Applied Energy 161 (2016) 465–475

Contents lists available at ScienceDirect

Applied Energy

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

Understanding the performance of the multiple injection gasoline partially premixed combustion concept implemented in a 2-Stroke high speed direct injection compression ignition engine

J. Benajes, J. Martín, R. Novella *, K. Thein

CMT-Motores Térmicos, Universitat Politècnica de València, Camino de Vera s/n, 46022 Valencia, Spain

HIGHLIGHTS

- An analysis of the PPC concept with a multiple injection strategy was carried out.
- The concept was implemented in a new poppet valves 2-Stroke HSDI diesel engine.
- The main trade-offs have been evaluated and solutions were developed and tested.
- A study was lead to evaluate the influence of the air loop devices on efficiency.
- The combustion noise level has been investigated to define control paths.

ARTICLE INFO

Article history:
Received 30 April 2015
Received in revised form 12 September 2015
Accepted 5 October 2015

Keywords:
Compression ignition engine
2-Stroke engine
Gasoline PPC concept
Emission control
Engine efficiency

ABSTRACT

The newly designed Partially Premixed Combustion (PPC) concept operating with high octane fuels like gasoline has confirmed the possibility to combine low NO_x and soot emissions keeping high indicated efficiencies, while offering a control over combustion profile and phasing through the injection settings. The potential of this PPC concept regarding pollutant control was experimentally evaluated using a commercial gasoline with Research Octane Number (RON) of 95 in a newly-designed 2-Stroke poppet valves Compression Ignition (CI) engine for automotive applications. Previous experimental results confirmed how the wide control of the cylinder gas temperature provided by the air management settings brings the possibility to achieve stable gasoline PPC combustion at low and medium speed conditions (1250–2000 rpm) for the whole load range (3.1–10.4 bar IMEP) with good combustion stability (Coefficient of Variation (CoV) of IMEP below 3%), high combustion efficiency (over 97%), and low NO_x/soot levels.

In this context, present research focuses on the two main specific drawbacks of this concept. Firstly, the high Brake Specific Fuel Consumption (BSFC) due to the work required by the mechanical supercharger since the turbocharging system does not provide the suitable pressure ratio at low speeds. Secondly, the high level of noise generated by the combustion process, especially at high loads. Therefore, a dedicated analysis has been carried out to fully exploit the benefits of the gasoline PPC concept combined with the innovative 2-Stroke engine architecture with the aim of identify and break the most relevant trade-offs.

1. Introduction

The Partially Premixed Combustion (PPC) concept has been developed during the last years to operate Compression-Ignition (CI) engines, as an alternative between fully premixed combustion (typically, HCCI and PCCI) and fully diffusive combustion (Conventional Diesel Combustion). PPC has been well developed in heavy-duty Diesel engines, operating with conventional Diesel fuel and multiple injection strategy, showing good results of performance and emissions [1]. It was then firstly introduced by Kalghatgi et al. in a light-duty application, replacing the Diesel fuel by gasoline [2,3]. These researches highlighted that PPC allows to keep the pollutants emissions at low levels while retaining control over the combustion timing with the injection event. The injection process is advanced towards the compression stroke to be detached from the combustion event, enabling partial mixing of the mixture to avoid over-rich regions where soot is formed, while NO_x emissions are reduced by the introduction of large amounts of EGR allowing to lower the combustion temperatures [4]. Different studies have shown how both NO_x and soot emissions can be simultaneously

* Corresponding author.
E-mail address: rinoro@mot.upv.es (R. Novella).

http://dx.doi.org/10.1016/j.apenergy.2015.10.034
0306-2619/

Nomenclature

aTDC	after top dead center
$(A/F)_{st}$	Stoichiometric air to fuel ratio
CA10	Crank angle for 10% of fuel burnt
CA50	Crank angle for 50% of fuel burnt
CAD	Crank angle degree
CD	Combustion duration
CDC	Conventional Diesel Combustion
CI	Compression Ignition
ΔP	Pressure difference between in take and exhaust ports
$dP/d\alpha_{max}$	Maximum pressure gradient
EGR	Exhaust gas recirculation
EVO	Exhaust valve opening (angle)
HCCI	Homogeneous charge compression ignition
HSDI	High speed direct injection
IGR	Internal Gas Recirculation
IMEP	Indicated mean effective pressure
IVC	Intake valve closing (angle)
ISFC	Indicated specific fuel consumption
$ISFC_{corr}$	Corrected ISFC considering energy consumption of the air loop devices (turbocharger and supercharger)
MT	Mixing time
PCCI	Premixed charge compression ignition
P_{in}/P_{ex}	Intake/exhaust pressure
P_{max}	Maximum cylinder pressure
PPC	Partially Premixed Combustion
P_{rail}	Injection rail pressure
Φ_{eff}	In-cylinder effective equivalence ratio
RoHR	Rate of Heat Release
SoC	Start of Combustion
SoE	Start of Energizing (injector signal)
SoI	Start of Injection
CoV	Coefficient of Variation
T_{in}/T_{ex}	Intake/exhaust temperature
T_{IVC}	Mean gas temperature at intake valve closing
TDC	Top dead center
TR	Trapping ratio
VVT	Variable Valve Timing
VVT_{in}	Intake Variable Valve Timing
VVT_{ex}	Exhaust Variable Valve Timing
η_{comb}	Combustion efficiency
$\eta_{indicated}$	Indicated efficiency

