

Aspects of experimental investigations of laser plug ignition use at spark ignition engine

*Bogdan Done**

University POLITEHNICA of Bucharest, Faculty of Mechanical Engineering and Mechatronics,
Department of Thermotechnics, Engines, Thermal and Frigorific Equipment, Splaiul Independentei
no.313, Bucharest, Romania

Abstract. Nowadays, the necessity of pollutant emissions reduction brings to the fore new technologies developed for a better control of the combustion process. Ignition is the process of starting radical reactions until a self-sustaining flame has developed and strongly affects the formation of pollutants. Among the new technologies used for ignition and combustion control, the Laser Plug Ignition system is defined as an innovative technology which overcomes several limitations of conventional spark ignition. Laser ignition technology presents many advantages for engine operating control, engine performance improvement and pollutant emissions reduction. The objective of the paper is the experimental research of the laser ignition used in the spark ignition engine. The laser plug ignition system was mounted on an experimental spark ignition engine and tested at the regime of 90% load and 2800 rpm and dosage, $\lambda=1$. The experimental results present the influence of laser ignition on different engine parameters compared to electric spark ignition. The influence on in-cylinder pressure, heat release rate, engine efficiency and pollutant emissions level is analyzed. Compared to a conventional spark plug, a laser ignition system assures efficient engine operation at lean dosages.

1 Introduction

The negative effects of environmental pollution with gas emissions produced by the combustion of fossil fuels, an interesting aspect discussed also at the 21st Session of the Conference of the Parties from the 2015 Paris Climate Conference in November 2015, brings to the fore more than ever before the necessity of developing new technologies for the control of the combustion process in thermal machines. New technologies can be applied to automotive internal combustion engines in order to improve their performance, efficiency and pollutant emissions by applying a direct control on combustion process, [1-2]. Among the newly developed technologies for combustion management, laser technology is one of the newest and it can be successfully applied in classic spark ignition engines. Laser technology can be used to develop a new Laser Plug Ignition system (LPI) with the ability to control the ignition and combustion processes that will lead to the improvement of engine performance in terms of pollutant emissions and fuel efficiency, [3]. Phases of spark

*Corresponding author: bogdan.done@yahoo.fr

formation in correlation with breakdown intensity and the subsequent ignition, which depends on minimum ignition energy (MIE) must be established for LPI use, [1]. From this point of view the issue may be represented by the fact that the delivered energy is sufficient for ignition but its intensity is very low, so the spark cannot be formed; also, the spark formation may occur but the energy for combustion may be insufficient, [1, 3]. The mechanisms through which laser radiation can ignite a mixture of air-fuel are: thermal initiation (TI), non-resonant breakdown (NRB), resonant breakdown (RB) and photo-chemical ignition (PCI) [3]. During the thermal initiation (TI) phase the laser energy is taken by the in-cylinder mixture, the mixture being heated over the limit ignition temperature. Also, by heating a specific target surface inside the combustion chamber the TI phase can be established [3, 4]. Analogous to the electric spark ignition, during the non-resonant breakdown (NRB) phase the laser beam creates an electric field of high intensity which leads to the dielectric state, [1]. At one or more specific wavelengths, the resonant absorption at atomic level is specific to the resonant breakdown phase (RB). Comparative to NRB, during the RB the free electrons required for the breakdown process are created. There are two preceding stages to create free electrons: the stage of non-resonant (NRPD) photo-dissociation of a molecules and the resonant photo-ionization of the atom created during the NRPD stage. The essential stage for processes of non-resonant breakdown (NRB) and resonant breakdown (RB) is the non-resonant photo-dissociation of a molecules (NRPD) by absorption and ionization. The non-resonant breakdown is a laser ignition mechanism that produces and emits light, heat and a shockwave, [5, 6]. The photo-chemical ignition (PCI) is a process that requires the absorption and dissociation of a single photon in ultraviolet radiation [5, 6]. Two-protons or non-resonant photo-dissociation of a molecule absorption in matter can lead to energy release in the form of a single high-energy photon, when the intensity is high. The advantage of this aspect is that the short wavelengths can be used for resonant absorption based on the action of longer wavelength laser light, [5, 6]. Regarding the mechanism of non-resonant breakdown Dearden et. al. used laser-induced sparks that offer advantage of small size design, but shorter in duration and which operates at higher temperatures [5, 7].

