Applied Energy 193 (2017) 515–530

Contents lists available at ScienceDirect

Applied Energy

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

Impact of injection settings operating with the gasoline Partially Premixed Combustion concept in a 2-stroke HSDI compression ignition engine

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HIGHLIGHTS

- The PPC concept was implemented in a 2-stroke poppet valves HSDI diesel engine.
- Several injection conditions have been investigated to improve results at high load.
- 3D-CFD simulations were performed to understand the in-cylinder conditions and emissions.
- Pollutant emissions were kept at low levels even at high loads with competitive efficiencies.

ARTICLE INFO

Article history:
Received 7 November 2016
Received in revised form 30 January 2017
Accepted 14 February 2017

Keywords:
2-Stroke engine
CFD modeling
Gasoline PPC concept
Pollutant emissions
Engine efficiency

ABSTRACT

Partially Premixed Combustion (PPC) using gasoline-like fuels has proven its potential to control or even break the NO_x and soot emissions trade-off, retaining the high efficiency levels characteristic of the conventional diesel combustion (CDC) concept. However, selecting an appropriate fuel and a suitable injection strategy is essential to assure a successful PPC operation in the full engine map. Additionally, extending the limit of PPC beyond 10 bar IMEP was not possible due to excessively high pressure gradients and onset of knocking-like combustion, so the CDC concept has to be adopted and the conventional trade-off between NO_x and soot emissions was recovered. Present investigation focuses on evaluating the use of a multiple injection strategy for extending the load range of the PPC concept to medium/high load conditions, when using a commercial RON95 gasoline in a 2-stroke engine under development. Experimental results confirm how with a fine tuned triple injection strategy it is possible to reach extremely low NO_x and soot levels keeping combustion efficiency over 96%, while indicated efficiency is improved compared to a well-optimized point obtained operating with the CDC concept. Finally, the research work is completed by including 3D-CFD modeling activities that are carried out to contribute to the understanding on how the mixture preparation and stratification prior to the start of combustion impacts its development and particularly the experimentally observed pollutant emissions trends.

1. Introduction

Among the recently investigated alternatives to reduce fuel consumption and CO_2 emissions, an attractive option for extremely downsized engines consists of taking advantage of the 2-stroke engine cycle, which increases drastically the engine specific power by doubling the firing events per crankshaft revolution, to reduce the number of cylinders keeping the NVH (noise, vibration, harshness) performance and similar torque response [1,2]. With this motivation, an innovative 2-stroke High-Speed Direct Injection (HSDI) compression ignition (CI) engine with poppet valves in the cylinder head is being investigated for a heavily downsized passenger car application, where high power-to-mass ratio is mandatory.

Previous research work performed by the authors in conventional diesel combustion (CDC) confirmed how the proposed 2-stroke architecture provides much higher flexibility in terms of air management settings to control the cylinder conditions and affect combustion environment and final emissions level in a wide range compared to 4-stroke engines [3]. Furthermore, Homogeneous Charge Compression Ignition (HCCI) combustion with diesel fuel was implemented in the proposed 2-stroke engine at low load conditions, and its potential for simultaneous reductions of NO_x

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http://dx.doi.org/10.1016/j.apenergy.2017.02.044

and soot emissions was successfully proven [4]. However, the high reactivity of diesel fuel added to the high residual gas fraction (IGR) characteristic of the scavenge loop architecture, made it impossible to attain a properly-phased combustion even when operating at low loads with optimized engine settings and hardware, so this combustion concept was discarded for the 2-stroke architecture under study [5].

Several problems have been reported along the years in HCCI combustion when using high cetane diesel fuel, such as the control of HC and CO emissions [6,7], or the trade-off between the combustion noise and the engine efficiency [8]. The control of the mixture reactivity has also been reported as problematic [9], event though researches performed by Zhao et al. could provide some solutions by introducing and adapting new control systems to this kind of combustion [10,11]. However, most of these issues can be overcome by operating with retarded injection timings compared to those required to achieve pure HCCI due to the benefits provided by the mixture stratification, such as combustion control by the injection event up to some extent and HC and CO reduction by partially avoiding fuel overmixing. This relatively new approach, known as Partially Premixed Combustion (PPC), is achieved by advancing the injection process 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, whereas NO_x emissions are reduced by lowering combustion temperatures by the introduction of large amounts of EGR [12].

Research work performed by Kalghatgi et al. in both large [13,14] and small [15] single-cylinder engines demonstrated that gasoline-like fuels, having a higher resistance to auto-ignition, are better suited for extending mixing times before the onset of combustion than diesel-like fuels. As a result, low engine-out soot and NO_x emissions were obtained in a wider range of engine loads compared to PPC of diesel-like fuels.

