

Experimental Evaluation of an Advanced Ignition System for GDI Engines

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ABSTRACT

A plasma ignition system was tested in a GDI engine with the target of combustion efficiency improvement without modifying engine configuration. The plasma was generated by spark discharge and successively sustained to enhance its duration up to 4 ms.

The innovative ignition system was tested in an optically accessible single-cylinder DISI engine to investigate the effects of plasma on kernel stability and flame front propagation under low loads and lean mixture ($\lambda \cong 1.3$). The engine was equipped with the head of a commercial turbocharged engine with similar geometrical specifications (bore, stroke, compression ratio). All experiments were performed at 2000 rpm and 100 bar injection pressure.

UV-visible 2D chemiluminescence was applied in order to study the flame front inception and propagation with particular interest in the early combustion stages. A bandpass filter allowed selecting luminous signal due to OH radicals. Plasma ignition improved the efficiency and stability of early combustion stages. Moreover, increase in the OH emission intensity and area was detected. Flame front and OH emissions morphology were correlated with thermodynamic data and CO, NO_x, HC exhaust emissions.

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INTRODUCTION

Ever increasing energy demand and stringent regulations on combustion emissions represent a major challenge to renovate conventional combustion technology in order to drastically improve conversion efficiency, fuel flexibility and reduce pollutant emissions [1]. These issues have led policy-makers, automotive manufacturers and researchers to elaborate technological solutions [2] and advanced combustion modes essentially based on higher pressure working conditions, lower flame temperature, leaner charge mixture and on the use of alternative fuels [3], [4], [5].

Extensive experimental and numerical investigations demonstrated that improvements in spark ignition (SI) engines efficiency can be realized through high-pressure direct injection and "downsizing" by turbo-charging [6], [7]. In this way an equivalent engine performance with a smaller displacement can be achieved [1]. In addition "down-speeding" enables the engine to be operated at an equivalent output at a substantially lower engine speed [8].

Moreover, with the aim of an efficiency increase without penalty in terms of driving performance, a higher compression ratio is needed for improved fuel economy in the part-load range, as well as high

torque. This can be performed through higher boosting levels which in the lower revolutions range, lead to abnormal combustion events, such as pre-ignition and heavy knocking [9], [10], [11], [12], [13].

Mitigation strategies are basically oriented towards changing fuel properties and octane ratings [14], [15], [16] that on the other hand can induce issues due to weaker vaporization properties. In part load conditions, EGR is preferred in respect to lean operation, as it allows the use of three way catalytic technology for obtaining low emission levels and can reduce pumping losses [17], [18], [19]. On the contrary, EGR increases combustion instability, thus limiting its maximum acceptable level even for high reactivity fuels [20].

To support the new technological innovations and improve engine stability, alternative ignition systems have been developed [21], [22], [23]. Impressive results have been achieved by plasma assisted ignition (PAI) [24], [25] through microwave discharge [26], multi-spark discharges [27], radio frequency discharge [28], laser ignition [29], [30], as well as corona [31] and nanosecond pulsed discharge [32]. Experiments on production and research engines demonstrated that PAI permits to extend the lean operation limit and to improve engine efficiency at all engine loads [33], [34], [35]. Exhaust emission measurements show no differences for CO and HC emissions, while NO_x levels are higher with the plasma systems due to faster combustion [36].

Although the effectiveness of plasma in combustion has been widely demonstrated, more work is necessary to define the most important kinetic pathways, radicals, and excited intermediate species that featured PAI in internal combustion engines. In fact, despite of conventional spark ignition systems, PAI exploits new reaction pathways, such as atomic O production from the collisions between high energy electrons or ions and oxygen molecules that can strongly modify fuel oxidation mechanisms in combustion systems [21], [24], [25].

