A COMPARATIVE STUDY OF CYCLE VARIABILITY OF LASER PLUG IGNITION VS CLASSICAL SPARK PLUG IGNITION IN COMBUSTION ENGINES

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Abstract. Over the past 30 years numerous studies and laboratory experiments have researched the use of laser energy to ignite gas and fuel-air mixtures. The actual implementation of this laser application has still to be fully achieved in a commercial automotive application. Laser Plug ignition as a replacement for Spark Plug Ignition in the internal combustion engines of automotive vehicles, offers several potential benefits such as extending lean burn capability, reducing the cyclic variability between combustion cycles and decreasing the total amount of ignition costs, and implicitly weight and energy requirements. The paper presents preliminary results of cycle variability study carried on a SI Engine equipped with laser Plug Ignition system. Versus classic ignition system, the use of the laser Plug Ignition system assures the reduction of the combustion process variability, reflected in the lower values of the coefficient of variability evaluated for indicated mean effective pressure, maximum pressure, maximum pressure angle and maximum pressure rise rate. The laser plug ignition system was mounted on an experimental spark ignition engine and tested at the regime of 90% load and 2800 rev/min, at dosage of $\lambda=1.1$. Compared to conventional spark plug, laser ignition assures the efficiency at lean dosage.

Keywords: laser, cycle variability, spark ignition engine, combustion and performance.

1. INTRODUCTION

In the current global context of severe restrictions regarding the limits of the level of pollutant emissions and greenhouse gases produced by automotive internal combustion engines and in view of efficiency improvement, researchers have been focusing on the use of new technologies regarding combustion process control, [1], [11].

Consequently, pollution reduction and fuel efficiency can be controlled at primary level in the engine in-cylinder, with direct control on ignition and combustion processes. Such a new technology may be represented by the Laser Plug Ignition system (LPI), also known as Laser Ignition system (LI), [2]. In order to take place, the process of LI requires two basic steps: spark formation (generally limited by breakdown intensity) and subsequent ignition (generally limited by a ‘minimum ignition energy’ or MIE), [1]. For example, it is possible either to deliver sufficient energy for ignition but with insufficient intensity (i.e. no spark forms), or to form a spark but with insufficient energy for combustion. There are four well-known main mechanisms in use by which laser radiation can ignite combustible gas mixtures [2] and which are constantly evolving: I. Thermal initiation (TI); II. Non-resonant breakdown (NRB); III. Resonant breakdown (RB); IV. Photo-chemical ignition (PCI).
The most widely studied LI mechanism is NRB. It is similar to conventional electric SI as it produces plasma that emits light, heat and a shockwave, [5], [6], [7]. However, laser-induced sparks are generally smaller in size, shorter in duration and have higher temperatures [5], [13]. Another important issue is the reduction of cycle variability in engine operation, with benefits on efficiency and emissions, [10], [13]. Basically, the phenomena of cycle dispersion are the results of the variations of the combustion process, produced by imperfect mixing of in-cylinder fill in terms of homogeneity, by the phenomena produced in the formation of the plasma channel between the spark plug electrodes, by heat transfer from the flame core to spark plug electrodes, by convective heat transfer from the developed nucleus to the mass of initial mixture and by variation of the engine in-cylinder turbulence, [10], [14], [15], [16]. Cycle variability is strongly influenced by dosage, local air-fuel ratio and by the in-cylinder turbulent velocity field, [10], [12], [13].

Researchers from the National Institute for Laser, Plasma and Radiation Physics (INFLPR) and Renault Technologie Roumanie (RTR), Bucharest, Romania, have presented comparative results regarding the operation of an automobile engine that was ignited with classical spark plugs but also with laser spark, [4]. In the case of the K7M 812k engine, at a speed of 1500 rpm, the coefficient of variation \((\text{COV})_{\text{Pmax}}\) decreases by 15% and the \((\text{COV})_{\text{IMEP}}\) improvement was in the range of 18.5% (at 920-mbar load) to 22.6% (at 880-mbar load), [4]. The researchers noticed that the cyclic variability of an engine is improved at both high speed and load regimes, showing a lower influence of LPI on the coefficients of variability, expected in these conditions [4]. At 2000 rpm speed regime and high 920-mbar load, small differences between \((\text{COV})_{\text{Pmax}}\) and \((\text{COV})_{\text{IMEP}}\) for classic and LI ignition systems were noticed, [4]. Also, the results indicate a higher stability of the car engine that was operated at medium speeds by LPI, resulting in reduced noise, vibrations and mechanical stress, [4].