Since this early work, many researchers performed additional numerical [16] and experimental investigations, using various engine size and operating with a large variety of fuels. Heavy-duty 4-stroke diesel engines have been wildly investigated, by Johansson et al. using ethanol [17,18], or low-to-high octane gasoline fuels [19,20]. Additionally, studies have also been performed on light-duty 4-stroke diesel engines to compare the results obtained with a large range of octane fuels especially at low loads [21,22], while Sellnau et al. focused their works at medium-to-high loads [23]. Different injection strategies were explored with various levels of EGR, boost pressure, intake temperature and swirl ratios at different engine loads and speeds. In general, reported results confirmed how it is possible to achieve PPC combustion with very high efficiency, very low NO_x emissions and lower soot levels compared to CDC in a wide range of load operation. However, even when results are highly promising, many practical issues still remain under investigation before reaching a production-viable powertrain system; i.e. injection systems requirements (injector type and optimum injection pressures), piston and combustion chamber design, boost system requirements, among others.

Additionally, there is an optimum zone in the engine map where the ignition characteristics of a given fuel are better matched to the engine operating condition, which results in a limited load range for PPC operation depending on the octane number of the fuel as demonstrated by Johansson et al. [15,24] and Ciatti et al. [25]. Additionally, the combination of EGR and air/fuel ratio is vital for achieving the in-cylinder conditions (composition and temperature) required for PPC operation [17]. This supposes that the PPC concept needs different fuel reactivities and/or advanced valvetrain and boost/EGR systems [26] to assure proper control over the combustion process, and be able to optimize emissions and efficiency in the entire engine map.

Recent investigations demonstrate how using multiple injection strategies (double and triple injections) have shown to improve fuel-air stratification, minimizing maximum heat release rate, combustion noise, and heat transfer losses; thus, resulting in increased thermal efficiency compared to single injection strategies [26,27]. Nevertheless, the injection characteristics, such as rail pressure, fuel split ratio between injections and timing of each injection must be carefully optimized depending on the operating condition [22].

Focusing on the 2-stroke HSDI CI engine configuration under development, the potential of the 2-stroke architecture for achieving successful PPC operation in medium/low load conditions was demonstrated, with 5 bar and 3 bar of IMEP, when using a single injection strategy with RON95 gasoline. Low NO_x emissions (below 0.4 g/kW h) and very low soot emissions were obtained at these load conditions, while 98% of combustion efficiency and good combustion stability (CoV IMEP under 3%) was retained. However, to achieve safe high load operation (above 10 bar IMEP) a mixing-controlled combustion had to be adopted, and the conventional trade-off between NO_x and soot emissions was recovered [28,29].

Thus, present investigation focuses on evaluating the strengths and limitations of using a multiple injection strategy for extending the load range of the PPC concept to medium/high load conditions, using a commercial RON95 gasoline in the 2-stroke poppet valves HSDI CI engine under development. Additionally, the research work aims to contribute to the understanding of the effects of most important injection parameters over the main combustion characteristics, final emissions levels and engine efficiency when operating with the gasoline PPC concept. As specific targets, NO_x emissions and indicated fuel consumption should be competitive compared to the levels attained operating in conventional diesel combustion, while achieving extremely low levels of soot emissions and high combustion efficiencies (over 95%) to maintain CO and HC emissions within acceptable limits. The implementation of the gasoline PPC concept in an innovative highly-flexible 2-stroke engine opens the possibility of investigating operating conditions beyond those evaluated in 4-stroke engines or even in not-so-flexible 2-stroke engines in terms of in-cylinder thermochemical conditions along the combustion process. Thus, the engine was configured to operate with a suitable combination of IGR/EGR ratio and also with tuned Miller cycle in order to use conventional RON95 gasoline fuel efficiently, which is really difficult to reach in 4-stroke engines. In addition, the combination of experimental and CFD modeling activities also provide worth information for the scientific community since it was possible to clarify/confirm the sources of pollutant formation and their relation with local mixture conditions along the combustion process. The analysis of the local evolution of CO is of especial interest for the authors since it was proven in previous studies how the NO_x-soot trade-off observed operating with the conventional diesel combustion is replaced by the Noise-combustion efficiency and NO_x-combustion efficiency trade-offs. Then, gaining knowledge about how CO emissions arise and how they evolve along combustion is mandatory to identify potential strategies focused on improving combustion efficiency. Then, this research is a step further in order to identify the real potential of the PPC concept operating with regular gasoline for automotive applications.

2. Experimental and theoretical tools

2.1. Engine architecture and test cell characteristics

Experimental activities were performed in a single cylinder research version of an innovative two-cylinder 2-stroke HSDI compression ignition engine with scavenge loop, which is currently