In this paper, an innovative plasma assisted ignition system, developed by Eldor Corporation spa, was used in a GDI engine. The work was aimed at investigating the effect of PAI on combustion process in lean burn condition ($\lambda \approx 1.3$) at part load. All experiments were performed at 2000 rpm and 100 bar injection pressure in a transparent single-cylinder DISI engine equipped with the head of a commercial turbocharged engine with similar geometrical specifications (bore, stroke, and compression ratio). Crank angle resolved 2D chemiluminescence in the UV-visible range and at 310 nm was used to follow the temporal and spatial evolution of the flame front and OH radical in the combustion chamber. Macroscopic flame and OH emission parameters, such as area and distortion were correlated with thermodynamic data during the early combustion stage (up to 10%MFB).

EXPERIMENTAL SETUP AND METHODS

An optically accessible DISI engine was used for performing the investigations (Figure 1). The cylinder head of a 4-cylinder, 16 valve commercial power unit was coupled to the cylinder block; it featured a wall-guided 100 bar injection system, with a 6-hole injector placed on the intake valves side and oriented so that the fuel jet impinges primarily on the piston crown.

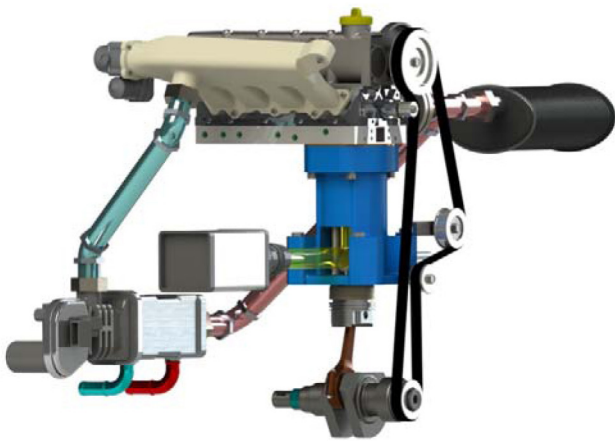


Figure 1. Schematic of the experimental setup.

Engine geometry and valves timing are listed in Table 1 (with IVO and IVC for intake valves opening and closure, EVO and EVC for exhaust valves opening and closure, CAD for crank angle degrees, TDC for top dead centre, with B for before and A for after; all references are made to the TDC at the end of compression).

Table 1. Engine specifications

Displacement	399 cm ³
Stroke	81.3 mm
Bore	79.0 mm
Connecting Rod	143 mm
Compression ratio	10:1
Number of Valves	4
IVO	357 CAD ATDC
IVC	144 CAD BTDC
EVO	153 CAD ATDC
EVC	0 CAD ATDC
Ignition	centrally located spark plug

Optical measurements were performed via the access provided by a 18 mm thick fused silica window fitted in the piston crown; the Bowditch design allowed a 45 degree UV-enhanced mirror to be mounted beneath the transparent window, and the reflected natural flame emission was recorded with an ICCD camera. It should be noted that all recorded images were acquired via the field of view from the bottom of the combustion chamber that ensured $\sim 75\%$ coverage of the entire cross-section of the cylinder bore.

Sealing was guaranteed by two uninterrupted Teflon-bronze rings that along with a slotted graphite ring allowed oil-less lubrication on the upper part of the engine. Coolant and lubricant temperature was maintained at 335-340 K, at the upper limit recommended for the uninterrupted sealing rings. Intake air temperature was around 300 K and ambient pressure was 1 atm. A fixed value for engine speed was set at 2000 rpm, chosen as representative for mid-road load automotive use.

A specific procedure was applied for experiments: after 1 min of warm-up in motored condition, the engine worked 1 min in fired condition. The pressure signals were acquired on 200 consecutive engine cycles and the optical measurements were carried out in the last 100 cycles to reach more stable operation.

Intake pressure was set at 0.65 bar and fuel delivery was performed in a single event, with the start of injection (SOI) set at 300 CAD BTDC. Lean air-fuel mixtures were set (i.e. $\lambda \approx 1.3$) based on the readings of a wide band oxygen sensor (with an accuracy of $\pm 1\%$) fitted at the exhaust. Spark timing was swept in order to identify the point of maximum brake torque (MBT) that represented the basis for choosing the conditions for optical measurements.

