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Research Paper

Miller cycle for improved efficiency, load range and emissions in a heavy-duty engine running under reactivity controlled compression ignition combustion

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HIGHLIGHTS

- Miller strategy can extend ignition delay and reduce in-cylinder pressure gradients.
- Miller strategy controls in-cylinder temperature histories and therefore NOx emissions.
- RCCI strategy keeps reduced soot emissions by the promoting lean equivalent ratios.
- HC emissions mainly depend on the difficulty of burning fuel in cold regions.
- By combining Miller cycle with RCCI combustion strategy fuel consumption is improved.

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ABSTRACT

The low temperature, premixed combustion strategies are being investigated in the recent years as a mean to break the NOx-soot trade-off appearing during the diffusive conventional diesel combustion. This approach relies on promoting premixed combustion events with shortened duration, which reduces the heat transfer losses, improves the thermal efficiency, and allows a simultaneous reduction of engine-out NOx and soot emissions. However, since the combustion onset only depends on chemical kinetics, most of these strategies cannot be implemented at medium and high loads due to excessive pressure gradients, which lead to unacceptable noise levels and reliability issues.

This experimental work investigates the potential of the Miller cycle as a strategy to minimize the aforementioned challenges when operating under reactivity controlled compression ignition combustion. Moreover, the coupled effect of the Miller cycle with the fuel reactivity modulation is also explored as a way for improving the combustion control. For this purpose, parametric studies varying the effective compression ratio and gasoline fraction have been done in a single-cylinder heavy-duty engine operating at 14 bar indicated mean effective pressure and 1200 rev/min as a baseline condition. The results show that this strategy allows better control of the in-cylinder thermodynamic conditions, enabling a simultaneous reduction of nitrogen oxides and soot emissions down to the EURO VI limits, while keeping a reduced fuel consumption and suitable in-cylinder maximum pressure gradients.

1. Introduction

Nowadays, conventional diesel combustion (CDC) is the main combustion strategy used for heavy-duty applications, mainly due to its reliability and fuel efficiency [1]. However, the CDC process entails a trade-off between nitrogen oxides (NOx) and soot emissions, from which the reduction of one pollutant provokes and increase of the other [2]. To fulfill the limits imposed in the emissions regulations [3], the compression ignition (CI) engines, mainly running on CDC, need using aftertreatment systems to cut the emissions before being emitted to the atmosphere [4]. Motivated to reduce the cost of these aftertreatment devices, the engine manufacturers are focusing part of their resources on developing new strategies to minimize the emissions directly from their source, i.e., during the combustion process [5].

In this scenario, the highly premixed combustion (HPC) strategies have arisen as combustion strategies in which the temperatures are too low for promoting the NOx formation [6,7], and the local equivalence ratios are enough lean to avoid the soot formation. Those lean, diluted

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Abbreviations

ASTM	American Society for Testing And Materials
ATDC	After Top Dead Center
BSFC	Brake Specific Fuel Consumption
CAD	Crank angle degree
CA5	Angle when 5% of the fuel is burnt
CA50	Angle when 50% of the fuel is burnt
CA90	Angle when 90% of the fuel is burnt
CDC	Conventional Diesel Combustion
CO	Carbon monoxide
CO_2	Carbon dioxide
CR	Compression ratio
CR_{ef}	Effective compression ratio
EDUR	Exhaust Event Duration
EGR	Exhaust Gas Recirculation
EVC	Exhaust Valves Closing (angle)
FSN	Filter Smoke Number
HC	Unburned Hydrocarbon
HCCI	Homogeneous Charge Compression Ignition
HPC	Highly-Premixed Combustion
HVA	Hydraulic Valve Actuation
GF	Gasoline Fraction
IDUR	Intake Event Duration
IMEP	Indicated Mean Effective Pressure
IP	Injection Pressure
IVC	Intake Valves Closing (angle)
IVO	Intake Valves Opening (angle)
MPP	Maximum Pressure Rise Rate
NOx	Nitrogen Oxides
ON	Octane Number
O_2	Oxygen
PCCI	Premixed Charge Compression Ignition
P_{int}	Intake Pressure
PPC	Partially Premixed Combustion
RCCI	Reactivity Controlled Compression Ignition
RoHR	Rate of Heat Release
SoI	Start of Injection
T_{ad}	Adiabatic flame temperature
T_{IVC}	In-cylinder averaged temperature at IVC
TDC	Top Dead Centre
VVA	Variable Valve Actuation

conditions are attained by decoupling the fuel injection event from the combustion event [8]. The main challenges with the HPC strategies is that they lead to high levels of noise, hydrocarbons (HC) and carbon monoxide (CO) emissions. Moreover, the operating range becomes limited due to the lack of control over the combustion phasing, which also causes excessive maximum pressure rise rates (MPRR) as the engine operation load increases [9,10].

