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The role of the in-cylinder gas temperature and oxygen concentration over low load reactivity controlled compression ignition combustion efficiency

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A B S T R A C T

Several studies carried out with the aim of improving the RCCI (reactivity controlled compression ignition) concept in terms of thermal efficiency conclude that the main cause of the reduced efficiency at light loads is the reduced combustion efficiency. The present study used both a 3D computational model and engine experiments to explore the effect of the oxygen concentration and intake temperature on RCCI combustion efficiency at light load. The experiments were conducted using a single-cylinder heavy-duty research diesel engine adapted for dual fuel operation.

Results suggest that it is possible to achieve an improvement of around 1.5% in the combustion efficiency with both strategies studied; the combined effect of intake temperature and in-cylinder fuel blending as well as the combined effect of oxygen concentration and in-cylinder fuel blending (ICFB). In addition, the direct comparison of both strategies suggests that the combustion losses trend is mainly associated to the in-cylinder equivalence ratio stratification, which is determined by the diesel to gasoline ratio in the blend since the injection timing is kept constant for all the tests. Moreover, the combined effect of the intake temperature and ICFB promotes a slight improvement in the combustion losses over the combined effect of the oxygen concentration and ICFB.

1. Introduction

Since decades, internal combustion engines (ICE) play a fundamental role in the society. The capability of the ICEs to cover fundamental requirements such as people and goods transportation and power generation, has result in their mass production. Due to the extensive use of the ICEs, stringent regulations are being introduced around the world to limit their pollutant emissions with the aim of reducing their environmental impact. In addition, a prime requirement by the users is to improve the fuel economy, which in turn results in higher ICE efficiency. In this sense, the higher compression ratio (CR), un-throttled operation and shorter combustion duration of the compression ignition (CI) engines than the spark ignition (SI) engines offers a greater potential to increase the thermal efficiency. In spite of its potential, the rich local equivalences ratios, high temperatures achieved during a conventional mixing-controlled diesel combustion in CI diesel engines as well as the oxygen availability in the outside of the spray plume results in an unacceptable NO_x and soot emissions, taking into account the current regulations such as EURO VI. Soot emissions can be reduced by using a DPF (diesel particulate filter), which requirement of regeneration results in a fuel consumption penalty. Since TWC (three-way catalyst) achieves their maximum efficiency operating with equivalence ratios near stoichiometric or slight richer, a poor NO_x reduction efficiency is obtained. Thus, NO_x emissions can be minimized through the use of an LNT (lean No_x trap) or SCR (selective catalytic reduction) technology requiring periodically regeneration (operating rich) and the introduction of a reducing agent respectively, which worsens the fuel consumption. In order to reduce aftertreatment costs and fuel consumption it is necessary to avoid the generation of these pollutants in the focus of the emission, i.e. during the combustion development. In this sense, 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 purpose of reducing fuel consumption and engine-out emissions.

The more promising combustion strategies to simultaneously improve the engine efficiency while reducing the most relevant diesel engine-out emissions, NO_x and soot, under the regulation limits are the low temperature combustion (LTC) strategies. LTC

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strategies are based on promoting a lean air–fuel mixture together with a low temperature combustion avoiding the NO_x and soot formation. The efficiency is improved as a consequence of the fast heat release obtained when the proper in-cylinder conditions are achieved, as well as the reduction in heat transfer (HT) losses due to the lower in-cylinder temperature peaks. In this sense, the well-known combustion concept based on fully premixed lean mixtures homogenous charge compression ignition (HCCI) [3,4] has been widely investigated. Although HCCI achieves important emission benefits [5], this combustion concept presents some practical issues that must be solved before it can be implemented in CI diesel engines, which limit the HCCI operating range to low engine speeds and loads [6]. The most relevant limitations consist of achieving an appropriate combustion phasing, cycle-to-cycle control of the combustion process, spray impingements and its effects on the emissions [7], combustion noise and operating range extent. Several techniques such as EGR (exhaust gas recirculation) [8], variable valve timing [9,10], variable compression ratio [11] and intake air temperature variation [12] 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-to-cycle control. Thus, when increasing engine load not enough mixing time before the start of combustion is provided. On this regard, Bessonette et al. [13] suggested that different in-cylinder reactivity is required for the proper HCCI operation under different operating conditions. Specifically, high cetane fuels are required at low load and a low cetane fuels are needed at medium–high load.

