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A RCCI operational limits assessment in a medium duty compression ignition engine using an adapted compression ratio

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ABSTRACT

Reactivity Controlled Compression Ignition concept offers an ultra-low nitrogen oxide and soot emissions with a high thermal efficiency. This work investigates the capabilities of this low temperature combustion concept to work on the whole map of a medium duty engine proposing strategies to solve its main challenges. In this sense, an extension to high loads of the concept without exceeding mechanical stress as well as a mitigation of carbon oxide and unburned hydrocarbons emissions at low load together with a fuel consumption penalty have been identified as main Reactivity Controlled Compression Ignition drawbacks. For this purpose, a single cylinder engine derived from commercial four cylinders medium-duty engine with an adapted compression ratio of 12.75 is used. Commercial 95 octane gasoline was used as a low reactivity fuel and commercial diesel as a high reactivity fuel. Thus, the study consists of two different parts. Firstly, the work is focused on the development and evaluation of an engine map trying to achieve the maximum possible load without exceeding a pressure rise rate of 15 bar/CAD. The second part holds on improving fuel consumption and carbon oxide and unburned hydrocarbons emissions at low load. Results suggest that it is possible to achieve up to 80% of nominal conventional diesel combustion engine load without overpassing the constraints of pressure rise rate (below 15 bar/CAD) and maximum pressure peak (below 190 bar) while obtaining ultra-low levels of nitrogen oxide and soot emissions. Regarding low load challenges, it has developed a particular methodology sweeping the gasoline-diesel blend together with intake temperature or exhaust gas recirculation maintaining constant the combustion phasing and ultra-low nitrogen oxide and soot emissions. As a result a drastic decrease carbon oxide and unburned hydrocarbons emissions is obtained with a slight fuel consumption improvement.

1. Introduction

Nowadays, for medium and heavy-duty applications, compression ignition engines are the most widely used all around the world. These engines are usually operated under conventional diesel combustion (CDC). This strategy has a clear diffusion combustion behavior governed by the injection timing. Thus, combustion phasing can be controlled with high precision. Consequently, high thermal efficiency is achieved. Despite compression ignition (CI) engines work with lean mixture, this strategy produces fuel-rich equivalences ratios due to mixture stratification. As a consequence, high combustion temperatures are achieved promoting nitrogen oxides (NOx) and soot formation.

In this sense, strict regulations have been introduced, in recent years, to limit pollutants emissions from CI engines. These limitations represent a challenge for the research community. Thus, present HD diesel engines require a huge exhaust after-treatment in

Abbreviations: ASTM, American Society of Testing and Materials; ATDC, after top dead center; CAD, crank angle degree; CA10, crank angle at 10% mass fraction burned; CA50, crank angle at 50% mass fraction burned; CDC, conventional diesel combustion; CI, compression ignition; CO, carbon monoxide; CR, compression ratio; DI, direct injection; DPF, diesel particulate filter; ECU, engine control unit; EGR, exhaust gas recirculation; EOI, end of injection; EU, European union; EVO, exhaust valve open; FPGA, field-programmable gate array; FSN, Filter Smoke Number; HC, hydro carbons; HD, heavy-duty; HCCI, homogeneous charge compression ignition; MCE, multi cylinder engine; MPRR, maximum pressure rise rate; IMEP, indicated mean effective pressure; ISFC, indicated specific fuel consumption; IVC, intake valve close; IVO, intake valve open; LHV, lower heating value; LTC, low temperature combustion; MON, motor octane number; OEM, original equipment manufacturer; ON, octane number; PCI, peripheral component interconnect; PER, premixed energy ratio; PFI, port fuel injection; PPC, partially premixed charge; PRR, pressure rise rate; PXI, PCI eXtensions for Instrumentation; RCCI, reactivity controlled compression ignition; RoHR, rate of heat release; RON, research octane number; SC, screw compressor; SCE, single cylinder engine; SCR, selective catalytic reduction; SOC, start of combustion; SOI, start of injection; TDC, top dead center.

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order to meet emissions regulations, such as EURO VI. These systems are complex and imply a more expensive engine production. In addition, urea (known commercially as AdBlue) is needed to reduce NOx formations and make possible meeting the ultra-low NOx limitation. The use of these elements implies an extra cost in terms of fuel consumption, due to the penalty suffered from the DPF regeneration, and the consumable component urea from the SCR system.

In order to reduce after-treatment and fuel consumption costs [1], several advanced strategies have been developed to maintain the benefits of CDC operation, facing the trade-off between NOx and soot emissions and improving engine efficiency simultaneously [2,3]. In this sense, many researchers have focused on low temperature combustion strategies (LTC), which mitigate the NOx and soot formation while improves engine efficiency. This can be achieved due to heat transfer reduction provided by the premixing between fuel and air which generates long ignition delays and lower bulk gas temperatures. However, due to fuel premixing, chemicals kinetic controls the ignition timing and the heat release instead of mixing. Therefore, the stability of the combustion can be altered and the control of the combustion can be reduced.