Pollutant exhaust gas concentrations were determined through a gas analyser using the non-dispersive infrared measurement principle for carbon monoxide (CO) and unburned hydrocarbons (HC), and the electrochemical method for nitrogen oxides (NO_x) emissions. Accuracy was within $\pm 3\%$ and the resolution of readings for the first component was 0.01% and 1 ppm for the other two species.

Ignition Systems

An automotive ignition system was used as reference case. The ignition coil was charged for 3.3ms in order to achieve the optimum current level at the time of start of spark (SOS). For the plasma assisted ignition, an innovative system developed by Eldor was used. Specific coil and electronic control unit were used whereas the commercial NGK spark plug (0.8 mm gap) was maintained. The system breaks down the dielectric in the same way of standard ignition system, and then supports the plasma by keeping the spark current constant thanks to a closed loop control.

For standard ignition systems, the actual spark duration heavily affects efficiency (i.e. how energy is transferred to the working fluid) due to specific issues of energy storage before being delivered to the spark plug's electrodes. In the plasma assisted ignition (PAI) system considered, energy (80mJ) is released in periods of 1ms (in this case 4 successive periods per engine cycle) of sustained plasma; it should be noted that previous investigations identified the total sustained plasma period of 4ms as the optimum value for achieving the best improvement of engine output and stability. Plasma ignition systems can improve combustion quality through three pathways, namely thermal, kinetic and transport [24], [36], [37]. In the thermal mechanism, plasma increases temperature and accelerates chemical reactions and fuel oxidation. In the kinetic pathway, high energy electrons and ions produced by the plasma generate other active radicals (as OH) via impact and recombination dissociation, and collision dissociations of reactants with excited molecules. In addition, plasma can produce long-lifetime reactive (as O_3) and catalytic intermediate species (as NO) that can speed up fuel oxidation. The balance among the enhancement combustion mechanisms induced by plasma ignition is strongly related to the engine operative conditions. Moreover, quantitative results of PAI effect on flame front propagation, particularly in GDI engines, have not been achieved.

As a monitor for the correct operation of the plasma control, the secondary current was routed to an amplifier and there forth acquired with the same resolution of 0.2 CAD as for the in-cylinder pressure signal (see [appendix](#) for details). In this way, a direct correlation between recorded thermodynamic data and the operation of the ignition system can be ensured. In [Figure 2](#), a typical PAI trace corresponding to a current of 70 mA and 4ms plasma duration is reported. It can be observed that after the initial discharge phase with up to 40kV break down voltage, plasma was maintained by applying a voltage of 2kV for a duration of 4 ms with an alternating current at 10-20kHz for 40-70mA.

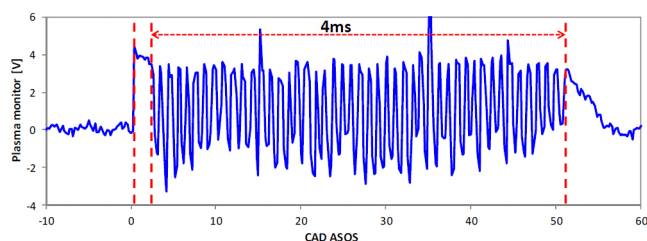


Figure 2. Typical plasma ignition trace (70 mA current; 4ms plasma duration) detected at 2000 rpm in lean burn condition and part load.

Optical Measurements and Data Processing

UV-visible chemiluminescence crank angle resolved imaging was applied to visualize the flame inception and growth in the combustion chamber. Synchronization of various control triggers for ignition, injection and camera was achieved using the optical encoder mounted on the crankshaft as an external clock connected to an electronic timing unit.

