U.P.B Sci. Bull. Series D, Vol. 79, Iss. 2, 2017 ISSN 1454-2358

ASPECTS OF THE CYCLE VARIABILITY STUDY OF A SI ENGINE WITH LASER PLUG IGNITION SYSTEM

Bogdan DONE[1], Alexandru CERNAT[2], Dinu FUIORESCU [3], Cristian NUTU[4]

The laser Plug Ignition system can replace the Spark Plug Ignition system of the Spark Ignition Engines with advantages on engine performance and reduction of pollutant emissions, a topic research in the last 30 years. 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.

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

1. Introduction

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

Thus, the pollution reduction and fuel efficiency can be controlled at the primary level into 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), shortly defined 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

[1] PhD. student, Faculty of Mechanical Engineering and Mechatronics, University POLITEHNICA of Bucharest, Romania, e-mail: bogdan.done@yahoo.fr
[2] Lecturer, Faculty of Mechanical Engineering and Mechatronics, University POLITEHNICA of Bucharest, Romania.
[3] Lecturer, Faculty of Mechanical Engineering and Mechatronics, University POLITEHNICA of Bucharest, Romania.
[4] Assistant, Faculty of Mechanical Engineering and Mechatronics, University POLITEHNICA of Bucharest, Romania.

(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 principle mechanisms by which laser radiation can ignite combustible gas mixtures [2]:

I. Thermal initiation (TI);
II. Non-resonant breakdown (NRB);
III. Resonant breakdown (RB);
IV. Photo-chemical ignition (PCI).

TI involves the gas mixture consuming laser energy to heat to beyond the threshold ignition temperature [2], [3]. TI is also possible by heating of a target surface in the combustion chamber.

In NRB, which is similar to electric SI, the focused laser beam creates an electric field of sufficient intensity to cause dielectric breakdown of the air-fuel mixture, [1].

RB involves resonant absorption (by the atoms) of laser radiation at one or more specific wavelengths. Mechanism III differs from mechanism II by the fact that the free electrons needed for breakdown are created following two preceding steps: non-resonant (MP) photo-dissociation of a molecule, and then resonant photo-ionization of the atom created by the first step. MP absorption and ionization are thus key initiating steps for both II/ and III/ mechanisms.

PCI involves single photon absorption and dissociation, usually requiring UV light. At high intensities, two-photon or MP absorption in matter can result in release of the accumulated energy as a single high-energy photon. In this way, resonant absorption at short wavelengths by the action of longer wavelength laser light is possible, [5], [6], [7].

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 the cycle variability in engine operation, with benefits on efficiency and emissions, [10], [13]. Basically, the phenomena of cycle dispersion are the results of the variation into combustion process produced by imperfect mixing of in-cylinder fill in terms of homogeneity, by phenomena produced in the formation of 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 in 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].

Recently, researchers from 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].

For the engine K7M 812k, at speed of 1.500 rpm the coefficient of variation $(COV)_{Pmax}$ decreases with 15% and the $(COV)_{IMEP}$ improvement was in range of 18.5% (at 920-mbar load) to 22.6% (at 880-mbar load), [4]. The researchers remark that the cyclic variability of an engine is improved at both high speed and load regimes, showing a less influence of laser Plug Ignition on the coefficients of variability, expected in these conditions [4]. At 2000 rpm speed regime and high 920-mbar load, small differences between $(COV)_{Pmax}$ and $(COV)_{IMEP}$ for classic and LI ignition systems were noticed, [4]. Also, the results indicate a better stability of the car engine that was operated at medium speeds by laser Plug Ignition, resulting in reduced noise, vibrations and mechanical stress, [4].

Mullett and Dearden [5], study the LI system performance and cycle variability on a Ford Zetec engine at the regime of 1500 rev/min and 30° before top dead centre (TDC), [5]. Mullett calculate, for different values laser energy in cylinder changed between 12...16 mJ, the ratio between the COV of IMEP determinant for the LI system and for SI system, [5].