Comparative results regarding the operation of an automobile engine that was ignited with classical spark plugs as well as with laser spark plugs were presented recently by research groups from National Institute for Laser, Plasma and Radiation Physics (INFLPR) and Renault Technologie Roumanie (RTR), Bucharest, Romania [8]. After measurements made for the K7M 812k engine, lower CO and HC emissions level were identified, using the Laser Plug Ignition. At the speed regime of 1500 min^{-1} , due to improvement of the combustion process using laser ignition, the CO emissions decreased by 18...25% and the HC emission decreased by 14...17%. For higher engine speeds, over 2000 min^{-1} , the decreases are limited to ~3%. For laser use the NO_x emission increases by 8% for a speed of 1500 min^{-1} and by 2% for a speed of 2000 min^{-1} , the researchers from INFLPR and RTR explained that the higher flame temperature reached in the first part of combustion leads to the production of significant quantities of NO_x , [8]. As a solution for NO_x emission reduction the INFLPR and RTR propose the increase of EGR rate (Exhaust Gas Recirculation), [8]. The researchers of INFLPR explain the CO_2 emission increases on laser ignition use by stating that the carbon content entering into combustion and resulting from the combustion process is constant and is a compromise between HC and NO_x when the internal combustion engine calibration is necessary, [8]. Measurement results show that the power of the engine ignited by laser system increases by ~3% in comparison with classical ignition system. For INFLPR the most critical problem of laser ignition (LI) use during the experimental investigation was the possibility of destroying the optical element coatings. The optical element is designed to construct the focusing line and during engine operation damage of the lenses from the pump line can sometimes appear, [5, 7, 8]. Usually, the laser lenses are

purchased from the standard market, and are designed with no special coatings. This technical issue is eliminated by the special coating technology applied to the lenses using high-damage threshold layers, [15]. Also, to eliminate this disadvantage the uncoated lenses at critical points in the laser beam (for high intensity laser beam) can be used. The second solution, proposed by many researchers, has already been used for different engines but the deposit of the combustion products on the sapphire window was also present. H. Ranner et. al. [7] investigated and proposed for this problem the solution of self-cleaning, a method that cleans the window with the laser beam itself, and can be done in three steps. As for the first method Ranner [7] explains that the initial part from the higher laser pulse energy, $E_p = 4$ [mJ], was able to clean the laser window, although just partially. The second method is the possibility of using two laser pulses due to the increased duration of the pump pulse. To clean the lenses the first laser pulse was used, this cleaning method being the most efficient. A third cleaning method was applied by Ranner [7] who used a four stroke engine which admits double triggering per cycle. Thus, in order to clean the window of cylinder no. 4 before a new ignition started, the laser pulses were applied to cylinder no. 4 in the exhaust stroke while the ignition was being initiated in cylinder no.1, [7]. The window of laser plugs for cylinder no. 2 and 3 were cleaned in the same way. Due to the fact that Ranner used a water compact cooling system for each laser plug the engine was able to operate for a few hours without coating issues for windows or for optical elements [9, 10]. Mullett and Dearden [5, 11] studied the LI system performance on a Ford Zetec engine at a speed regime of 1500 min^{-1} and 36° before Top Dead Centre (TDC) and calculated several laser energy values between $4 \dots 92$ [mJ], [5].

Regarding the emissions control, the reduction of pollutant emission, especially the NO_x emission, can be successfully assured by the use of exhaust gases to dilute the inlet fresh charge. The use of high ratios of exhaust gas recirculation (EGR), especially in partial load operation regimes, can significantly improve the engine efficiency, knowing that in urban traffic, automobiles consume 30% of their fuel in idle conditions [12, 13]. R. D. Fruechte et al. reach the conclusion that a reduction in idle speed from 800 min^{-1} to 650 min^{-1} could assure fuel savings up to 24% at idle regime [12, 14]. With no electrodes to quench the flame kernel, like in classical spark plugs, the LPI could offer improved cold start performance. Laser energies could be readily increased during cold start to improve the ignitability of the fuel. The experiments made at the Technical University of India, in Lonere-Raigad-Maharashtra, show that LPI has advantages compared to the conventional spark plug ignition (SPI), [15]. The laser ignition system used leads to the attenuation of fuel consumption and to a pollutant emissions decrease by almost 20% compared to the classic spark plug ignition system, [15]. Swapnil Harel et.al. [15] affirm that it is important for these advantages of LI use to be achieved for the same engine noise level and same smoothness of running level. Harel [15] use a frequency-doubled Nd:YAG laser to study the influences of the wavelength on laser ignition process [15], finally finding out that there are no influences. Harel shows that the fuel consumption and the emissions from the exhaust gases can be significantly improved by the use of laser ignition within the fuel spray, [15]. Technology of classic spark plug ignition within the fuel spray cannot be used because the conventional spark plug will not operate normally, the laser plugs not being affected by this issue, [15]. Harel also studied the reliability of the laser ignition system trying to find out if the deposits resulting from the combustion process can affect the laser beam window and the normal running of the laser ignition system, [15]. Using the classic spark plugs ignition system and maintaining the installed the laser beam window in the combustion chamber, the engine ran around 20 hours, at different loads, with simulated regimes of cold start and missfiring. After 100 running cycles the engine was stopped, the laser window was dismantled, inspected and Harel noticed that the deposit from the combustion had been eliminated by the laser beam, [15]. Harel shows that when using a certain threshold intensity at the laser beam entrance window,

