Available online at www.sciencedirect.com

ScienceDirect

Energy Procedia 82 (2015) 89 – 95

Energy Procedia

ATI 2015 - 70th Conference of the ATI Engineering Association

Experimental Characterization of a Multiple Spark Ignition System

Claudio Poggiani[a,*], Michele Battistoni[a], Carlo N. Grimaldi[a], Adriano Magherini[b]

[a]*Dipartimento di Ingegneria – Università di Perugia, Via Duranti 93, Perugia I-06124, Italy*
[b]*Idea Meccanica, Via Fellini 8, San Gemini I-05029, Italy*

Abstract

The paper reports on the experimental analysis of a multiple spark ignition system, carried out with conventional and optical non intrusive methods. The system features a plug-top ignition coil with integrated electronics which delivers high ignition energy and high voltage compared to conventional ignition coils, and is capable of multiple discharges with reduced dwell time. The ignition system is characterized in terms of electrical parameters to evaluate the spark power and energy as a function of different hardware configurations and operating conditions. A high speed camera is used to visualize, at different ambient pressures, the time evolution of the electric arc discharge in order to highlight its position variability, which could have an impact on combustion kernel development and deflagration front stability in engines.

Peer-review under responsibility of the Scientific Committee of ATI 2015

Keywords: multiple spark ignition systems, SI engines, optical analysis, cycle to cycle variation, combustion stability.

1. Introduction

In 2010 the total amount of vehicles on the road reached more than 1 billion worldwide, and this number keeps increasing every day. This fact poses important mobility challenges, and pushes toward the reduction of energy consumption and CO2 emissions. In fact the use of internal combustion engines for road vehicle propulsion will continue for several years, because it is very unlikely that the entire fleet will be completely replaced, in the short and medium term, by electric vehicles with energy produced from renewable sources. Accordingly, research on internal combustion engines is nowadays even more imperative, in order to reduce their environmental impact and their energy consumption.

The SI engines are the most common for passenger cars and their development is therefore very important. The main research and development lines of SI ICEs currently concern the engine downsizing,

* Corresponding author. Tel.: +39-075-585-3749.
E-mail address: claudio.poggiani@studenti.unipg.it.

Peer-review under responsibility of the Scientific Committee of ATI 2015
doi:10.1016/j.egypro.2015.11.887

turbocharging, GDI injection systems in order to obtain stratified or homogeneous charge in the combustion chamber, thermal management systems [1, 2], VVA systems [3, 4] to allow pumping work reduction at part load or internal EGR, advanced ignition systems.

In case of operation in lean or diluted conditions, it is very important to obtain a reliable ignition of the air-fuel mixture, overcoming the problems that may arise by the occurrence of misfire, or from values of the coefficient of variance (COV) of the mean effective pressure above of 5%.

Besides the development of stratified charge combustion chambers, also suitable ignition systems can help the first flame kernel generated after the ignition to develop a stable deflagration front. In this framework, in recent years different advanced ignition systems, characterized by different types of electrical discharge, have been studied: multi-spark discharge, continuous discharge, repetitive pulse discharge, corona effect, discharge, etc. [5, 6, 7, 8].

As mentioned above, one of the main purposes of such ignition systems is to decrease the COV of IMEP, which strongly depends on the characteristics of the development process of the deflagration front, mainly in the early combustion stage. Influencing factors are the local air-fuel ratio, the local flow field, and, last but not least, the energy and location of the electrical discharge produced by the ignition system [9]. In other words, it is believed that not only the spark energy, but also the spark location may play an important role in the interaction with mixture composition and charge motion; moreover the spatial distribution, between the spark electrodes gap, of the energy supplied by the discharge can also play a role in the development of advanced CFD-3D simulation codes [10, 11].

In this paper a Multi-Spark Discharge (MSD) ignition system provided by Federal Mogul has been analyzed. Energy and location of the ignition spark have been studied, using conventional electrical measurement systems and a high-speed camera for the direct observation of discharge phenomena.