Homogeneous charge compression ignition (HCCI) was widely investigated by the research community. This LTC strategy uses premixed charged of fuel and air. The combustion is dominated by the chemical kinetic due to the ignition, which depends of the pressure, temperature, equivalence ratio and fuel properties. HCCI provides higher or equal thermal efficiency than CDC mode and a huge reduction in terms of NOx and soot. However, the homogeneous cylinder charge provokes a rapid heat release occurring steeps pressure gradients. As a result the engine can be submitted under high engine stress and excessive combustion noise. Thus, HCCI has been limited up to partial load [4]. Regarding this limitation, Bessonette et al. [5] suggested that HCCI operation under different conditions would require different fuel reactivity's. In particular, low loads require high fuel reactivity and higher engine loads require low fuel reactivity.

Partially Premixed Combustion (PPC) strategies have been deeply studied [6–10]. PPC is presented with the idea of improving HCCI weaknesses in terms of controllability and knocking by using low reactivity fuels. So, PPC with gasoline allows controlling better the heat release rate providing NOx and soot emissions reduction [11,12]. By contrast, several fuel combustion studies made with different octane number fuels showed that the higher the research octane number (RON), the higher the unburning problems and dispersion cycle-to-cycle, being critical for gasolines with RON higher than 91. In addition, this problematic area overlaps with the area with major potential of the strategy in terms of NOx and soot reduction [13,14]. This resistance to ignite from the gasoline can be taken to increase the delay timing. On the other hand, this characteristic from the gasoline makes difficult to manage when it has to be burned at low load. Therefore, diesel ignites easier than the gasoline, so it is easier to burn at low load, requiring higher exhaust gas recirculation (EGR) rates while load is increased [15].

These results provided a detailed study by Park et al. [16], where the effects of fuel blends formed by diesel and gasolines were deeply studied. The study states that the gasoline in the fuel blend provides a reduction in density, kinetic viscosity and surface tension, improving the atomization process. In addition, it provides also high ignition delays enhancing a more homogeneous blend formation. As a result, the trade-off between NOx and soot is reduced. However, the emissions in terms of carbon monoxide (CO) and unburned hydrocarbons (HC) are increased. While the load is increased, the fuel blend tends to be moved forward to a high portion of diesel, worsening the benefits of this combustion previously mentioned. Regarding these conclusions, by using different fuels shows high combustion improvement potential.

Following that trend, Inagaki et al. [17] studied PCI combustion controlled by different ignitability fuels. It achieved low NOx and smoke emissions. Isooctane fuel was supplied by a port fuel injector and the diesel fuel was injected directly in the combustion chamber as ignition trigger. The ignition trigger was able to manage by modifying the portion of each type of fuel (low cetane number fuel at high load and high cetane number at low load), in other words, adjusting the reactivity of the fuel blend. Regarding these hypotheses, Kokjohn et al. [18] baptized as reactivity controlled combustion ignition (RCCI) combustion mode, injecting gasoline as a low reactivity fuel (low cetane number) and diesel as a high reactivity fuel (high cetane number). Port fuel injection (PFI) is used for gasoline and direct injection (DI) is used for diesel. Gasoline is injected generating a premixed blend of air and fuel, included EGR as well. Then, diesel is injected in one or two injections. As the high reactivity fuel is injected, added to the conditions at the combustion chamber, starts de ignition and derives into the burning of the premixed energy ratio as well. Therefore, it is possible to create different fuel blends in order to adjust the combustion phasing and the rate of heat release by controlling fuel reactivity [19].

Thus, RCCI operation mode shows a lot of potential in order to solve the main problems found at the LTC strategies. In addition, RCCI also provides ultra-low emissions in terms of NOx and soot simultaneously breaking the trade-off. This is achieved due to the premixing time, which avoids the formation of high equivalence ratios areas. Moreover, the combustion phasing is controlled by the direct injection of the high reactivity fuel and the rate of heat release is governed by the fraction of the fuels.

Despite the benefits obtained with RCCI concept, it has been appreciated some relevant challenges. In order to achieve ultra-low NOx and soot emissions at high or full loads a highly premixed combustion is needed. Thus, the maximum RCCI load is restricted by the high pressure rise rates. In this sense, it is stated the lack of RCCI experimental results in those loads. In addition, high levels of CO and unburned HC emissions have been stated in the whole engine map, but it should be highlighted its magnification at low loads. Thus, the main objective of the present work is to extend the RCCI concept to the maximum load without exceeding 15 bar/cad as the maximum pressure rise rate and fulfilling Euro VI soot and NOx limitations. Nonetheless, future works will be required in order to face the transition between different loads as well as engine speeds. In particular, the transition from one load to other load represents a challenge in terms of combustion stability.

2. Experimental configuration

2.1. Test cell and engine description

The experiments presented in this work were conducted using a fully instrumented test bench in which was installed the engine. The engine is a VOLVO D5K with 4 in-line cylinders and it has been modified in order to work the first cylinder as a single-cylinder diesel engine and the other 3 cylinders will work with the stock configuration. Main specifications of the engine are shown in Table 1. The engine is a EURO VI medium-duty diesel engine developed for urban freight distribution purposes. Despite the engine has been presented as EU VI new engine, the after-treatment system has been removed, and even the high pressure EGR loop.

Regarding the test bench, it is fitted with all the equipment necessary to operate and control as it can be seen in Fig. 1. The set–up found in this test bench is quite particular because of the hybrid solution developed to operate with a single-cylinder engine. The engine is not a conventional SCE research engine, it is a hybrid between a multi cylinder engine (MCE) and a SCE. A cylinder of