During the UV-visible chemiluminescence investigations (200-750nm wavelength), the radiative emission from the combustion chamber was detected through a 78 mm focal length, f/3.8 UV Nikon by an intensified CCD camera (array size of 1024×1024 pixels with a pixel size of $13 \times 13 \mu\text{m}$, 16-bit pixel digitization and 1MHz sustained repetition rate). The intensified camera was employed in full-chip configuration. The set-up allowed a resolution of $90 \mu\text{m}$ per pixel. In addition to the broadband acquisition that exploits the high quantum efficiency of the ICCD in the spectral range 250-700 nm, one $50 \times 50\text{mm}$ band-pass filter (Asahi Spectra Inc.) was used to selectively record flame emissions at 310 nm. The high transmission (65%) and small width (4 nm FWHM) allowed selecting the OH emission due to A-X transition [38] without interference due to other species [39], [40], [41].

For both optical configurations (UV-visible chemiluminescence and OH detection), ICCD sequential and repetitive gating modes were used in order to obtain data related to the optical signal evolution during the combustion process (sequential mode) and to perform a suitable statistical analysis at fixed crank angle after the spark timing (repetitive mode). Sequential acquisition allowed collecting one frame per cycle with fixed gate width but variable delay with respect to the trigger. This corresponded to the falling edge of the ignition coil charge signal. Optical data were recorded at a step of 1 CAD at 2000 rpm (83 μs), with an exposure time of 83 μs . Repetitive mode detected one frame per cycle with fixed gate width (83 μs) and delay with respect to the trigger. All the optical investigations were carried out on 100 consecutive engine cycles. Macroscopic parameters related to the flame morphology were evaluated via image processing by Vision Assistant 2011 of National Instruments. [Figure 3](#) shows schematically the steps of image processing. The procedure was able to retrieve quantitative information from the combustion visualization also for images with low signal to noise ratio. In details, [Fig. 3a](#) shows the transition from the false-colour 16-bit image to the 8-bit grey-level image by applying a circular mask and extracting the intensity plane. Successively, the look-up table of the images was adjusted by fixing the brightness at 175, contrast at 55 and the gamma value at 0.76. ([Figure 3b](#)). After this phase, a binarization procedure was applied. In particular an automatic thresholding was performed ([Figure 3c](#)).

It does not require setting minimum and maximum image intensities by the user [42], [43]. Specifically the “cluster” methods named “inter-variance” was applied [44]; it is based on selecting a threshold for segmenting the image into two classes so that the variance within each class is minimized [45].

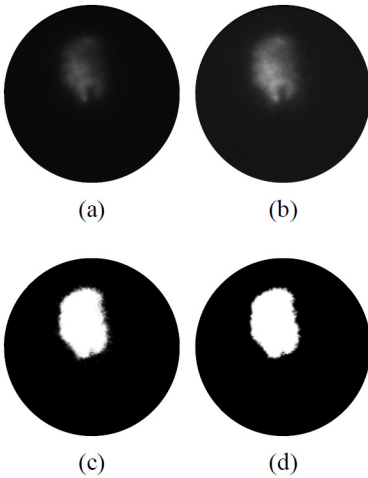


Figure 3. Sketch of the image processing steps.

Assuming an image is represented in L grey levels $[0, 1, \dots, L-1]$, the number of pixels at level i is denoted by n_i , and the total number of pixels is denoted by N . The probability p_i of gray level is calculated,

$$p_i = n_i/N; p_i \geq 0; \sum_{i=0}^{L-1} p_i = 1, \quad (1)$$

and pixels are divided into two classes, namely C_1 with grey levels in the range of $[0..t]$ and C_2 for grey levels $[t+1..L-1]$, with t as the threshold. The grey level distributions for the two classes can be calculated using eq. (2),

$$w_1 = Pr(C_1) = \sum_{i=0}^t p_i; w_2 = Pr(C_2) = \sum_{i=t+1}^{L-1} p_i, \quad (2)$$

and the mean grey levels for classes C_1 and C_2 are

$$u_1 = \sum_{i=0}^t (i \cdot p_i) / w_1; u_2 = \sum_{i=t+1}^{L-1} (i \cdot p_i) / w_2, \quad (3)$$

