

Impact of Spark Assistance and Multiple Injections on Gasoline PPC Light Load

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ABSTRACT

Along the last years, engine researchers are more and more focusing their efforts on the advanced low temperature combustion (LTC) concepts with the aim of achieving the stringent limits of the current emission legislations. In this regard, several studies based on highly premixed combustion concepts such as HCCI has been confirmed as a promising way to decrease drastically the most relevant CI diesel engine-out emissions, NO_x and soot. However, the major HCCI drawbacks are the narrow load range, bounded by either misfiring (low load, low speed) or hardware limitations (higher load, higher speeds) and the combustion control (cycle-to-cycle control and combustion phasing). Although several techniques have been widely investigated in order to overcome these drawbacks, the high chemical reactivity of the diesel fuel remains as the main limitation for the combustion control.

The attempts of the researchers to overcome these disadvantages are shifting to the use of fuels with different reactivity. In this sense, gasoline PPC has been able to reduce emissions and improve efficiency simultaneously, but some drawbacks regarding controllability and stability at low load operating conditions still need solution. In this field, previous researches have been demonstrate the multiple injection strategy as an appropriate technique to enhance the combustion stability. However, PPC combustion has been found limited to engine loads higher than 5 bar BMEP when using fuels with octane number greater than 90. In this regard, previous work from the authors showed the capability of the spark plug to provide combustion control in engine loads below this limit even using 98 ON gasoline.

The main objective of the present work is to couple the control capability of the spark assistance together with an appropriate mixture distribution by using double injection strategies with the aim of evaluating performance and engine-out emissions at low load PPC range using a high octane number gasoline. For this purpose the optical and metal version of a compression ignition single-cylinder engine, to allow high compression ratio, has been used during the research. A common rail injection system enabling high injection pressures has been utilized to supply the 98 octane number gasoline. An analysis of the in-cylinder pressure signal derived parameters, hydroxyl radical (OH*) and natural luminosity images acquired from the transparent engine as well as a detailed analysis of the air/fuel mixing process by means of a 1-D in-house developed spray model (DICOM) has been conducted. Results from both analysis methods, suggest the spark assistance as a proper technique to improve the spatial and temporal control over the low load gasoline PPC combustion process. A noticeable increase in the cycle to cycle repeatability (5% versus 15.1% CoV IMEP at 2 bar load) as well as a reduction in the knocking level (20.5 versus 33.6 MW/m² at 7 bar load) is observed. In addition, the combination of the spark assistance with the use of the double injection strategy provides a great improvement in terms of combustion efficiency (93% versus 88% for a single injection strategy) with a benefit around 18% in the IMEP.

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INTRODUCTION

The automotive scientific community and manufacturers are currently focusing part of their efforts on the investigation of new combustion modes [1,2] and on the optimization of the current technology with the aim of reducing fuel consumption and emissions in CI diesel engines [3]. Most of these new combustion concepts are achieved by using different strategies that produce a lean air-fuel mixture together with a low

temperature combustion. It contributes to decrease drastically the most relevant CI diesel engine-out emissions, NO_x and soot [4]. In addition, due to the in-cylinder mixture homogeneity, a fast heat release is obtained when the proper in-cylinder conditions are achieved providing high combustion efficiency.

These combustion concepts based on fully or partially premixed lean mixtures are commonly known as Homogeneous Charge Compression Ignition (HCCI) [5,6]. Even though they achieve important emission benefits [7], these combustion concepts present some practical issues that must be overcome before they can be implemented in CI diesel engines being confined to low engine speeds and loads [8]. The most relevant limitations of this combustion modes consist of achieving an appropriate combustion phasing, the cycle-to-cycle control of the combustion process, spray impingements and its effects on the emissions [9], the noise and operating range extent. Several techniques such as EGR [10], variable valve timing [11,12], variable compression ratio [13] and intake air temperature variation [14] have been investigated in order to overcome these drawbacks. Due to the high chemical reactivity of the diesel fuel, the mentioned techniques cannot provide precise control over the combustion phasing since they require large time scales to achieve cycle-to-cycle control. Thus, not enough mixing time before the start of combustion is provided.