reduced by the combustion of diesel fuel in a sufficiently premixed cylinder charge, and this is the basis of HCCI or PCCI premixed combustion strategies [5–8]. But in these two last concepts, the – often – unavoidable over-mixed mixture and a liquid fuel impingement onto the walls increase HC and CO emissions. The main advantage of the PPC is its proclivity to present a high indicated efficiency, while still avoiding the usual NO_x/soot trade-off, as observed in CDC. Indeed, the characteristic constant-volume combustion of a highly premixed mixture helps to reduce heat transfer during the compression and get an efficient expansion [9,10].

However, the load range in which PPC can be applied is limited due to an indirect control over the combustion process, as the injection events are detached from the combustion. This is necessary to achieve premixed conditions, but the combustion profile becomes very difficult to manage properly, and depends mostly on the chamber local conditions. Thus, the gap between misfire and knocking-like combustion is very reduced, with a clear trend to generate sharp combustions. In order to soften it, a multiple injection strategy [11] and a fine optimization of the injector nozzle/bowl design matching [12] have shown to be the key factors.

Another main issue related to PPC is the RON/load matching, which limites the load range. Due to either the strong propensity of a high cetane fuel to auto-ignite along the compression stroke (suitable combustion at low-load, but hard knock at high load), or the low-reactivity of the low cetane fuels (allowing a good combustion at high load, but deteriorating the combustion at low load, reaching misfire), achieving a wide load operating range is not possible [13–19]. Previous researches carried out operating with the Conventional Diesel Combustion (CDC) concept confirmed how the poppet valves 2-Stroke architecture equipped with intake and exhaust VVT systems provides great flexibility for controlling the in-cylinder thermochemical conditions at IVC, especially the temperature, by adjusting the residual gas fraction [20,21]. Thus, this engine architecture can be a suitable solution for extending the PPC range in both low and high load directions using a single fuel with low reactivity. Higher temperatures at IVC helps a high octane fuel such as gasoline to ignite even at low load avoiding misfires, while lower temperatures at IVC combined with a large fraction of cooled EGR can be introduced in order to reach higher loads, avoiding knock by reducing the chemical reactivity of the mixture [22].

However, a high intake pressure is required to reach both the necessary EGR rate to control the combustion, and the high A/F ratio needed to get a proper combustion. This has a dramatic effect on the engine brake efficiency, even considering the high indicated efficiency provided by the PPC concept (more than 50% in the best conditions [23]). Indeed, a volumetric compressor is mandatory to reach these conditions (especially at low load), punishing the BSFC (in this study, the ISFC will be corrected to take into account the pumping work, becoming $ISFC_{corr}$). In this framework, optimizing the air loop strategy by taking advantage of the exhaust acoustics to improve the scavenging process is a key issue to get sustainable conditions.

Previous authors' researches [11,24,25] on this newly designed 2-Stroke engine combined with a multiple injection strategy confirmed the possibility to extend the load range keeping the same RON gasoline. The pollutant emissions are manageable, and the NO_x/soot trade-off can be controlled and even removed within a wide range of operating conditions. Nevertheless, new trade-offs have been observed between the NO_x/noise levels and the combustion efficiency. NO_x and noise level are linked, as a sharp – and noisy – combustion is the main source of the NO_x generation [26].

As mentioned, one of the major matter of the combustion concept is the sharpness of the heat release rate profile at high load, generating high noise levels, which is a critical aspect for a engine designed for commercial application. The highly premixed condition inside the cylinder results in a very reactive mixture, igniting at quasi-constant volume, arising to a very quick and sharp, knocking-like combustion [27,28]. Moreover, it may eventually physically damage the engine.

As it has been previously observed, the combustion phasing and the emissions levels are controlled by the injection settings, whereas the air management influences only the performances [11,21,24,25,29]. The following study will then present the different strategies that were explored and defined to get proper air management settings, to determine improvement paths for the global efficiency. Then, a study lead on the noise reduction will be exposed, through a numerical simulation correlated to experiments.