2. Experimental Setup and Test Plan

This experimental study was carried out by analyzing the behavior of different configurations and operating conditions of the MSD system supplied by Federal Mogul. The system is composed of a plug-top coil and a programmable interface; two types of coils were used, the *slow* one (MSP2), characterized by a charge time $t_{ch} = 3$ ms, and the *fast* one (MSP3), with $t_{ch} = 1.2$ ms. By programming the interface, the number of commanded spark events can be set, up to a maximum of 17.

In the tests presented in this work, the MSP2 coil was operated in *single spark* mode, and this case was considered as the reference, and in *4 spark train* mode; while the MSP3 coil was programmed to work in *4 spark train* and in *9 spark train* modes.

In order to analyze the dependency of the system behavior on the ambient pressure, a closed vessel was designed and set up, with a wide optical access, and capable of operating at pressures up to 10 bar. Square 64x64 pixel images of the spark events have been recorded by means of a Vision Research Phantom V710 high speed camera, working at 130,000 frames per second, with a 7 μs exposure time and a 7.7 μm/pixel spatial resolution. The spark voltage V_s and current I_s were measured at 2 Msample/s rate by a digital oscilloscope, and recorded in 2 Msamples long traces (1 s total time). A pulse generator was set at 50 Hz to drive the spark train frequency, corresponding to a 4-stroke engine speed of 6000 rpm.

All the collected data have been post-processed by a suitable code developed by the authors in Matlab(r). The power W_S is determined, as a function of time, from V_s and I_s values, along with the corresponding energy E value; the mean value of the energy supplied by the spark trains, the σ and the COV are also calculated. The about 130,000 images collected in each test were used to determine the spark average position, in terms of its X and Y coordinates, by retaining the points with a brightness level above a prefixed threshold value. Besides the spark position, also the spark brightness level was calculated, in order to check the correlation with the instantaneous power level, as a function of time;

these kind of spatial energy maps could also be used in possible future studies as input data for numerical simulations of the ignition process.

The tests were performed using commercial spark plugs, with two different electrode gaps (0.85 mm and 1.00 mm) according to the following Table 1

Table 1. Test plan for gap 0.85 mm and for gap 1.00 mm spark plugs (overall, 16 operating conditions)

Coil Type	p_{air}, bar	No. of sparks in the train
MSP2	3	1 and 4
	6	1 and 4
MSP3	3	4 and 9
	6	4 and 9

3. Experimental Tests, Results and Comments

The main parameter wich characterizes a spark is the power W_S developed by the discharge process. Typical patterns of the power evolution in time of the MSD system analyzed in this work, are presented in Fig. 1: the typical curves are shown, related to the three main MSD system operating conditions used in these tests: single spark, four spark and nine sparks trains.

