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Evaluation of massive exhaust gas recirculation and Miller cycle strategies for mixing-controlled low temperature combustion in a heavy duty diesel engine

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ABSTRACT

The future of compression ignition engines depends on their ability for keeping their competitiveness in terms of fuel consumption compared to spark-ignition engines. In this competitive framework, the Low Temperature Combustion (LTC) concept is a promising alternative to decrease NOx and soot emissions. Thus, this research focuses on implementing the LTC concept, but keeping the conventional mixing-controlled combustion process to overcome the well-known drawbacks of the highly-premixed combustion concepts, including load limitations and lack of combustion control.

Two strategies for implementing the mixing-controlled LTC concept were evaluated. The first strategy relies on decreasing the intake oxygen concentration introducing high rates of cooled EGR (exhaust gas recirculation). The second strategy consists of decreasing the compression temperature by advancing the intake valves closing angle to reduce the effective compression ratio, compensating the air mass losses by increasing boost pressure (Miller cycle). These strategies were tested in a single-cylinder heavy-duty research engine. Additionally, 3D-CFD modeling was used to give insight into local in-cylinder conditions during the injection-combustion process.

Results confirm the suitability of both strategies for reducing NOx and soot emissions, while their main drawback is the increment in fuel consumption. However, they present intrinsic differences in terms of local equivalence ratios and temperatures along combustion.

1. Introduction

The major use of Diesel engines is heavy duty applications, because of their high fuel efficiency, durability, reliability and their high torque output. However, the gas exhausted by diesel engines contains undesirable and harmful species, which have to be reduced according with the newest emissions regulations. On this concern, the scientific community, in close collaboration with the engine manufacturers, is focusing their efforts in a combination of in-cylinder reduction strategies and exhaust gas after-treatment technologies. Due to the difficulties faced for reducing the cost of after-treatment devices, in-cylinder emission control strategies are still attractive to reduce simultaneously soot and NOx engine-out emissions.

Highly premixed combustion concepts have been widely investigated as combustion technologies to avoid soot and NOx engine-out emissions [1]. These strategies use volumetric auto-ignition and combustion in lean or dilute mixtures for which combustion temperatures are too low for significant NOx formation, and air-fuel mixtures (A/F) are too lean for soot formation. To achieve the high degree of fuel-air mixing needed for premixed combustion, researchers have found that the fuel injection event must be concluded prior to auto-ignition [2,3]. Successful results have been obtained by means of highly premixed combustion strategies [4,5]. However, despite the recent research efforts on this combustion concept, ignition timing control and load limit still remain as the main challenge for its practical application; an increase on the local equivalence ratios results in a fast transition to knocking combustion [6].

Conventional mixing-controlled Diesel combustion is well known for its suitability at complete engine operation range. Nevertheless, this combustion strategy relies on exhaust gas after-treatment technologies for controlling NOx and/or soot emissions. Through detailed studies, many researchers confirmed how high temperatures at the stoichiometric diffusion flame surface imply high NOx formation [7–9]; and also that soot formation occurs

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inside the envelope of the diffusion flame, in the high temperature and fuel-rich regions of the spray after the lift-off length [10–13]. Soot is finally exhausted if it is not further oxidized in later phases of the combustion process.

On light of the drawbacks from those combustion strategies, mixing-controlled low temperature combustion (MC-LTC) strategy arises as an alternative to overcome the lack of ignition timing control of the highly premixed strategies as well as the NOx-soot trade-off characteristic of the conventional diffusive combustion. Pickett et al. [14] reported three different alternatives to attain mixing-controlled non-sooting low flame temperature diesel combustion in an optically-accessible, quiescent constant-volume combustion vessel. The first one is based on the use of reduced nozzle hole diameters; the second consists of sharply decrease the ambient gas temperature; and the third needs the use of extensive exhaust gas recirculation (EGR) to reduce the ambient gas oxygen concentration (YO_2). Different investigations confirmed the feasibility of the mixing-controlled low temperature combustion for avoiding NOx and soot emissions formation in an HSDI engine [15,16]. There, the MC-LTC strategy was implemented by introducing massive EGR rates, so following the third alternative. Authors stated that the sootless and zero-NOx combustion process intrinsically generates high levels of HC and CO emissions, lowering engine efficiency.

With the aim of overcoming the drawbacks from using extensive EGR, Benajes et al. [17] investigated the suitability of the Atkinson cycle for lowering the in-cylinder gas temperature. It was performed by advancing the intake valves closing angle, keeping constant intake and exhaust pressures, in an HD diesel engine equipped with a fully variable valve actuation (VVA) system. Results corroborated the potential from Atkinson cycle for reducing the in-cylinder gas temperature during the compression stroke, but also the gas pressure and its density. According with the results obtained by Jia et al. [18], NOx emissions decrease due to the lower temperatures along the combustion process, but the spray mixing process is intrinsically slowed down as a result of the lower gas density. Therefore, the mixing-controlled combustion process deteriorates and soot, CO and fuel consumption increase.