The scientific community is currently trying to overcome these disadvantages by using fuels with different reactivity [15, 16, 17]. In this sense, Partially Premixed Combustion (PPC) using a low reactivity fuel has been confirmed as promising method to control the heat release rate providing a reduction in NO_x and soot emissions as well. The use of a high ON fuel, such as gasoline, in a CI engine under PPC conditions provides more flexibility to reach lean and low combustion temperatures due to the extra mixing time achieved [18] through the fuel properties. However, the concept has demonstrated difficulties at low load conditions using gasoline with octane number greater than 90, concluding that the use of a low reactivity fuel under PPC conditions provide some control on combustion phasing but still do not solve the possibility of cycle-to-cycle control. In order to mitigate the main drawbacks encountered when using single injection strategies at low load, several researchers investigated the use of multiple injection strategies, which improve the control over the fuel/air mixture preparation before SOC. Thus, some level of mixture stratification in the chamber has been shown necessary to improve low load operation. The double injection strategy provides sufficient mixing time before the SOC to achieve a homogeneous charge as well as the reactive conditions required to trigger the combustion process, improving the combustion stability. However, to achieve auto-ignition time scales small enough for combustion in the engine, an increase in the intake pressure and temperature is required [19]. Thus, multiple injection strategies have been found as a suitable method for improving the combustion stability but fuels with octane number greater than 90 do not allow to run PPC below 5 bar BMEP load.

Recent investigations on gasoline engines (SI) running in homogenous or premixed combustion modes such as CAI (always PFI) [20,21], have shown the potential of using the assistance of a spark plug for achieving cycle-to-cycle control and combustion phasing control. The results suggest that this strategy can provide good combustion phasing while the

response time is short enough for cycle-to-cycle application. Nevertheless, further research on spark assistance in new combustion modes is necessary for continuing its development with low reactivity fuels [22,23].

Thus, with the aim of integrating phasing and cycle-to-cycle control by means of a spark plug ignition system in a CI engine working in partially premixed charge, the PPC concept with spark assistance fuelled with high ON gasoline has been studied. This engine architecture has a high compression ratio and it is equipped with a common rail injection system that enables high injection pressures. In addition, the impact of double injection strategies has been investigated. The present work focuses on couple the control capability of the spark assistance together with an appropriate mixture distribution by using double injection strategies with the aim of evaluating their impact on gasoline PPC performance and engine-out emissions using a high ON gasoline. For this purpose the optical and metal version of a compression ignition single-cylinder engine, to allow high compression ratio, has been used during the research. A common rail injection system enabling high injection pressures has been utilized to supply the 98 ON gasoline. An analysis of the in-cylinder pressure signal derived parameters, OH* and natural luminosity images acquired from the transparent engine as well as a detailed analysis of the air/fuel mixing process by means of a 1-D in-house developed spray model (DICOM) has been conducted.

EXPERIMENTAL FACILITIES AND PROCESSING TOOLS

Test Cell

This section presents the experimental configuration of the test cell and the main subsystems used in this study. As [Figure 1](#) shows, the single cylinder engine is installed in a fully instrumented test cell, with all the auxiliary facilities required for operation and control.

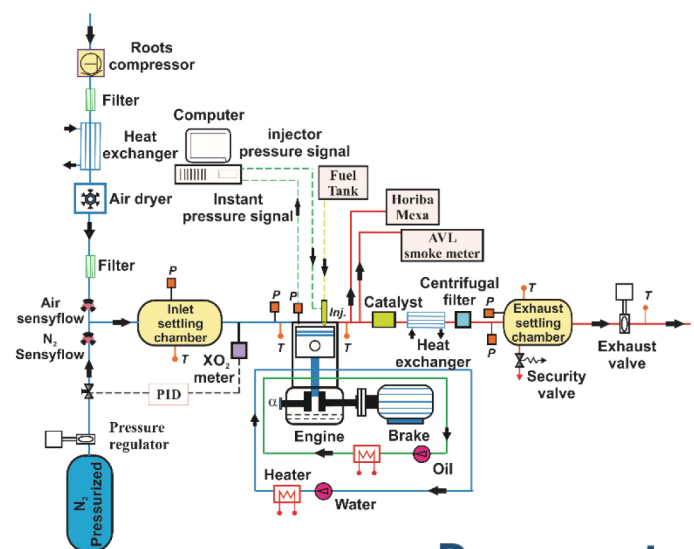


Figure 1. Complete test cell setup



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The intake air is supplied by a roots compressor with an upper pressure limit of 3 bar. Then, the air flows through a filter to remove possible impurities. The heat exchanger and the air dryer allow controlling the temperature and humidity of the intake air independently on the ambient conditions. The temperature in the inlet settling chamber is maintained constant by using a heater in the intake line. The oxygen concentration variation is performed using a synthetic EGR system. EGR is substituted by nitrogen gas, which greatly simplifies the system ensuring a controllable gas composition without an excessive time to adjust the facility. Despite the limited practical application, it was decided to use this method to have a better control of the variables, which allows studying the underlying phenomena more carefully. The concept is based on decreasing the O_2 concentration at the inlet manifold by increasing the flow of N_2 and keeping constant the total intake mass flow rate (substitution EGR). For this purpose a PID controller is equipped to operate the N_2 valve governed by the intake O_2 meter. With this system, the in-cylinder thermodynamic conditions can be reproduced systematically. To ensure a homogeneous mixture of N_2 and O_2 and to attenuate pressure pulses in the intake manifold, a settling chamber of 500 liters volume is used in the installation.