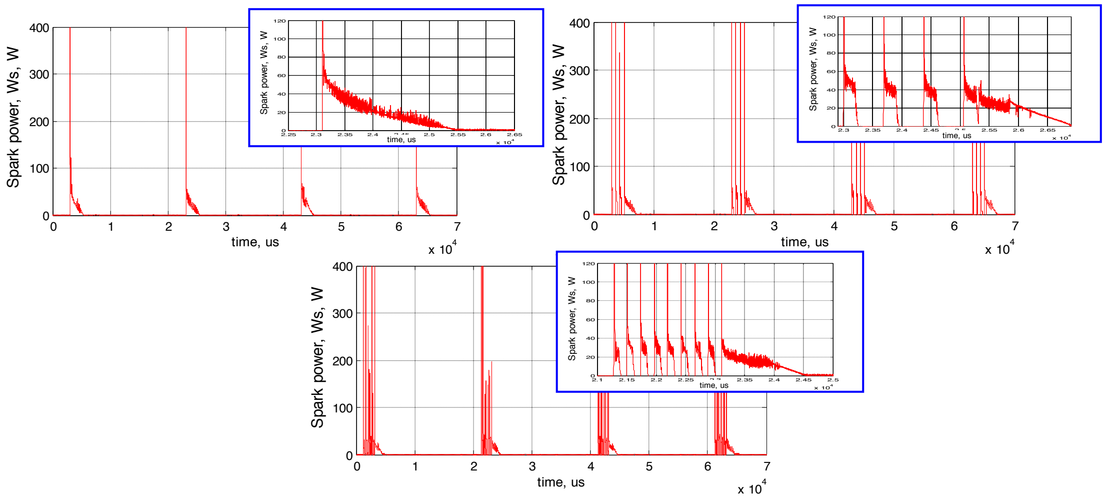


Fig. 1. Typical spark power patterns: (a) single spark; (b) four spark train; (c) nine spark train

Observing the W trends in Figure 1, three typical characteristic times for each operating mode can be defined: Δt, the time between two subsequent power rises; t_{ON}, the duration of each discharge event; t_{tail}, the duration of the last discharge event of each train.

As far as the discharge process visualization is concerned, two typical image series are reported in Fig. 2, where each image is taken during one of the nine sparks of a train. It can be noted that in the first train the spark channel moves from left to right, in opposite direction the second train.

Each of the about 130,000 images collected in each test performed on the bench shown in Fig. 3a, were post-processed analysing the brightness levels of each pixel. The Matlab code developed in this work was used to determine the location of the spark average position, by retaining the points with a brightness level above a prefixed threshold value, and to evaluate the global brightness of the discharge channel, frame by frame. An example of the different positions of the spark images average position are reported in Fig. 3b, superimposed to the image of the spark plug electrodes.

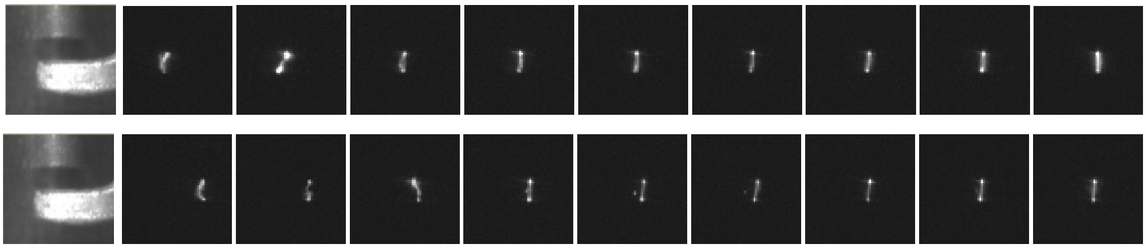


Fig. 2. Typical spark image series (nine spark trains)

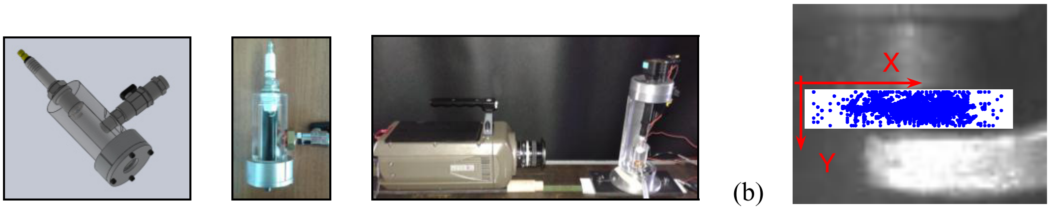


Fig. 3. (a) test bench with the pressurized vessel, (b) example of spark average position sequence

In Fig. 4 an example of the spark brightness trends obtained from the image post-processing is shown: the comparison with the simultaneously acquired electric power trends shows a strong correspondence. The good correlation between light and power levels confirms the observations presented in [6], were the use of spatial energy maps as input data for numerical simulations of the ignition process was proposed.