with the total mean of grey levels $u_t = w_1 \cdot u_1 + w_2 \cdot u_2$. The variance for each class can be calculated using equation (4),

$$\sigma_1^2 = \sum_{i=0}^t (i - u_1)^2 / w_1; \sigma_2^2 = \sum_{i=t+1}^{L-1} (i - u_2)^2 / w_1, \quad (4)$$

with the within (σ_w) given as

$$\sigma_w^2 = \sum_k w_k \cdot \sigma_k^2, \quad (5)$$

and between class variance (σ_b) given as

$$\sigma_b^2 = w_1 \cdot (u_1 - u_T)^2 + w_2 \cdot (u_2 - u_T)^2, \quad (6)$$

and the total variance of grey levels is $\sigma_T^2 = \sigma_w^2 + \sigma_b^2$.

Despite of the classical Otsu's method that chooses the optimal threshold t by maximizing the between-class variance [46], the inter-variance method minimizes the within-class variance [47].

After the definition of the threshold (Fig. 3c), a low-pass frequency filter with 55% truncation frequency was applied through a fast Fourier transform (FFT) of the foreground (Fig. 3d) to remove small border objects [48].

For each binarised image, the effective area (total number of pixels in the foreground), the Waddell disk diameter (a disk with the same area as the foreground) and the elongation factor were evaluated [49], [50]. The elongation factor is calculated as the ratio between the maximum Feret diameter and the equivalent rectangle short side. Elongation factor of a circle is 1, deviation from 1 features a distorted shape. More elongated is the shape, higher is the elongation factor. Elongation factors lower than 1 are typical for strongly convex shapes with deep negative curvature.

In-cylinder Pressure Measurement and Analysis

A piezo-electric transducer was used for measuring in-cylinder pressure with an accuracy of $\pm 1\%$, at a resolution of 0.2 CAD; acquisition triggering and synchronization with the engine's crank shaft rotation was performed via an optical crank angle encoder. Pressure pegging was achieved by using the signal given by a piezoresistive pressure transducer fitted on the intake manifold. The combined accuracies of the equipment used resulted in an overall error at the limit of the observed differences between the two ignition systems; for this reason, the number of trials for each point was increased (as the article will reiterate) in order to ensure good consistency. Overall performance was evaluated by calculating indicated mean effective pressure (IMEP) and its coefficient of variation (COV), as well as considering the location of 50% mass fraction burned (MFB); all four parameters were calculated based on data averaged over 200 consecutive fired cycles, chosen by considering the COV and the fact that quasi steady-state was achieved during measurements [51].

In order to provide a general view of thermodynamic processes that were taking place inside the cylinder for the investigated conditions, pressure traces were analysed employing a simplified heat release approach [52]. The rate of heat release was calculated using the following equation:

$$dQ = \gamma / (\gamma - 1) \cdot p \cdot dV + 1 / \gamma - 1 \cdot V \cdot dp, \quad (7)$$

where Q is the net heat released through fuel oxidation measured in J, γ the ratio of specific heats, p in-cylinder pressure in Pa and V cylinder volume in m^3 . A constant value of 1.35 was set for γ , even though this simplification introduces additional uncertainty in the evaluation of different phenomena [53]. For the scope of this research the influence on results interpretation should be minimal, also considering the fact that only qualitative comparisons were sought after.

RESULTS AND DISCUSSION

Thermodynamic Analysis and Exhaust Gas Measurements

As mentioned in the previous section, a spark timing sweep was performed in the 35-55 CAD BTDC range in order to identify the MBT point.