In order to improve the controllability and widen the engine operating range, Partially Premixed Combustion (PPC) strategy has been studied. This LTC strategy is based on reduce the air–fuel mixing degree by injecting later in the cycle than in HCCI strategy, attaining an in-cylinder equivalence ratios stratification. The strategy offers higher control on the ignition delay as well as the combustion duration, which depends on the partial stratification of the fuel provided by the injection timing. In addition, lower in-cylinder pressure gradients are obtained reducing the knocking level. Despite their benefits, as in HCCI strategy, the use of diesel fuel [14] requires high levels of EGR when increasing engine load to achieve a proper combustion phasing [15], which reduces the thermal efficiency. In order to avoid this shortcomings, the use of fuels with lower reactivity [16–20] than diesel fuel (lower cetane number) such as gasoline has been proposed. The use of gasoline provides more flexibility to achieve the required extra mixing time at medium–high loads [21]. Several studies confirmed gasoline PPC as a promising method to control the heat release rate providing a reduction in NO_x and soot emissions [19,22,23]. However, the concept has demonstrated difficulties at low load conditions [24,25] 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 offers the possibility of cycle-to-cycle control. Thus, it seems that additionally to the equivalence ratio stratification, an in-cylinder PRF (primary reference fuel) stratification will be required to proper operating LTC strategies at different operating conditions.

Reactivity controlled compression ignition (RCCI) combustion allows both sources of stratification (equivalence ratio and PRF) by direct in-cylinder blending different reactivity fuels. To delivery both fuels separate injection systems for the low-reactivity and high-reactivity fuel are used, being port fuel injected (PFI) and direct injected (DI) respectively. Thus, a flexible operation over a wide operating range is possible by modifying both, the low reactivity fuel percentage in the blend and the direct injection timing. Recent experimental and simulated studies confirm that RCCI concept allows an effective ignition control and a low maximum PRR (pressure rise rate) while maintaining low engine-out emissions levels and high fuel efficiency simultaneously, proving that the RCCI concept is a more promising LTC technique than HCCI [26] and PPC. In this sense, Kokjohn et al. [27] and Splitter et al. [28] studied RCCI combustion over a wide range of engine loads and conditions concluding that the main cause of the reduced efficiency at light loads is the reduced combustion efficiency. Thus, it is possible to achieve combustion efficiencies near 98% by reducing the combustion losses, which is considered an acceptable value for a premixed combustion strategy. The main objective of the present work is to evaluate the coupled effect of the in-cylinder gas temperature or oxygen concentration with the in-cylinder fuel blending ratio on RCCI combustion losses (CO and unburned HC) in a heavy-duty (HD) CI engine. For this purpose EGR and intake temperature sweeps have been carried out. Both sweeps (intake temperature and EGR) have been performed keeping constant the combustion phasing (CA50) by adjusting the gasoline percentage in the blend as required in each case and keeping constant the rest of the engine settings. In addition two constraints have been taken into account for the tests: NO_x and soot under EURO VI limits for HD diesel engines (NO_x < 0.4 g/kWh and soot < 0.01 g/kWh) and ringing intensity (RI) below 5 MW/m^2, which was established by Dec and Yang [29] as a proper upper limit to achieve an acceptable combustion noise and knock-free operation. In addition to the experimental tests, a computational analysis by means of a CFD (computational fluid dynamics) code has been conducted in order to better explain the results.

2. Experimental facilities and processing tools

2.1. Test cell and engine description

A single cylinder, HD diesel engine representative of commercial truck engine, has been used for all experiments in this study. Detailed specifications of the engine are given in Table 1.

The engine was installed in a fully instrumented test cell, with all the auxiliary facilities required for its operation and control, as it is illustrated in Fig. 1. Moreover, to achieve stable intake air conditions, a screw compressor supplied the required boost pressure before passing through an air dryer. The air pressure was adjusted within the intake settling chamber, while the intake temperature was controlled in the intake manifold after mixing with EGR. The exhaust backpressure produced by the turbine in the real engine was replicated by means of a valve placed in the exhaust system, controlling the pressure in the exhaust settling chamber. Low pressure EGR was produced taking exhaust gases from the exhaust settling chamber. Then, once it was filtered by a DPF, its temperature was reduced passing through a heat exchanger. After that, water steam and condensate were separated from gas by means of a centrifugal filter, and resulting gases were passed through a secondary filter. Furthermore, a roots-type supercharger was used

Table 1
Single cylinder engine specifications.

Engine type	Single cylinder, 4 St cycle, DI
Bore × stroke [mm]	123 × 152
Connecting rod length [mm]	225
Displacement [L]	1.806
Geometric compression ratio [–]	14.4:1
Bowl type	Open crater
Number of valves	4
IVO	375 CAD ATDC
IVC	535 CAD ATDC
EVO	147 CAD ATDC
EVC	347 CAD ATDC