Mullett and Dearden [5], studied the LI system performance and cycle variability on a Ford Zetec engine at the regime of 1500 rpm and 36° before Top Dead Centre (TDC), [5]. Mullett calculated, for different values of laser energy in-cylinder, between 4...92 mJ, the ratio between the \((\text{COV})_{\text{IMEP}}\) determinant for the LI system and for SI system, [5]. The ratio of \((\text{COV})_{\text{IMEP}}\) values for IMEP evaluated for Laser Plug Ignition system and for classic ignition system continuously decreased with the increase of in-cylinder laser energy, [8]. Regarding the combustion stability, for stoichiometric operation, \(\lambda = 1\), the LI system was found to outperform the SI system in terms of reduced \((\text{COV})_{\text{IMEP}}\) [8]. Dickinson compares the values of \((\text{COV})_{\text{IMEP}}\) over a wide range of ignition angles at 1500 rpm, 2.62 bar brake mean effective pressure (BMEP), and analyses the effect of load on \((\text{COV})_{\text{IMEP}}\) when operating at 1500 rpm at minimum advance for best torque (MBT), [8].

Shenton, Mullett and Dearden show that LI system improves the combustion stability, explained by measured values of \((\text{COV})_{\text{IMEP}}\), [8] and with proper control, these improvements can enable engines to be run under leaner conditions, with higher EGR concentrations, or at lower idle speeds without increasing the noise, vibration and harshness characteristics of a vehicle. LI gives significantly shorter plasma duration compared to SI, [8]. With the recent development of higher average power and higher pulse frequency lasers, it is expected that a multi-strike LI system and associated combustion control can reduce the probability of misfires under high levels of dilution. The prospects for LI are also interesting from a control perspective, from optical sensing of the in-cylinder combustion made possible through self-cleaning (SC) of the laser beam pathway, to the array of possible ignition activation and control mechanisms, [8]. It is anticipated that, combined with the capability to control the
ignition location and timing, this will play a significant role in the optimization of future engines by dynamic feedback control [7]. In case of new ignition system use, like Laser Plug Ignition system, a study of cycle variability for the main parameters that characterize the engine running is imminent.

2. EXPERIMENTAL INVESTIGATION

The experimental research was developed on an experimental single cylinder SI engine, equipped with laser Plug Ignition. The operating regime was 2800 rev/min, 90% load. This operating regime, defined by the fact that speed is close to the maximum torque speed regime, is often used in exploitation and presents interest for investigation. The load is reduced at 90% in order to assure acceptable mechanical stress of the engine and does not affect the mechanical structure and function of the laser spark plug during this preliminary investigation. The experimental engine was mounted on the test bed adequate instrumented for the experimental investigations carried, its schema being presented in Figure 1.

Figure 1: Experimental test bed schema

Figure 2: Compared LPI and SPI

The test bed: 1- laser plug ignition, 2 - optical fibre, 3- laser diode, 4 - laser power supply, 5 - PC with soft laser, 6,7 - the ensemble breaker distributor (cam with one corner), 8 - inlet air temperature measurement indicator, 9 - exhaust gas temperature measurement indicator, 10 - engine oil temperature measurement indicator, 11 - engine oil pressure measurement indicator, 12 -cooling liquid temperature measurement indicator, 13 - PC equipped with AVL acquisition board, 14 - crank angle encoder, 15 - cooling fan, 16 - cooler, 17 - engine water pump, 18 - Kistler charge amplifier, 19 - piezoelectric Kistler pressure transducer, 20 - spark plug ignition, 21 - coupling, 22 - Schönebeck B4 hydraulic dynamometer, 23 - mechanical snuff speed, 24 - air flow meter, 25 - hydraulic dynamometer water pump, 26 - AVL DiCom Analyzer 4000, 27 - air flow meter, 28 - gasoline fuel pump, 29 - gravimetric fuel flow meter, 30 gasoline consumption tap, 31 - tank.