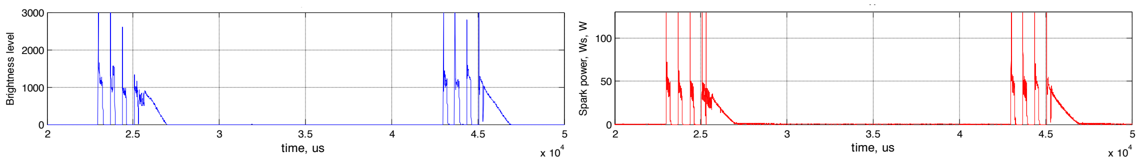


Fig. 4. Synchronous signals: (a) spark brightness level, (b) spark power level

3.1. Energy analysis

In order to highlight the influence of the operating parameters on the main characteristics of the spark energy release process, in the following the detailed results concerning 6 of the examined cases are discussed (Table 2), where the mean value, the standard deviation and the COV of energy release are also reported.

The levels of energy released as a function of time for subsequent discharge events in Case 1 operating conditions are reported in Fig. 5a, obtained by integrating the spark power, also shown in the same figure: the global level of energy released per each event is about 50 mJ. If the 4 spark mode is set on the same MSP2 coil (Case 2, Fig.5b), the overall energy level rises to about 68 mJ per train of sparks: it has to be noted that about 40 mJ are released by the last spark, value that remains almost constant for different events, while the little differences between train overall values can be ascribed to the first three sparks.

Table 2. Spark energy release results.

#	Case	E, mJ	□□ □ mJ	COV,
1	Gap 0,85 - MSP2 – 3 bar – 1	50,25	1,96	3,91
2	Gap 0,85 - MSP2 – 3 bar – 4	67,91	3,11	4,58
3	Gap 0,85 - MSP2 – 6 bar – 4	65,66	3,52	5,36
4	Gap 0,85 - MSP3 – 6 bar – 4	37,33	1,43	3,82
5	Gap 0,85 - MSP3 – 6 bar – 9	50,25	1,90	3,78
6	Gap 1.00 - MSP3 – 6 bar – 9	51,29	2,05	4,00

The increase of the test pressure to 6 bar (Case 3), keeping other parameters unchanged, does not cause remarkable changes in energy release, while the adoption of the MSP3 *fast* coil (Case 4, Fig.5c) produces variations in energy release trend and maximum value (that drops to about 37 mJ): the reason lies in the shorter t_{ON} time (from 280 µs in Case 2 and 3, to 140 µs in Case 4), while also the shorter Δt interval (from 700 µs to 240 µs) between two subsequent spark events of the same train, causes the steps in the trend to be less noticeable.