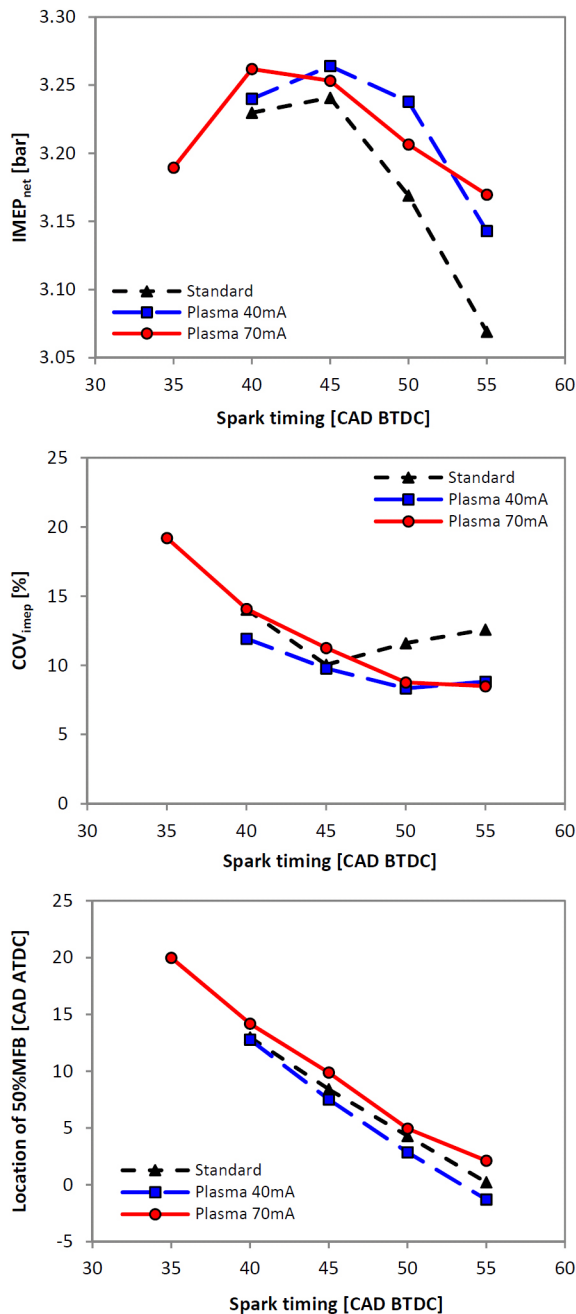


Figure 4. IMEP, its COV and location of 50%MFB curves for the chosen spark timing sweep and the three ignition strategies.

Indicated mean effective pressure (IMEP) was quite flat around the optimum ignition setting, which was found to be 45 CAD BTDC when using the standard system and 40mA plasma assisted strategy, while for 70mA, it was delayed at 40 CAD BTDC (Figure 4). Differences between the two optimum spark timing settings were quite small; however, in order to provide a comprehensive analysis of the process of flame development, both 40 and 45 CAD BTDC ignition points were investigated with combined thermodynamic and optical measurements. Regarding other engine control parameters, such as start of injection and throttle settings, given that these were maintained constant, their influence was practically inexistent during the trials. It should be noted that the chosen start of injection was found to be a good compromise between intake air velocity and jet

impingement pattern, thus ensuring a high degree of fuel evaporation; also, the injected fuel quantity was relatively reduced, thus further minimizing any effect of mixture stratification at the time of ignition.