The laser spark used in the experiments was provided by INFLPR, Laboratory of Solid-State Quantum Electronics, Magurele, Romania. The photo in Figure 2 shows a laser spark plug compared with a classical spark plug. The plasma induced in air by optical breakdown is visible. The laser medium was a Nd:YAG/Cr4+:YAG ceramic structure (Baikowski Co., Japan) that consisted of a 8.0-mm long, 1.0-at.% Nd:YAG ceramic, optically-bonded to a Cr4+:YAG ceramic with saturable absorption (SA) [4], [9]. The initial transmission of Cr4+: YAG SA was around 40%. Monolithic configuration of the resonator was obtained by coating the high reflectivity mirror at lasing wavelength, $\lambda_{em} = 1.06 \mu m$ on the Nd:YAG free side and the
outcoupling mirror with reflectivity $R = 50\%$ at $\lambda_{em}$ on the Cr$^{4+}:$YAG free surface. The Nd:YAG side was coated for high transmission ($T > 0.98$) at the pump wavelength, $\lambda_p = 807$ nm. The optical pump was performed with a fiber-coupled diode laser (JOLD-120-QPXF-2P, Jenoptik, Germany) that was operated in quasi continuous-wave mode; the pump pulse duration was 250 $\mu$s and repetition rates up to 100 Hz were used. Typically, the laser yielded pulses with energy of 3.8 mJ at 1.06 $/g_{152}/g_{32}$ for the pump with pulses of $\sim$35 mJ at 807 nm; the laser pulse duration was around 1 ns. Cyclic variability is evaluated mainly by the variation of pressure differences, which are reflected in the calculated values of coefficients of cyclical variability, [10], [13]. The cycle variability can be characterized by coefficients of a cylinder pressure variation. The intensity of the cycle variability phenomena is defined by the coefficient of cycle variability, [10], [13]. For “n” consecutive cycles, if is considered a normal distribution of the deviation probabilities, the squared average deviation can be calculated and the cycle variability coefficient is defined as:

$$
(COV)_{a_i} = \frac{\sum_{i=1}^{n} (a_i - \frac{\sum_{i=1}^{n} a_i}{n})^2}{\sum_{i=1}^{n} a_i} \cdot 100\%
$$

where $n$ is the number of cycles, $a$ is the parameter of which variability is studied and is defined for indicated mean effective pressure IMEP, maximum pressure $p_{max}$, maximum pressure rise rate $(dp/d\alpha)_{max}$ and the angle where maximum pressure occurs, $\alpha_{pmax}$ in the cycle number “i”.

The way of cycle variability evaluation for regimes with spark timing closer to the value of spark timing for maximum torque brake (MTB) the coefficient of variation (COV) of maximum pressure is suitable, [10], [13]. When the maximum pressure occurs, the COV of maximum pressure angle is used for characterization of the combustion cycle variability during the initial phase of combustion [10], [13].

The variation of the IMEP, appreciated by $(COV)_{\text{IMEP}}$, is the most suitable instrument to define the engine respond to the combustion process variability. From this point of view, the limit value of $(COV)_{\text{IMEP}}$ defines practically the limit of mixture leaning, [10], [13]. This cycle coefficient can also indicate the variability of flame development during the initial phase of combustion [10], [11]. A higher combustion velocity reduces the influence of turbulence and reduces the cycle variability [10, 11].

The quality of the in-cylinder mixture influences the combustion process through chemical reaction speed, with a maximum in the area of rich dosage. As a result, the initial and final phases of the combustion process have minimal duration at the dosage for which the chemical reaction speeds are maximum, $\lambda = 1.1$ [11], [12]. At the mixture leaning, the duration of those two phases increase and the total combustion duration also increases. The normal automotive engine manoeuvrability is assured if the coefficients values are fewer than 10% [10], [13].
3. RESULTS

The experimental research was carried on the SI engine firstly equipped with Spark Plug Ignition system (SPI), defined as reference, and secondly for the engine equipped with laser Plug Ignition system (LPI). The operating regime was 2800 rev/min, 90 % load and air-fuel ratio $\lambda=1.1$. For the investigated regime, the data were measured with a resolution of 1 CAD and recorded with the AVL data acquisition system. Analysis of the consecutive pressure diagrams, the cycle variability coefficients were calculated for IMEP, maximum pressure, maximum pressure rise rate and angle of maximum pressure. COV values are presented in the following figures.