The ratio of COV values for IMEP evaluated for laser Plug Ignition system and for classic ignition system was continuously decreasing 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 $(COV)_{IMEP}$ [8]. Dickinson compares the values of $(COV)_{IMEP}$ 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 $(COV)_{IMEP}$ when operating at 1500 rpm at minimum advance for best torque (MBT), [8].

Shenton, Mullett and Dearden shows that LI system improves the combustion stability, explained by measured values of $(COV)_{IMEP}$, [8]. The author affirms that 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 laser s, 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 particularly exciting 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 this, combined with the capability to control the ignition location and timing, 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.

Through this, it can be verified if the normal engine operation is assured by the new ignition system.

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 Fig. 1.

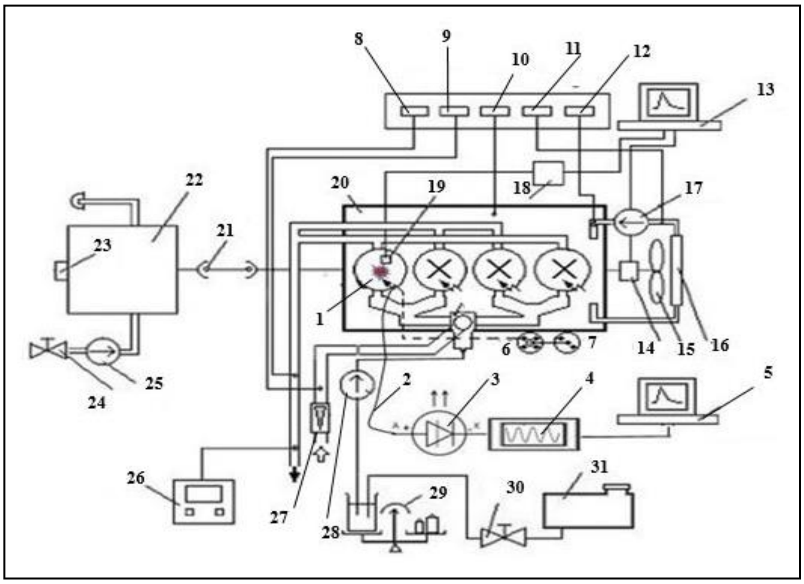

Fig. 1: Experimental test bed schema

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.

Fig. 2.

The laser medium was a Nd:YAG/Cr^{4+}:YAG ceramic structure (Baikowski Co., Japan) that consisted of a 8.0-mm long, 1.0-at.% Nd:YAG ceramic, optically-bonded to a Cr^{4+}:YAG ceramic with saturable absorption (SA) [4], [9]. The initial transmission of Cr^{4+}: YAG SA was around 40%. Monolithic configuration of the resonator was obtained by coating the high reflectivity mirror at lasing wavelength, λ_{em}= 1.06 μm on the Nd:YAG free side and the outcoupling mirror with reflectivity R= 50% at λ_{em} on the Cr^{4+}:YAG free surface. The Nd:YAG side was coated for high transmission (T> 0.98) at the pump wavelength, λ_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 μs and repetition rates up to 100 Hz were used. Typically, the laser yielded pulses with energy of 3.8 mJ at 1.06 μm for the pump with pulses of ~35 mJ at 807 nm; the laser pulse duration was around 1 ns.

Cyclical 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].

$$COVp_{\max} = \frac{\sqrt{\frac{1}{N_C - 1}\sum_{k=1}^{N_C}(p_{\max k} - \bar{p}_{\max})^2}}{\bar{p}_{\max}} \quad (1)$$

$$\bar{p}_{\max} = \frac{1}{N_C}\sum_{k=1}^{N_C} p_{\max k} \quad (2)$$

$$COVp_i = \frac{\sqrt{\frac{1}{N_C - 1}\sum_{k=1}^{N_C}(p_{ik} - \bar{p}_i)^2}}{\bar{p}_{\max}} \quad (3)$$

$$\bar{p}_i = \frac{1}{N_C}\sum_{k=1}^{N_C} p_{ik} \quad (4)$$

Where N_c is the number of cycles, pi represents the indicated mean effective pressure (IMEP) and p_{max} maximum pressure for relation 1 and 3, [10], [13]. The average values of IMEP and maximum pressure are determined with relations 2 and 4, [10], [13]. The coefficients of cycle variability for maximum pressure rise rate $(dp/d\alpha)_{max}$ and the angle where maximum pressure occurs, α_{pmax}, are determined using similar relations, [10], [13].