The improvements on the injection systems technologies have allowed to minimize the mentioned challenges, enabling the evolution of the HPC strategies. Firstly, the Homogeneous Charge Compression Ignition (HCCI) combustion was developed [11]. During HCCI operation, the diesel fuel is injected at the intake port and then it mixes with the air before entering into the cylinder. In the Premixed Charge Compression Ignition (PCCI) combustion strategy [12], the diesel fuel is injected directly into the cylinder, early during the compression stroke, to provide enough mixing time to generate lean equivalence ratios [7]. Finally, other strategies using multiple direct injection pulses with different type of fuels such as the Partially Premixed Combustion (PPC) [13] have been used to achieve equivalence ratio stratification [14,15].

Despite the evolution of the HPC concepts, the challenge about the narrow engine operating range was still unsolved [16]. Therefore, the proper operation with the HPC strategies requires using other additional strategies to control the ignition delay and in-cylinder pressure gradients [17]. One of the most effective ways to extend the ignition delay is the use of exhaust gas recirculation (EGR), which is based on increasing the in-cylinder specific heat capacity and reduce the oxygen content to slow down the temperature rise during the compression stroke [18]. Other effective methods arose thanks to the improvements in the air management technologies, such as the variable valve actuation systems [19]. These systems enabled the engine operation with variable compression ratio to control the in-cylinder temperature and pressure [20,21]. The fuel reactivity control is one of the latest strategies that has appeared inside the HPC concepts [22], which is used to tune the fuel auto-ignition characteristics according to the engine operating conditions [23]. This method for controlling the combustion process is the basis of the relatively new combustion concept commonly known as reactivity controlled compression ignition combustion (RCCI) [24].

The RCCI concept relies on injecting a low reactivity fuel through the intake port and a high reactivity fuel injected directly into the cylinder [25]. The use of one injection system for each fuel allows optimizing the global fuel reactivity according to changes in the engine operating conditions. This can be done almost on a cycle-to-cycle basis by varying the gasoline fraction (GF) [26]. Moreover, the fuel reactivity stratification inside the cylinder can be easily modulated through the direct injection timing modification [27]. This action promotes an equivalence ratio and octane number stratification [28], leading to a more sequential combustion event than other HPC strategies [29]. On the other hand, since the mechanism for starting the combustion process is the autoignition of the in-cylinder charge, the control of the thermodynamic conditions is also a key aspect for optimizing this type of combustion.

Literature demonstrates that RCCI combustion concept is able to modify the NOx-soot trade-off appearing with CDC, reducing both pollutants to near-zero levels with thermal efficiencies similar or better than CDC [30]. However, several studies have found the operational range of RCCI to be limited as load increases due to excessive in-cylinder pressure gradients [31,32]. The objective of this investigation is to analyze the capabilities of extending the RCCI operating range by modulating the in-cylinder thermodynamic conditions and fuel auto-ignition properties. In this sense, the coupled effect of both actions is expected to reduce the in-cylinder peak pressures and temperatures, which will improve the RCCI combustion control at relatively high engine loads. To prove this, the effective compression ratio of the engine is varied through the Miller cycle strategy application, and the global fuel reactivity is tuned by varying the gasoline-to-total fuel ratio. The engine tests have been performed in a single-cylinder, heavy-duty compression ignition engine equipped with a hydraulic variable valve actuation (HVA) system running at 14 bar indicated mean effective pressure (IMEP) and 1200 rpm as a baseline condition.

2. Materials and methods

2.1. Engine, fuels and test cell description

The main component used in this research is a single-cylinder heavy-duty compression ignition engine equipped with a hydraulic VVA system with a dedicated oil circuit, whose main specifications are given in Table 1.

The hydraulic VVA system allows to actuate over all the valves independently trough different hydraulic pistons mounted in each valve. These hydraulic pistons are controlled by means of a dedicated electronic control unit that allows managing the opening timing, the opening duration and lift of each valve facilitating the Miller cycle