Applied Energy 129 (2014) 1–9

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Conceptual model description of the double injection strategy applied to the gasoline partially premixed compression ignition combustion concept with spark assistance

Jesús Benajes [a], Santiago Molina [a], Antonio García [a,*], Javier Monsalve-Serrano [a], Russell Durrett [b]

[a] CMT – Motores Térmicos, Universitat Politècnica de València, Camino de Vera s/n, 46022 Valencia, Spain
[b] Diesel Engine Systems Group, Propulsion Systems Research Lab GM R&D Center, MC 480-106-252, 30500 Mound Rd., Warren, MI 48090-905, USA

HIGHLIGHTS

- Double injection improves the combustion control in low load.
- Double injection enhances both phases of the combustion mode.
- Double injection increases the combustion area in the chamber.
- Combustion process described by mixing process, OH* and natural luminosity images.

ARTICLE INFO

Article history:
Received 11 November 2013
Received in revised form 17 February 2014
Accepted 27 April 2014
Available online 19 May 2014

Keywords:
Partially premixed combustion
Spark assistance
High octane number gasoline
Combustion control
Double injection
Natural luminosity and OH images

ABSTRACT

New combustion concepts applied to compression ignition engines are focused on achieve low temperature combustion together with a lean mixture distribution by allowing extra time from the end of injection to the start of combustion. Recently, the use of gasoline in a compression ignition engine under PPC conditions has been demonstrated as a suitable technique to achieve this extra mixing time, however the concept has also demonstrated difficulties under low load conditions using gasoline with octane number up to 95. The use of spark assistance with single injection operation has been found to be an appropriate way to improve the combustion control, providing both temporal and spatial control over the combustion process.

The current paper details the influence of the double injection strategy on the spark assisted partially premixed combustion concept compared with the single injection strategy. For this purpose, a reference combustion cycle for both injection strategies is compared in terms of the main parameters derived from the in-cylinder pressure signal as well as OH* and natural luminosity images acquired from the single-cylinder transparent engine. The cylinder head used along the research has been modified including a spark plug. In addition, a detailed analysis of the air/fuel mixing process has been developed by means of a 1-D in-house spray model.

1. 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, NOx 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

* Corresponding author. Tel.: +34 963879659; fax: +34 963877659.
E-mail address: angarma8@mot.upv.es (A. García).

http://dx.doi.org/10.1016/j.apenergy.2014.04.093
0306-2619/

Abbreviations

ASTM	American Society of Testing Materials
bTDC	before Top Dead Center
BDC	Bottom Dead Center
CAD	Crank Angle Degree
CI	Compression Ignition
CMOS	Complementary Metal Oxide Semiconductor
COV	Coefficient Of Variation
DI	Direct Injection
EOI_{main}	End of main injection
EOI_{pilot}	End of pilot injection
EVO	Exhaust Valve Opening
FeCE	Fuel energy Conversion Efficiency
HCCI	Homogeneous Charge Compression Ignition
IVC	Intake Valve Closing
IMEP	Indicated Mean Effective Pressure
LTC	Low Temperature Combustion
ON	Octane Number
PCCI	Premixed Charge Compression Ignition
PID controller	Proportional–Integral–Derivative controller
PPC	Partially Premixed Charge
SOI_{main}	Start of main injection
SOI_{pilot}	Start of pilot injection
SoC	Start of Combustion
SoS	Start of Spark
TDC	Top Dead Center

modes consist of achieving an appropriate combustion phasing, the cycle-by-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-by-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 [15–17]. 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 NOx 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-by-cycle control.

Recent investigations on gasoline engines (SI) running in homogenous or premixed combustion modes such as CAI (always PFI) [19,20], 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-by-cycle application. Nevertheless, further research on spark assistance in new combustion modes is necessary for continuing its development with low reactivity fuels [21,22]. 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 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. Thus, the partially premixed combustion concept with Spark Assistance 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, spark assistance has been found to be a suitable technique for improving combustion control, providing both temporal and spatial control over the combustion process [23,24]. In spite of its benefits, some drawbacks related to unappropriated mixture distribution and combustion temperatures are attained. Single injection provides excessive rich zones near to the spark plug and excessive lean regions close to the wall chamber resulting in high emission levels as well as deteriorated fuel energy conversion efficiency. Thus, the main objective of the present work is to analyze the effect of the double injection strategy on the mixture distribution and combustion development under partially premixed compression ignition spark assisted mode. The investigation was performed in an optical engine since it is a suitable tool for performing a basic combustion research combining in-cylinder pressure signal derived parameters and optical combustion images as an experimental sources of information together with a 1-D spray model.

The outline of this paper is as follows: in the first section, the experimental facilities and the different setups used to carry out this research are presented. Specifically, this section describes briefly the methodology, experimental facilities and processing tools used from the acquisition of the raw data during the experimental tests to the final results obtained by means of the post-processing tools. In the following section, which is the base of this paper, a summary of the preliminary results and a description of the combustion event comparing the single and double injection strategies are done. Finally, in Section 4, the main conclusions of this research are summarized.

2. Experimental facilities and processing tools

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. Experimental setup

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

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 of the ambient conditions. The temperature in the inlet settling chamber is maintained constant by using the heater in the intake line. The oxygen concentration variation is performed