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 $(COV)_{IMEP}$, is the most suitable instrument to define the engine respond to the combustion process variability.

From this point of view, the limit value of $(COV)_{IMEP}$ 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, λ=0.9 [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 λ=1. For the experimental investigated regime, a number of 175 consecutive cycles were measured with the resolution of 1 CAD (Crank Angle Degree) and registered with the AVL data acquisition system. By the 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.

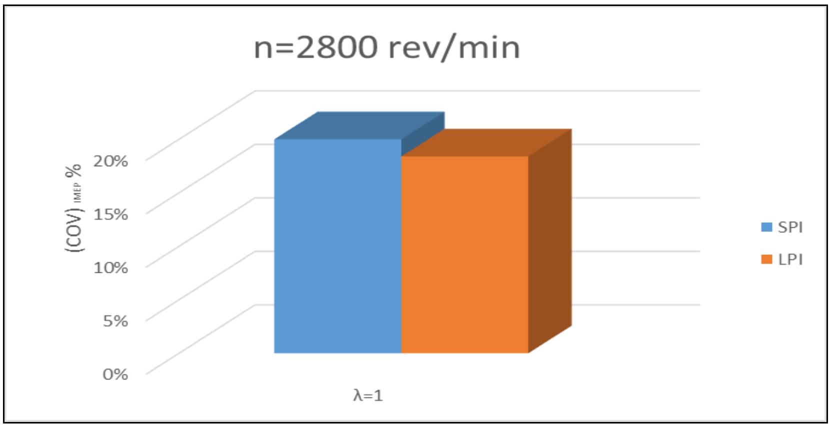

Fig. 3: The $(COV)_{IMEP}$ evaluated for SPI and LPI systems

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 1.6 % 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 laser Plug Ignition system use, as figure shows, indicates a better engine respond at the variability of the combustion process, at $\lambda=1$. 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.

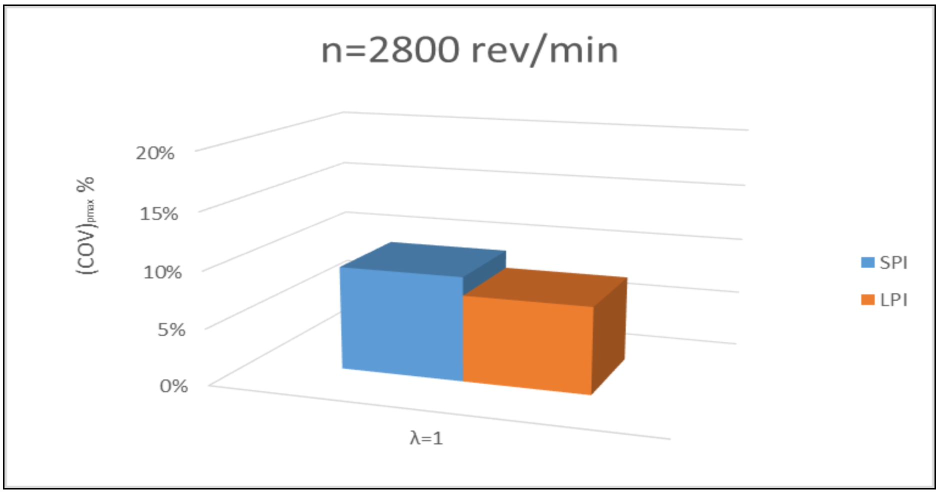

Fig. 4: The $(COV)_{pmax}$ evaluated for SPI and LPI systems

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 9.2% down to 7.6 %. The variability coefficient improves its value with almost 1.6 % 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.