In this framework, the following investigation focuses on improving the existing knowledge on the MC-LTC concept, and also on comparing the two key strategies available for implementing this advanced combustion concept, the massive EGR and the Miller cycle. In this case the massive EGR strategy was implemented as usual, while the Miller cycle was implemented by increasing the boost pressure. The objective was to recover the air mass loss due to the shortened intake event, avoiding the well-known drawbacks of the Atkinson cycle as a result of the lack of air for sustaining a suitable combustion process. Thus, this investigation was carried out with the aim of understanding the benefits/drawbacks provided by these two strategies.

The study includes a sequential analysis of the combustion process, final exhaust emissions and fuel consumption trends by combining direct experimental data with the detailed information on the local in-cylinder conditions obtained from 3D-CFD simulations. This information was combined for comparing the two strategies not only in terms of the final engine out emissions and efficiency, but also considering the detailed mechanisms involved in NOx and soot emissions control by analyzing the local conditions along the combustion process.

2. Objectives and methodology

This research work was focused on achieving non-sooting and low flame temperature mixing-controlled combustion in an HD Diesel engine by means of two different strategies to conclude which are their benefits and drawbacks. The massive EGR strategy relies on decreasing the intake oxygen concentration by means of introducing high rates of cooled external EGR. The Miller cycle strategy consists of decreasing the compression temperature by reducing the engine effective compression ratio (CR_{ef}) while increasing boost pressure to compensate the air mass loss. Firstly, these two strategies were analyzed in detail to identify the mechanisms for attaining non-sooting and low flame temperature mixing-controlled combustion. The analysis was carried out by combining direct engine testing with 3D-CFD modeling to relate the trends followed by pollutant emissions with the in-cylinder local conditions. To conclude, both strategies were critically compared and their potential for further development was evaluated.

The methodology followed to analyze massive EGR and Miller cycle strategies was based on a set of parametrical studies varying the intake oxygen concentration and the effective compression ratio. This way to proceed enables the understanding of isolated effects and it is suitable for comparing the strategies. The basic engine operation conditions are defined by 1200 rpm engine speed keeping a constant injected fuel mass of 91.2 mg/cycle.

Both parametrical studies are shown in the A/F-EGR map included in Fig. 1. There is shown how the massive EGR strategy was implemented by reducing the YO_2 at the beginning of combustion ($YO_{2,SOC}$) from 16% to 10%, but keeping constant the YO_2 at the end of combustion ($YO_{2,EOC}$). Since $A/F = 19$ was kept constant, the higher EGR the higher required boost pressure (BP). This procedure avoids the well-known negative effects of reducing $YO_{2,EOC}$ over soot emissions [19]. Settings used to implement this strategy are listed in Table 1. The Miller cycle was implemented to reduce the CR_{ef} from 14.4 to 8, shortening the intake stroke by advancing the intake valves closing angle (IVC). The reduction in air mass flow rate caused by this shortened intake stroke was compensated increasing boost pressure. A/F ratio and EGR ratio were kept constant for all points related to Miller cycle strategy, thus, these points overlap in the A/F-EGR map. Detailed settings used to implement this strategy are included in Table 2.

The study has been performed to investigate the basis of MC-LTC concepts. Further development, using the knowledge obtained from this research, will be needed to extend the concept to the whole engine operation map.

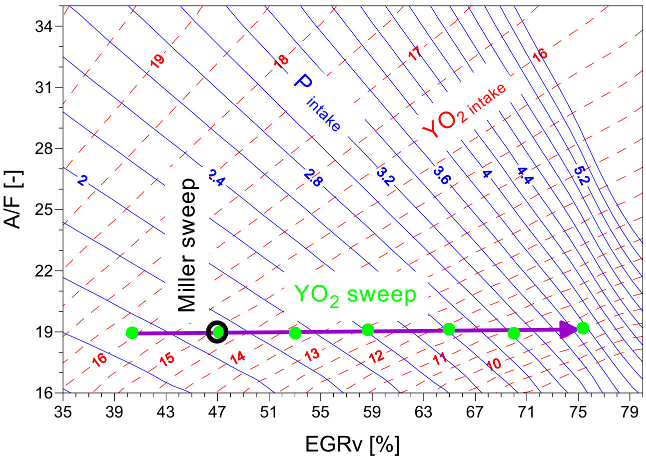

Fig. 1. Engine map which summarizes most settings of the YO_2 sweep in round dots, remarked by an arrow. In this map, the Miller sweep appears as only one point, the empty black circle. Dashed lines are intake volumetric oxygen concentration and continuous lines represent the intake pressure.