a simplification which actually conceals the real phenomenon. For this reason, a live study should operate with all the indicated pressure curves, with the concept of uncertainty, the algorithms related to the uncertainty theory and highlight the non-linear phenomena which accompany cyclic dispersion.

## V. CONCLUSION

The experimental results obtained from the LI used in the spark Ignition engine, compared to the classic Ignition system, have led to several important conclusions presented as follows:

a) the use of the variation coefficient to estimate cyclic dispersion has the disadvantage of representing the ratio of two values and, as a result, cannot lead to veridical conclusions;

b) the use of the distance between the external outlines of the curves of the diagram to estimate cyclic dispersion allows the highlighting of the real phenomenon, the study thus showing that cyclic dispersion varies depending on the crankshaft rotation angle, and is not constant, as results from the variation coefficient;

c) research carried out utilizing all the experimental data (the study presents only a part of it) confirms the well-known fact that cyclic dispersion, performance levels and toxic emissions are influenced by the Ignition advance and the quality of the air-fuel mix (through the excess air coefficient) resulting in the need to quantify them by resorting to dispersion analysis, information analysis and sensitivity analysis.

d) a comparative study of the two types of spark plugs, as close as possible to the real phenomenon, should target not only the median diagram, but also all the curves of the indicated diagram which involves resorting to the uncertainty concept as well as highlighting the non-linear phenomena that accompany cyclic dispersion by means of bi-spectral analysis in frequency, analysis in time-frequency and the chaos theory.

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