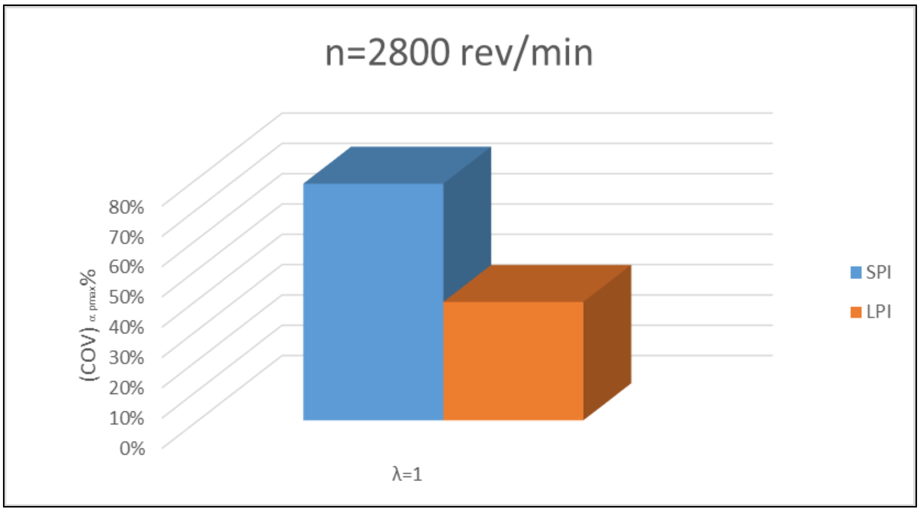

Fig. 5: The (COV) $_{\alpha pmax}$ evaluated for SPI and LPI systems

The COV of maximum pressure angle, illustrated in Figure 5, defined by the angle when maximum pressure occurs per cycle, decreases from 78% value registered for SPI down to 39% for LPI. The decrease of the COV of maximum pressure angle, with 39% 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.

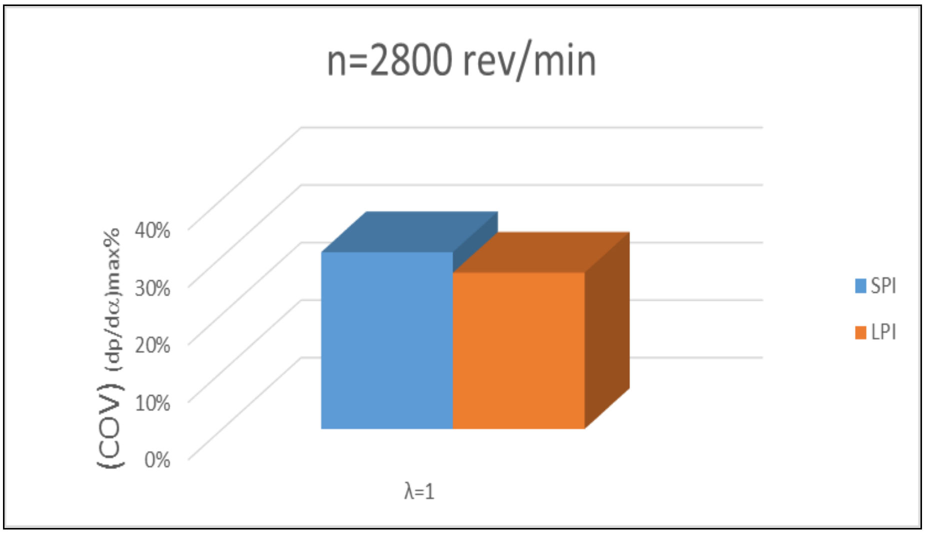

Fig. 6: The (COV)$_{(dp/d\alpha)max}$ evaluated for SPI and LPI systems

The COV of maximum pressure rise rate is presented in Figure 5. The calculated values for the LPI system of the COV of maximum pressure rise rate decreases with almost 4% comparative to the values registered for the classic ignition system with spark plugs. The decrease of the COV for $(dp/d\alpha)_{max}$ 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:

1. The values of COV calculated for IMEP for laser Plug Ignition system (LPI) decrease with 1,6 %, fact that shows an improvement of the combustion stability at the use of laser Plug Ignition system versus classic ignition system.
2. Due to a lower value of $(COV)_{IMEP}$, registered when the laser Plug Ignition system is used, indicates a better engine respond at the variability of the combustion process, for λ=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.
3. The values of $(COV)_{pmax}$ for laser Plug Ignition system (LPI) decrease from 9,2% down to 7,6%, the variability coefficient improves its value with almost 1,6%. The $(COV)_{pmax}$ decrease is in correlation with the variation tendency registered for $(COV)_{IMEP}$.
4. The decrease of the COV of maximum pressure angle, $(COV)_{\alpha pmax}$ with 39% 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 $(COV)_{IMEP}$.
5. The values of COV for maximum pressure rise rate, $(COV)_{(dp/d\alpha)max}$, decreases with almost 4% 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.

6. 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.

R E F E R E N C E S

[1]. *P. D. Ronney,* "laser versus conventional ignition of flames," Opt. Eng. 33(2), 510–522 (1994).

[2]. *C. Morgan,* "laser -Induced Breakdown of Gases," Rep. Prog. Phys. 38(5), 621–665 (1975).

[3]. *S. S. Vorontsov, V. N. Zudov, P. K. Tretyakov, and A. V. Tupikin,* "Peculiarities of the ignition of propane-air premixed flows by CO2 laser radiation," Thermophys. Aeromech. 13(4), 615–621 (2006).

[4]. *N. Pavel, T. Dascalu, G. Salamu, M. Dinca, N. Boicea, and A. Birtas*, "Ignition of an automobile engine by high-peak power Nd:YAG/Cr^{4+}:YAG laser -spark devices," Opt. Express 23(26), 33028-33037 (2015).

[5]. *G. Dearden and T. Shenton*, "laser ignited engines: progress, challenges and prospects," Opt. Express 21(S6 Suppl 6), A1113–A1125 (2013).

[6]. *Y. L. Chen, J. W. L. Lewis, and C. Parigger*, "Spatial & temporal profiles of pulsed laser -induced air plasma emissions," J. Quantitative Spectrosc. Radiative Transf. 67(2), 91–103 (2000).

[7]. *J. D. Mullett,* "Laser-Induced Systemsfor Gasoline Automotivr Engines," PhD Thesis, University of Liverpool (2009).

[8]. *P. B. Dickinson, A. T. Shenton, J. D. Mullett, G. Dearden, and A. Scarisbrick,* "Prospects for laser ignition in gasoline engine control," 10th Int. Symp. on Advanced Vehicle Control (AVEC10), 22–26 (2010).

[9]. *T. Dascalu, G. Salamu, O. Sandu, M. Dinca, and N. Pavel,* "Scaling and passively Q-switch operation of a Nd:YAG laser pumped laterally through a YAG prism," Opt. & laser Techn. 67, 164-168 (2015).

[10]. *Heywood, B.* Internal Combustion Engine Fundamentals. New York; Mcgraw-Hill Book Company; 1988.

[11]. *Negurescu, N. Pana, C. Popa, M. G.* Internal Combustion Engines. Processes. Bucharest; Matrixrom, 2009.

[12]. *Frank, R. Heywood, J.B.* The Effect of Fuel Caracteristics on Combustion in a Spark-Ignited Direct-Injection Engine. SAE 902063.

[13]. *Gaiginschi, R.* Increasing of Running Cycle Stability of the Four Stroke Spark Ignition Engine Operating with Lean Mixtures. Doctoral Thesis; Institute Politehnic of Bucharest; 1976.

[14]. *Sullivan, P., Ancimer, R., and Wallace, J.* (1999), "Turbulence averaging within spark ignition engines", Experiments in Fluids, Vol.27, No.1, pp.92-101.

[15]. Baby X, Dupont A, Ahmed A, Deslandes W, Charnay G and Michard M. A New Methodology to Analyze Cycle-to-Cycle Aerodynamic Variations. SAE 2002-01-2837. 2002.

[16]. *Ghandhi JB, Herold RE, Shakal JS and Strand TE.* Time-Resolved Particle Image Velocimetry Measurements in an Internal Combustion Engine. SAE Paper 2005-01-3868. 2005.