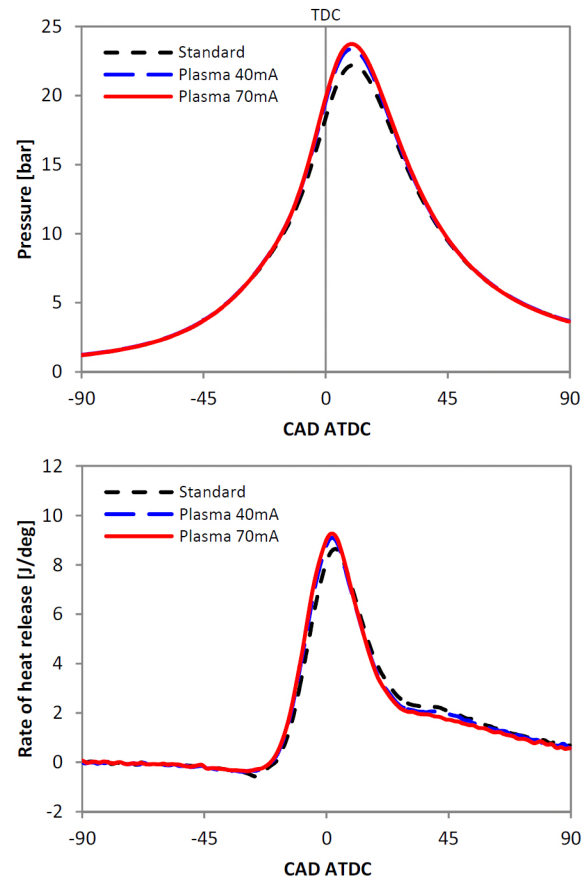


Figure 5. Average in-cylinder and rate of heat release for the three ignition settings for 45 CAD BTDC spark timing.

A slight increase in performance and a more significant improvement in engine stability was obtained by applying the alternative ignition system. IMEP values were higher and the COV lower for plasma assisted ignition throughout the spark advance range; given the small differences, three runs were performed for each point, thus confirming the consistency of the recorded results. Therefore, the curves shown in Figure 4 are the result of an average performed on a total of 600 cycles; due to the fact that the engine could be continuously fired for only around 1 minute at a time, three runs of 200 consecutive cycles each were performed. The location of 50%MFB point suggests slight differences in combustion development during the first stages (i.e. flame front propagation phase). A more detailed analysis of the pressure traces averaged over 200 consecutive fired cycles (without skip firing), confirmed that an advancement in combustion phasing was the reason for the observed changes in performance.

Figure 5 shows the pressure traces and heat release rates for 45 CAD BTDC spark timing, as being representative for the aforementioned change. Specifically, in the first combustion stages, the PAI system resulted in faster flame development and oxidation rates. Slightly higher peak pressure and rate of heat release were observed for the 70mA setting compared to the 40mA one, but the main difference was noticeable when switching from standard ignition to PAI. The

observed shift in combustion phasing is evident both during flame front propagation and final stages, the latter characterized by slower heat release. The standard ignition system featured lower values of heat release rate in the first combustion phase, while for the final period the contrary was observed. This suggests that more fuel was consumed during flame front propagation when applying the alternative ignition system. Higher density of active chemical species in the combustion chamber, promoted by the sustained plasma, for a period of 4ms, could be the reason for the observed increase in heat release rates. No clear conclusions in this regard could be formulated based on the thermodynamic data. Even if the method used for analyzing in-cylinder pressure data is relatively simple, it is doubtful that a more complex investigation (that includes models for heat and mass losses) would provide significant insight into specific phenomena associated with the application of PAI. This is due to quite similar in-cylinder pressure evolution; therefore, both heat transfer to the combustion chamber walls, as well as blow-by losses are likely to be very close for all settings.

Exhaust gas emissions (measured as undiluted, untreated engine-out gas stream) were found to be very close for all three ignition strategies. CO concentrations were very low, which had to be expected, given the increased air-fuel mixture dilution rate. This resulted in low temperatures, thus reducing the phenomenon of CO₂ dissociation; also, the improved availability of oxygen inside the combustion chamber favoured complete oxidation throughout the combustion process. Unburned hydrocarbons, on the other hand, were quite high for such lean air-fuel ratio. This can be associated with reduced oxidation rates towards the end of flame propagation; also extinguishment phenomena are not uncommon with such high dilution rates [52]. Even if only low differences in HC concentrations in the exhaust gas stream were recorded when changing ignition strategy, the application of sustained plasma seemed to promote fuel oxidation, resulting in slightly lower emissions of this pollutant category. The presence of active species, even after the flame front has propagated away from the spark plug, could improve combustion chemistry in the entrained gas. This seems to be confirmed by slightly higher NO_x emissions, in line with the recorded values for peak in-cylinder pressure; this can be correlated with the thermal mechanism of NO formation, in agreement with the data available in the literature. The effects on both HC and NO_x were more evident for 70mA.