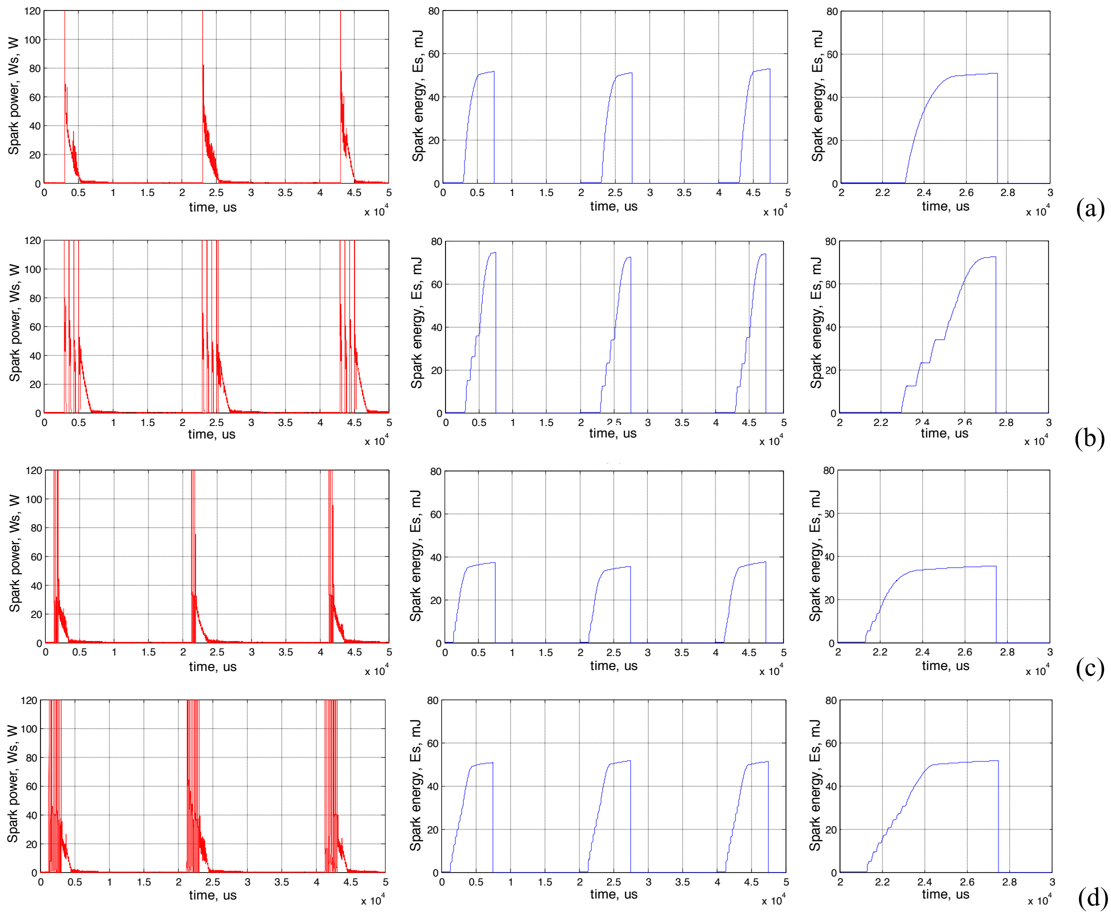


Fig. 5. Spark power and energy release results: (a) Case 1, (b) Case 2, (c) Case 4, (d) Case 5.

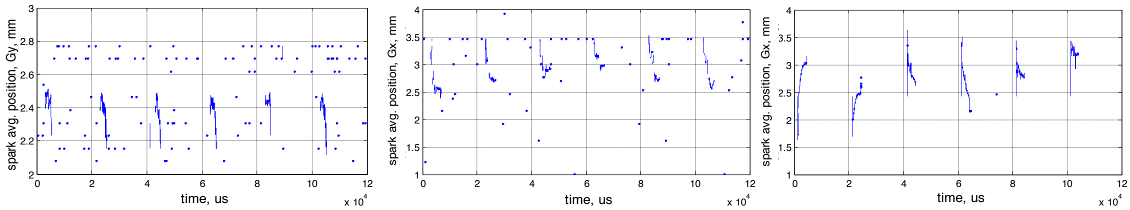
As it could be expected, in Case 5 (Fig.5d) the occurrence of 9 sparks causes a greater energy release by the train (about 50 mJ) if compared to Case 4, while Case 6 (gap between electrodes rising to 1 mm) does not produce notable effects.

3.2. Spark position analysis

The main results of the image processing, in terms of average spark position, are shown in Fig.6: X and Y coordinates are reported as a function of time, in separate plots, in order to highlight movements and/or distortion phenomena of the discharge channel that could be expected to take place in different ways along the main directions in the image plane.

As a matter of fact, along the Y (vertical) coordinate, spark movements are present but necessarily limited between the two physical boundaries represented by the electrodes: as an example, Gy plot for Case 1 reported in Fig.6a shows that the average vertical position varies during the spark discharge, but remains within few tenths of millimiter. This behaviour holds true for the different spark events and also for all other cases.

Differently, along the X axis the spark channel has a greater freedom of movement. In Fig.6 the Gx plots shows a greater variation in time of the average position: during a single discharge event, among the different sparks of one train, and among different trains (Fig.6b, Case 2, as an example). In some cases the position variation in X exceeds 1 mm in a single train, 1.5 mm in sequences of more events (Fig.6c, Case 6). Such a level of variability of the spark channel position encourages further insights.



(a) (b) (c)

Fig. 6. Spark channel average positions: (a) G_y in Case 1, (b) G_x in Case 2, (c) G_x in Case 6.