During the metal engine version tests, the exhaust gases were analyzed with a five gas Horiba MEXA 7100 D analyzer bench. In order to increase the robustness of these measurements, the different pollutant volume fractions were sampled and averaged over an 80 second time period after attaining steady state operation. CO and unburned HC measurements were used to determine the combustion efficiency (1):

$$Comb. Eff = \left(1 - \frac{HC}{mf} - \frac{CO}{4 \cdot mf}\right) \cdot 100 \quad (1)$$

Smoke emissions were measured with an AVL 415 variable sampling smoke meter, providing results directly in FSN. The FSN values used in this research are the average of three consecutive measurements at the same operating condition. These measurements were transformed into mg/m^3 by means of the correlation (2) proposed in the user manual of the device:

$$[mg/m^3] = \frac{1}{0.405} \cdot 4.95 \cdot FSN \cdot e^{0.38 \cdot FSN} \quad (2)$$

In the exhaust line, after the exhaust analyzer sample probe, a catalyst is mounted to prevent the accumulation of unburned hydrocarbons in the installation. Due to the low temperatures achieved during the combustion event and therefore in the exhaust line, the catalyst is often operating with low efficiency and a centrifugal filter is needed to remove the rest of the hydrocarbons. In the same way as in the intake line, a settling chamber is mounted in order to attenuate pressure pulses. Finally, an exhaust backpressure valve is equipped to maintain a relative pressure of 0.2 bar to the intake pressure, in order to simulate a representative air management conditions of a real turbocharged engine.

Engine Configurations and Cylinder Head Adaptation

Cylinder Head Adaptation

A spark plug is required to implement the partially premixed compression ignition with spark assistance combustion mode. As Figure 2 shows, the cylinder head has been modified by removing an exhaust valve and thus enabling the insertion of the spark plug in the combustion chamber. A standard spark plug (Veru Platinum) with a 1 mm gap is used along with a custom electronic control system. In the standard configuration, the tip protrudes 4.5 mm into the combustion chamber from the cylinder head plane and it is located 17 mm from the cylinder axis. The injector is centered and vertically assembled in the modified cylinder head with a graduated metal circle that can change the relative position between the spark plug and the injector fuel jets by rotating the injector around its vertical axis. This relative position is fixed to make the spray pass between the spark electrodes.

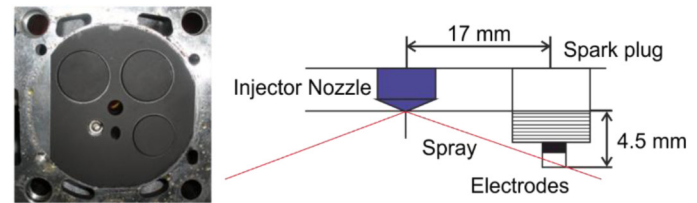


Figure 2. Image of the modified cylinder head with spark plug and injector hole (left). Diagram of the relative position between the injector and spark plug (right).

Metal Engine Configuration

The engine used in the present study is a 3-valve, 0.545 l displacement single cylinder engine with a modified cylinder head for the study of this combustion mode. The bowl dimensions are 45×18 mm (diameter x depth). Table 1 presents the main characteristics of the engine.

Table 1. Main characteristics of the single cylinder engine used in the present study.

Type	CI, 4stroke, DI
Max. engine speed	4500 rpm
Cylinder number	1
Displacement	544.75 cm ³
Bore	85 mm
Stroke	96 mm
Compression ratio	14.7:1
Bowl diameter	45 mm
Bowl depth	18 mm
Bowl volume	25 cm ³

In order to increase the reliability of the combustion mode, a Delphi multicharge ignition system [24,25] has been used. The high amount of energy released by this ignition system allows igniting the mixture even with local equivalence ratio conditions near their flammability limits with high EGR rates [24]. The spark ignition system is operated at a constant nominal primary voltage of 15 V from the battery and primary current of 25 A, providing around 120 mJ for the typical combustion chamber density test conditions, almost double than a conventional ignition system.