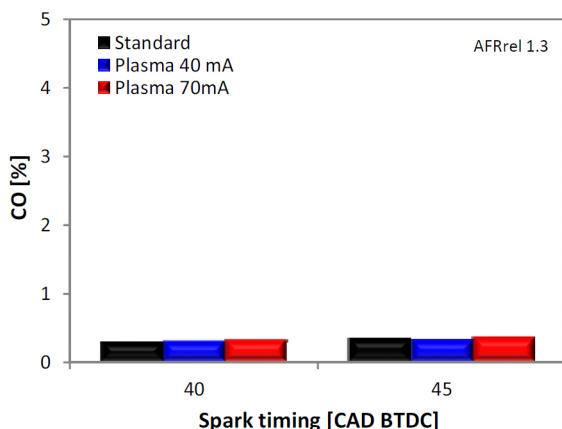


Figure 6.

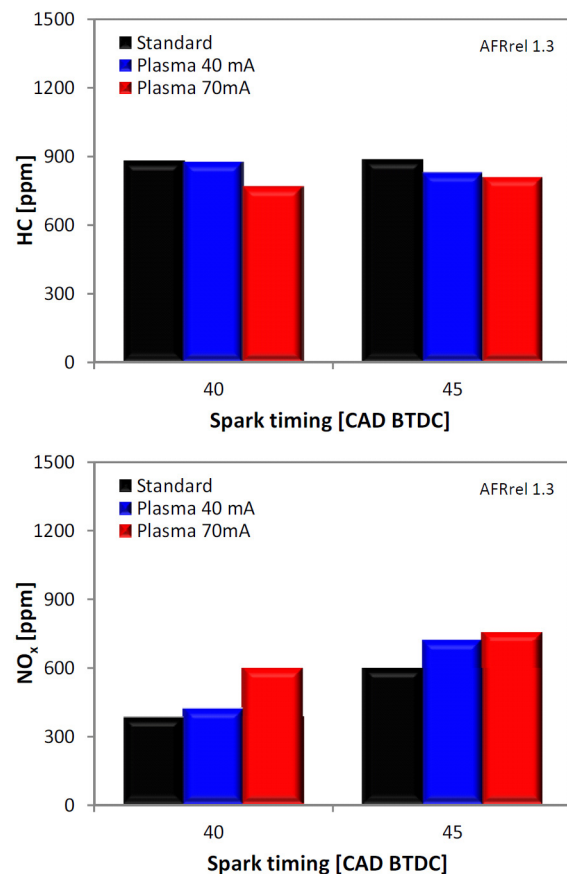


Figure 6 (cont). Exhaust gas emissions for the three ignition strategies at two different spark timing settings.

Following the overall evaluation based on the thermodynamic analysis, with the confirmation of reduced effects on CO and HC exhaust emissions, more detailed optical investigations were performed at the two MBT points identified in the spark timing sweep.

Optical Results: UV-Visible Chemiluminescence

For a more detailed understanding of the processes that take place during combustion, high spatial resolution chemiluminescence, with and without 310 nm filtering, was performed for 100 consecutive cycles in all six selected settings.

Figures 7-8 show comparisons at selected crank angles after spark timing (CAD ASOS) of flame front emission detected in the combustion chamber for all the ignition settings. Brightness and contrast is the same for each image. For all conditions, at 10 CAD ASOS the flame kernel emission is well resolved from the luminosity of plasma induced between the spark plug electrodes. The flame resulted strongly distorted and displaced towards the exhaust valves. This was due to concomitance of plug geometry and relative position with respect to the injector and of fluid motion, such as tumble, at the spark timing. The last effect can be directly related to the fact that most of the air enters the cylinder via the over-flow area of the intake valves, thus creating a large scale motion that tends to displace the flame towards the exhaust valves. This is more important for operation with dilute air-fuel mixtures, given that such 'extreme' conditions require quite advanced ignition. Therefore, the large scale structures feature high kinetic energy during the flame