4. Conclusions and Future Work

In this work the experimental analysis of a multiple spark ignition system was presented, determining the performance in terms of energy release, and evaluating the related coefficient of variance COV: the values found, between 3.5% and 5% suggests a possible influence on the COV of the IMEP during an engine operation, which should be further investigated at the engine test bench.

An optical non intrusive analysis was also carried out, observing the discharge phenomenon in different conditions: it was found a good correspondence between brightness level evolution in time and synchronous spark power signal. The average position of the discharge channel was also determined, highlighting, in the zone between the two electrodes, variations along the horizontal direction that could result in a larger variability of the flame front after the first combustion kernel formation.

Acknowledgements

The authors wish to thank Federal Mogul Italy for having supplied the MSD system components, and the members of the Champion Research Dept. Massimo Dal Re and Giuseppe Fulchini for the helpful discussions and hints during this work.

References

[1] Lin, C., Xu, S., Li, Z., and Chang, G., "Design and Thermal Analysis of a Passive Thermal Management System Using Composite Phase Change Material for Rectangular Power Batteries", SAE 2015-01-0254.

[2] Grimaldi, C:N:, Poggiani, C., Cimarello, A., De Cesare, M., Osbat, G., "An Integrated Simulation Methodology of Thermal Management Systems for the CO2 Reduction after Engine Cold Start", SAE 2015-01-0343.

[3] Jain, A., Tikar, S., Ramdasi, S., Thipse, S. et al., "Design and Development of Variable Valve Actuation (VVA) Mechanism Concept for Multi-Cylinder Engine", SAE 2015-26-0021.

[4] Postrioti, L., Battistoni, M., Foschini, L., Flora, R., "Application of a Fully Flexible Electro-Hydraulic Camless System to a Research SI Engine", SAE 2009-24-0076.

[5] Heise, V., Farah, P., Husted, H., and Wolf, E., "High Frequency Ignition System for Gasoline Direct Injection Engines," SAE 2011-01-1223.

[6] Alger, T., Gingrich, J., Roberts, C., Mangold, B. et al., "A High-Energy Continuous Discharge Ignition System for Dilute Engine Applications," SAE Technical Paper 2013-01-1628.

[7] Burrows, J., Reinicke, P.B., Riess,M., Sens,M., Mixell, K., "Corona ignition-assessment of physical effects by pressure chamber, rapid compression machine and single cylinder engine testing", 2nd Int. Conf. on Ignition Systems for Gasoline Engines, IAV, Nov 24–25, 2014, Berlin.

[8] Wolf, T., Schenk, M., Schröter, M., Zellinger, F., Klaus, B., Pfeiffer, D., Fischer, H., "RF corona ignition vs. spark ignition: a comparison for varying thermodynamic conditions and combustion strategies of modern turbocharged gasoline engines", 2nd Int. Conf. on Ignition Systems for Gasoline Engines, Nov 24–25, 2014, Berlin.

[9] Zhang, A., Cung, K., Lee, S., Naber, J. et al., "The Impact of Spark Discharge Pattern on Flame Initiation in a Turbulent Lean and Dilute Mixture in a Pressurized Combustion Vessel," SAE Int. J. Engines 6(1):435-446, 2013.

[10] Yorita, H., Okabe, S., Ishiguro, H., and Shibata, M., "Ignition Simulation and Visualization for Spark Plug Electrode Design," SAE Technical Paper 2007-01-0940

[11] Schaefer, L., Linse, D., Hasse, C.,"3D-CFD spark ignition model for gasoline engines including detailed chemical kinetics, curvature and diffusion effects", 2nd International Conference on Ignition Systems for Gasoline Engines, IAV, November 24–25, 2014, Berlin.

Biography

Claudio Poggiani, was born in San Gemini (TR) on 12/12/1985. Graduated in Mechanical Engineering at the University of Perugia in 2011, currently he is in the third year of his PhD program in Industrial Engineering. His research interests are primarily in the automotive field, focusing on engines experimental activities, 1D engine cycle simulations, and experiments on optical access engines.