The fuel injection system is based on an electronically controlled Bosch common rail system. The injector is a Bosch piezoelectric CRIP 3.3 model equipped with a seven-hole nozzle with 154° included angle. The nozzle hole diameter is 97 microns and its flow capacity is 210 cm³/30 s. The injection control system makes it possible to modify any parameter of the injection events such as the start of injection timing, injection duration and rail pressure. The fuel injection hardware characteristics are summarized in Table 2.

Table 2. Main characteristics of the injection system used in the present study.

Actuation Type	Piezoelectric
Steady flow rate @ 100 bar	210 cm ³ /30s
Number of Holes	7
Hole diameter	97 μm
Included Spray Angle	154°

In order to characterize the most relevant properties of the gasoline used in this research, various analyses of the fuel properties have been performed following ASTM standards. It is worthy to note that 300 ppm of additive (Havoline Performance Plus) was added to improve the lubricity of the gasoline up to diesel fuel level, increasing the service life of the high pressure pump and fuel injector. The addition of the additive does not modify neither density nor the viscosity. The results of the gasoline characterization are summarized in Table 3.

Table 3. Main characteristics of the gasoline used in the present study.

Fuel	Gasoline
Density (T= 15°C)	722 kg/m ³
Viscosity (T= 40°C)	0.37 mm ² /s
Research octane number	98
Lower heating value	44542 kJ/kg

Optical Engine Configuration

The engine is equipped with an elongated piston with a cylindrical bowl, which allows optical access to the combustion chamber through a sapphire window placed in its bottom.

Below the piston bowl, an elliptical UV mirror is placed on the cylinder axis. In front of the mirror, a beam splitter (50%-50%) is positioned in order to allow the simultaneous acquisition of the OH radical luminosity and the natural luminosity. For the acquisition of the natural luminosity images, a high speed Phantom V12 CMOS camera equipped with a 100 mm focal length Zeiss lens is utilized with an image resolution of 512 × 512 pixels. In order to acquire the OH radical luminosity images a Photron intensified camera equipped with a 100 mm UV lens together with a band pass filter centered at 310 nm is utilized. Figure 3 shows the optical scheme. It is interesting to note that the tests have been performed under skip-fired mode (1 cycle fired per 30) in order to avoid excessive thermal stress in the windows and ensure the same in-cylinder initial thermodynamic conditions for the recorded (fired) cycles. Due to the high dilution in the exhaust line, it is not possible to measure the engine-out emissions when the optical engine configuration is used. Thus, the fuel energy conversion efficiency (3) calculated from the rate of heat release not by means of the direct measurement of CO and unburned HC as done in when the metal engine version is used:

$$FeCE = \frac{100}{m_f \cdot LHV} \int_{IVC}^{EVO} RoHR(\alpha) \cdot d\alpha \quad (3)$$

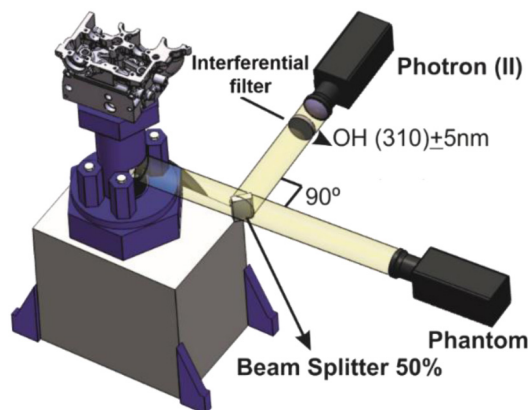


Figure 3. Optical scheme for the images acquisition during the combustion process. Natural luminosity (NL) and OH* radical.

Theoretical Tools

Analysis of Pressure Signal

The combustion analysis is performed with an in-house developed one-zone model named CALMEC, which is fully described in [26]. This combustion diagnosis tool uses the in-cylinder pressure as its main input. The in-cylinder pressure was measured with a Kistler 6067C1 pressure transducer. A shaft encoder with 1800 pulses per revolution was used, which supplies a resolution of 0.2 CAD. The pressure traces for 200 engine cycles were recorded in order to compensate the cycle-to-cycle variation during engine operation. Thus, each individual cycle's pressure data was smoothed using a Fourier series low-pass filter. Once filtered, the collected cycles were ensemble averaged to yield a representative cylinder pressure