the engine can operate normally, without misfiring, [15]. Harel used the high pulse energy of the first few laser pulses only to assure normal engine running at cold start, a fact that was also beneficial for the cleaning process of the beam entrance window [15].

The present paper shows some aspects of the experimental investigation of laser ignition used on an experimental engine equipped with laser plug ignition system. The effects of LI use on in-cylinder pressure, heat release rates and heat release laws versus classic spark plug ignition are analyzed.

2 Experimental investigation

The experimental research was developed on an experimental single cylinder SI engine, equipped with Laser Plug Ignition. The engine operating regime was 2800 rev/min, 90 % load. The experimental single cylinder engine was mounted on the test bed adequate instrumented, its schema being presented in Figure 1.

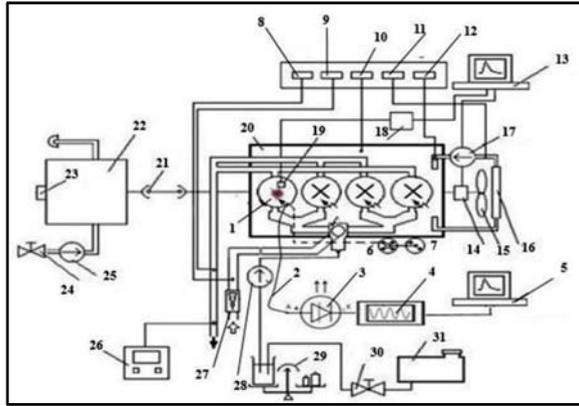


Fig. 1. Experimental test bed schema.

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.



Fig. 2. A photo of a laser spark plug is shown in comparison with a classical spark plug. The plasma induced in air by optical breakdown is visible

The laser spark plug 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 Figure 2.

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) [8, 16]. 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, $\lambda_{em} = 1.06 \mu\text{m}$ on the Nd:YAG free side and the outcoupling mirror with reflectivity $R = 50\%$ at λ_{em} on the Cr4+:YAG free surface. The Nd:YAG side was coated for high transmission ($T > 0.98$) at the pump wavelength, $\lambda_p = 807 \text{ nm}$. 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 $250 \mu\text{s}$ and repetition rates up to 100 Hz were used. Typically, the laser yielded pulses with energy of 3.8 mJ at $1.06 \mu\text{m}$ for the pump with pulses of $\sim 35 \text{ mJ}$ at 807 nm ; the laser pulse duration was around 1 ns .

3 Results

The experimental research was carried on the SI engine initially equipped with Spark Plug Ignition system (SPI), defined as reference and secondly on the engine equipped with Laser Plug Ignition system (LPI). The operating regime was 2800 rev/min , 90% load and air-fuel ratio $\lambda = 1$. For the investigated regime, it was measured with the resolution of 1 CAD and registered with the AVL data acquisition system.

Figure 3 presents the averaged in-cylinder pressure diagrams measured for Spark Ignition System and for Laser Ignition System. The peak pressure rose from 43 bar up to 46 bar . The increase of maximum pressure, by almost 7% , is in correlation with the increase of the maximum pressure rise rate registered for laser ignition versus classic ignition, from 1.7 bar/CAD to 1.9 bar/CAD . Also, the maximum pressure is achieved sooner per cycle for laser ignition compared to spark ignition, the angle of maximum pressure being reached with 2% closer to TDC for Laser Ignition, Figure 3. The initial phase ends ~ 4 degrees sooner for laser ignition compared to the spark ignition system.

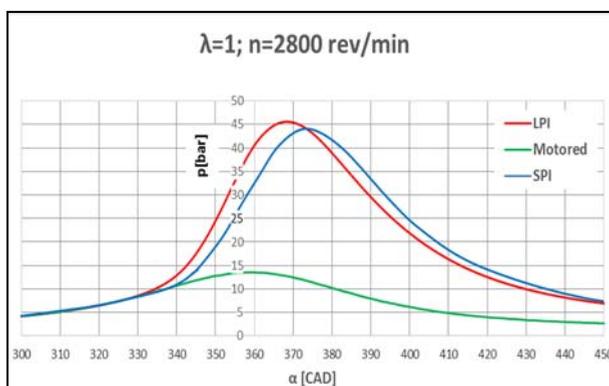


Fig. 3. Pressure diagrams registered for SPI and LPI

Heat release rate is presented in Figure 4. The peak values registered per cycle heat release rate are comparable for laser and classic ignition system, but the maximum is attained 5 CAD sooner per cycle for laser ignition. Also, the heat release rate for laser ignition starts sooner,

4 CAD quicker versus spark ignition and decreases faster, in a much more significant way compared to the tendency registered for classic ignition.