![Figure 3: The (COV)IMEP evaluated for SPI and LPI systems](image1)

![Figure 4: The (COV)pmax evaluated for SPI and LPI](image2)

The values of COV calculated for IMEP for Spark Plug Ignition (SPI) and for laser Plug Ignition (LPI) are presented in the Figure 3. The value of COV of IMEP decreases with 1.8 % at the use of LPI, fact that shows an improvement of the combustion stability at the use of laser Plug Ignition system versus classic ignition system. A lower value of (COV)IMEP, registered at the LPI use, as figure shows, indicates a better engine respond at the variability of the combustion process, at $\lambda=1.1$. Also, the reduced value of the COV for indicated mean effective pressure shows a much lower variability of the flame development into the initial phase of the combustion process when the LPI is used comparative to the spark plug system.

The values of COV calculated for maximum pressure for Spark Plague Ignition (SPI) and for laser Plug Ignition (LPI) are presented in Figure 4. The value of COV of maximum pressure decreases from 7.2% down to 6.7 %. The variability coefficient improves its value with almost 0.5 % when the laser Plug Ignition system is used comparative to the classic spark ignition system. The decrease of COV for maximum pressure is correlated with the variation tendency registered for the COV of IMEP.
The COV of maximum pressure angle, illustrated in Figure 5, defined by the angle when maximum pressure occurs per cycle, decreases from 41.5% value registered for SPI down to 31.6% for LPI. The decrease of the COV of maximum pressure angle, with 9.9% at LASER Plug Ignition system use, reflects a lower cycle variability of the combustion process registered during the initial phase of the combustion; this fact is correlated with the variation tendency registered also for COV of IMEP, Figure 3.

The COV of maximum pressure rise rate is presented in Figure 6. The calculated values for the LPI system of the COV of maximum pressure rise rate decreases with almost ~ 2% comparative to the values registered for the classic ignition system with spark plugs. The decrease of the COV for \((dp/d\alpha)_{\text{max}}\) appears in correlation with the reduction of the other COV values calculated for IMEP, maximum pressure and angle of maximum pressure.

4. CONCLUSIONS

Regarding the experimental research of a new laser Plug Ignition system used on a SIE, the main conclusions of the cycle variability study can be formulated as it follows:

The values of COV calculated for IMEP for laser Plug Ignition system (LPI) decrease with 1.8%, fact that shows an improvement of the combustion stability at the use of laser Plug Ignition system versus classic ignition system.

Due to a lower value of \((\text{COV})_{\text{IMEP}}\), registered when the laser Plug Ignition system is used, indicates a better engine respond at the variability of the combustion process, for \(\lambda=1.1\). Moreover, a much lower variability of the flame development during the initial phase of the combustion process when the LPI is used comparative to spark plug system.

The values of \((\text{COV})_{\text{pmax}}\) for laser Plug Ignition system (LPI) decrease from 7.2% down to 6.7%, the variability coefficient improves its value with almost 0.5%. The \((\text{COV})_{\text{pmax}}\) decrease is in correlation with the variation tendency registered for \((\text{COV})_{\text{IMEP}}\).

The decrease of the COV of maximum pressure angle, \((\text{COV})_{\alpha_{\text{pmax}}}\) with 9.9% when using laser Plug Ignition system, reflects a lower cycle variability of the combustion process registered during the initial phase of the combustion; this fact is correlated with the variation tendency registered for \((\text{COV})_{\text{IMEP}}\).
The values of COV for maximum pressure rise rate, \((\text{COV})_{(\text{dp}/\text{do})\text{max}}\), decreases with almost ~2% % for LPI system use comparative to the values registered for the classic ignition system with spark plugs. The decreases are in correlation with the reduction of COV values calculated for IMEP, maximum pressure and angle of maximum pressure.

The improved values of the cycle variability coefficients registered for laser ignition versus classic ignition system show a good perspective for further experimental investigations carried on other engine operating regimes.

Acknowledgements

The experiments were performed with a laser spark device developed at National Institute for laser, Plasma and Radiation Physics, Laboratory of Solid-State Quantum Electronics, Magurele, Ilfov, 077125, Romania. The authors would like to thank to Mr. Pavel Nicolaie, Mr. Dinca Mihai and Mrs. Croitoru Gabriela for their help and assistance during the experiments.

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