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Performance and engine-out emissions evaluation of the double injection strategy applied to the gasoline partially premixed compression ignition spark assisted combustion concept

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HIGHLIGHTS

- Double injection mixture distribution improves PPC spark assisted combustion.
- Double injection strategy improves PPC spark assisted combustion efficiency.
- Double injection strategy improves PPC spark assisted performance.
- Lower fuel mass percentage in the pilot injection reduces CO and UHC emissions.
- Double injection strategy wide the PPC spark assisted operating range in low load.

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ABSTRACT

Spark assistance has been found to improve combustion control when combined with both single and double injection operation applied to compression ignition (CI) engines using gasoline as the fuel. Previous work has verified the potential of a double injection strategy when applied to the gasoline spark assisted partially premixed compression ignition combustion (PPC) concept. The current research presents performance and engine-out emissions results using a double injection strategy with the spark assisted PPC concept and shows its benefits compared to a single injection strategy. For this purpose, a parametric study was carried out using gasoline in a high-speed single-cylinder diesel engine equipped with a modified cylinder head, which included a spark plug. The parameters that were varied during the double injection testing included: injection timing, dwell, fuel mass split between the injections and intake oxygen concentration. A detailed analysis of the air/fuel mixing process was also conducted by means of a 1-D in-house spray model (DICOM).

1. Introduction

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, strategies based on highly premixed combustion such as the well-known Homogeneous Charge Compression Ignition (HCCI) have been confirmed as a promising way to decrease drastically the most relevant CI diesel engine-out emissions, NOx and soot [1]. 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 such as EGR [2], variable valve timing [3,4], variable compression ratio [5] and intake air temperature control [6] 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.

Abbreviations: bTDC, before top dead center; CAD, crank angle degree; CA10, Cranck angle at 10% mass fraction burned; CI, compression ignition; DI, direct injection; EI, emission index; EOI_{main}, end of main injection; EOI_{pilot}, end of pilot injection; FeCE, Fuel energy Conversion Efficiency; FFT, fast fourier transform; FSN, filter smoke number; HCCI, Homogeneous Charge Compression Ignition; IMPG, Integrate Modulus of Pressure Gradient; ISFC, indicates specific fuel consumption; LTC, low temperature combustion; PCCI, premixed charge compression ignition; PPC, partially premixed charge; SoC, Start of Combustion; SOI_{main}, start of main injection; SOI_{pilot}, Start of pilot Injection; SoS, Start of Spark; TDC, top dead center.

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The attempts of the researchers to overcome these disadvantages are shifting to the use of fuels with different reactivity [7–9]. Specifically, the use of gasoline-like fuels with high autoignition resistance in compression ignition engines has been widely investigated at Shell [10–13], Lund [14–17], UW-Madison [18–22] and Argonne [23–25]. In this sense, the concept of gasoline Partially Premixed Combustion has been able to reduce emissions and improve efficiency simultaneously, but some drawbacks still need solution. Since a low reactive fuel is required to extend the ignition delay sufficiently at high loads, controllability and stability issues appear at the low load end. Thus, with the aim of improving the PPC controllability and stability at low load, the PPC concept with spark assistance fuelled with gasoline has been studied [26,27]. This combustion concept has been evaluated in terms of performance and engine-out emissions using a single injection strategy by studying the effect of injection pressure variations and intake oxygen concentration. Under these conditions, the concept has been found as a suitable technique for improving combustion control, providing both temporal and spatial control over the combustion process [28]. In spite of its benefits, some drawbacks related to unappropriated mixture distribution and combustion temperatures were observed. Single injection provides excessive rich zones near the spark plug and too lean regions close to the in-cylinder walls resulting in high emission levels as well as deteriorated Fuel energy Conversion Efficiency (FeCE).

Another strategy widely investigated by several researchers with the aim of solving the gasoline PPC controllability and stability issues encountered when using single injection strategies at low load is 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 [29]. In addition, recent studies with multiple injections have shown that fuels with octane number greater than 90 do not allow to run below 5 bar BMEP load [30] due to the auto-ignition characteristics of these fuels. In this regard, previous work from the authors [28] showed the capability of the spark plug to provide combustion control in engine loads below this limit even using 98 octane number gasoline. Thus, 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 different parameters have been varied during the double injection testing, specifically: injection timing, dwell time between injections, fuel mass repartition between injections and intake oxygen concentration. The investigation has performed in a compression ignition single-cylinder engine to allow high compression ratio fuelled with 98 octane number gasoline. A common rail injection system enabling high injection pressures has been used during the research. An analysis of the in-cylinder pressure signal derived parameters as well as a detailed analysis of the air/fuel mixing process by means of a 1-D in-house spray model (DICOM) has been conducted [31].

The outline of this paper is as follows: in the next section, the experimental facilities used to carry out this research are presented. Specifically, this section describes briefly the methodology, hardware and processing tools. In Section 3, an overview of the double injection strategy is given by presenting a comparison of the single and double injection strategies using different operating conditions. In Section 4, the results of the double injection strategy tests are presented. These tests consist of sweeps of the pilot injection timing and the intake oxygen concentration. Then, the effects of the mass repartition between the pilot and main injection are studied. Finally, in Section 5, the main conclusions of this research are summarized.

2. Materials and methods

This section describes the methodology used to acquire the experimental data and provides a description of the experimental facility, the different devices and systems that were specifically adapted for the study of this combustion mode.

2.1. Single cylinder engine

The engine used in the present study is a 4-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 × depth). Table 1 presents the main characteristics of the engine.

A spark plug is required to implement the partially premixed compression ignition with spark assistance combustion mode. As Fig. 1 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.

In order to increase the reliability of the combustion mode, a Delphi multicharge ignition system 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. 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.

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 1.

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 μm and its flow capacity is 210 cm^3/30 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 injector is centered in the cylinder and vertically mounted in the modified cylinder head with a graduated metal circle that can be used to change the relative position between the spark plug and the injector by rotating the latter around its vertical axis. The fuel injection hardware characteristics are summarized in Table 1.