These aspects are in correlation with the heat release allure, Figure 5. For laser ignition system the heat release starts 5 CAD earlier compared to the classic ignition system.

The initial phase of the combustion is reached 6 CAD sooner per cycle and has a shorter duration compared to the classic ignition system, almost 22% shorter, the value decreasing from 9 CAD down to 7 CAD. The reduction of the duration of the initial phase of combustion is due to a much higher energy developed by laser ignition system versus spark ignition system. Also this affects the main phase of the combustion which is registered 6...7 CAD sooner per cycle compared to classic ignition, Figure 4.

The heat release law rises faster for LPI compared to SPI and the 10% of conventional mass fraction burned is reached almost 5 CAD sooner per cycle for LPI system compared to classic ignition system. The 50% mass fraction burned per cycle is achieved before TDC at 355 CAD for laser ignition and at 360 CAD for spark ignition system. The conventional end of the combustion process, reflected by 90% of cycle heat release, appears 8 CAD sooner per cycle for laser ignition system, Figure 5. The main influence of laser ignition is reflected on the combustion process which starts earlier and ends earlier compared to the combustion phenomenology registered for the classic ignition system.

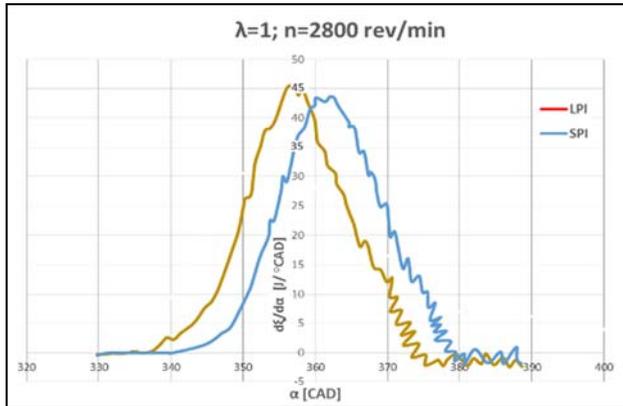


Fig. 4. Heat release rate diagrams evaluated for SPI and LPI

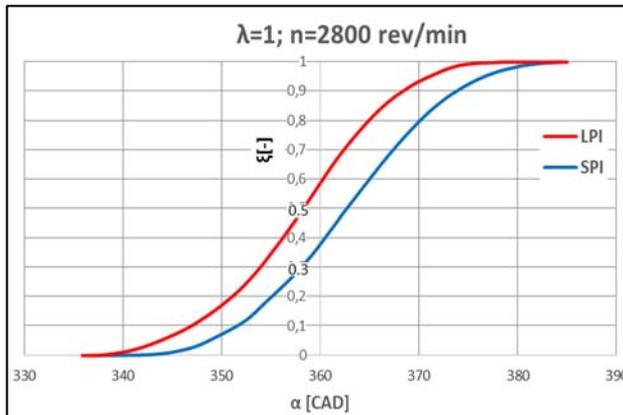


Fig. 5. Heat release law diagrams evaluated for SPI and LPI

4 Conclusions

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

The in-cylinder maximum pressure increases with almost 3 bar on laser use. Also the maximum pressure rise rate registered for classic ignition increases from 1.7 bar/CAD up to 1.9 bar/CAD for laser ignition. The maximum pressure appears earlier per cycle on laser use, the angle of maximum pressure being reached 2 % closer to TDC.

When the laser ignition system is used, the initial phase ends around 4 CAD earlier per cycle comparative to spark ignition system.

The maximum values of heat release rate and heat release law for SPI are comparable to the values registered for LPI, but the heat release rate and the heat release law are reached almost 5 CAD earlier per cycle for laser ignition.

The initial phase of the combustion decreases by 22% at laser ignition use versus the classic ignition system. The stage of 10% heat release per cycle is reached 6 CAD sooner per cycle in the case of the laser ignition system. The reduction of the duration of the initial phase of combustion is due to a much higher energy developed by laser ignition system versus the spark ignition system. 50% of mass fraction burned per cycle is achieved before TDC, 5 CAD earlier for laser ignition.

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