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Research Paper

Swirl ratio and post injection strategies to improve late cycle diffusion combustion in a light-duty diesel engine

Jesús Benajes [a], Jaime Martín [a], Antonio García [a,*], David Villalta [a], Alok Warey [b]

[a] CMT Motores Térmicos – Universitat Politècnica de València, Camino de Vera s/n, 46022 Valencia, Spain
[b] Propulsion Systems Research Lab, General Motors Global Research and Development, United States

HIGHLIGHTS

- The oxidation process is main responsible for the exhaust PM emissions in a CI engine.
- The mixing process and bulk gas temperature manage to soot oxidation process.
- Higher swirl ratio not implies an increase of mixing process during the late combustion.
- The post injection event improves the soot oxidation during late cycle combustion.

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ABSTRACT

Nitrogen oxides (NOx) and soot emissions are the most important pollutants from direct-injection diesel engines. In particular, soot formation and oxidation determine the net engine-out soot emissions. These phenomena are complex and competing processes during diesel combustion. Despite many researches implicate the mechanisms of soot formation with soot emissions, the enhancement of the late cycle soot oxidation is the dominant mechanism for a reduction of engine-out soot emissions. The mixing process and the in-cylinder bulk temperature are two important parameters in the development of soot oxidation process. The current research compares different engine strategies to enhance the late cycle mixing controlled combustion process and therefore enhance soot oxidation while maintaining similar gross indicated efficiency in a light-duty engine. For this purpose, a simplified methodology has been used, which analyzes the effect of mixing process and in-cylinder bulk gas temperature on soot oxidation during the late cycle combustion. For carrying out this research, theoretical and experimental tools were used. In particular, the experimental measurements were made in a single-cylinder direct-injection light-duty diesel engine varying the swirl ratio and the injection pattern as injection pressure, Start of Energizing (SoE), Energizing Time (ET) and number of injections events. To analyze soot emissions, the combustion luminosity was measured by an optoelectronic probe and the optical thickness parameter (KL) was evaluated by the two-color pyrometry method. The apparent combustion time (ACT-1) was used as mixing time tracer. Results show that an increase in swirl ratio implies an improvement on the mixing process and higher values of average bulk temperature during the late-cycle diffusion combustion. Both phenomena produce an enhancement in the soot oxidation process. In the lowest swirl ratio case, a suitable injection strategy based on multiple injections, provides similar results of soot oxidation process (and therefore, the emissions) as high swirl ratio case.

Abbreviations: ACT, Apparent Combustion Time; BMEP, Brake Mean Effective Pressure; CA50, Crank Angle at 50% mass fraction burned; CAD, Crank Angle Degree; CI, Combustion Ignition; DI, Direct-Injection; EGR, Exhaust Gases Recirculation; EoC, End of Combustion; EoI, End of Injection; ET, Energizing Time; EVO, Exhaust Valve Open; FSN, Filter Smoke Number; FWHM, Full Width al Half Maximum; GHG, Greenhouse Gases; GIE, Gross Indicated Efficiency; ICE, Internal Combustion Engines; IVC, Inlet Valve Close; $I_{b,\lambda}$, spectral intensity of black body; I_{soot}, spectral intensity; KL, optical thickness; LOL, lift-off length; NOx, nitrogen oxides; P_{in}, intake pressure; PM, particulate matter; POC, point of combustion; POI, point of injection; RoHR, Rate of Heat Release; SoE, Start of Energizing; SR, Swirl Ratio; TDC, Top Dead Center; T_{in}, intake temperature; α, absorptivity; ε, emissivity; λ, wavelength.

* Corresponding author.
E-mail address: angarma8@mot.upv.es (A. García).

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1. Introduction

Due to the increase of Greenhouse Gas (GHG) emissions produced by the Internal Combustion Engines (ICE), stringent regulations are being introduced all around the world to limit their exhaust emissions with the objective of decreasing their environmental impact. The automotive manufacturers and researchers focus their attention on the development of cleaner and more efficient powertrain engines. In particular, the nitrogen oxides (NOx) and particulate matter (PM) are the most important pollutants from direct-injection diesel engines. Thus, different strategies are implemented to reduce these emissions: high pressure fuel injection systems [1,2], multiple injections [3], high boost pressure [4], exhaust gases recirculation [5], high swirl [6], new cleaner fuels [7] and new combustion concepts [8,9]. The present research was focused on comparing different engine operating conditions, which can achieve a reduction in engine-out exhaust emissions.

Soot emissions in diesel exhaust depend on formation and oxidation processes. Both processes are distinct in temporal and spatial evolution. The soot formation process is more important during the fuel injection event and it is approximatively located in the region closest to the nozzle [10]. Large amount of soot forms quickly during the earliest combustion period due to high local equivalence ratio in the fuel-rich premixed burn region [11–13]. In this stage, soot oxidation is poor. From the End of Injection (EoI), the soot oxidation process becomes more relevant. The oxidation stage spans the range from EoI up to the End of Combustion (EoC). In this stage, the diffusion flame disappears, the soot formation decreases and the soot oxidation rate increases. In these conditions, the mixing process and the in-cylinder bulk temperature govern the soot oxidation process. It is important to highlight that only a small amount of soot formed makes it into the exhaust. Fig. 1 shows the correlation between the maximum amount of soot formed (peak value of soot concentration, KL) and concentration of PM emissions in the exhaust for different measured engine conditions [14]. Thus, two groups of results are clearly observed: on the one hand, the square symbols points out a group of results in which the PM emissions are similar and low independently on the peak value of soot concentration, KL and therefore independently on the value of soot formed in-cylinder. On the other hand, group of circle symbols indicate other results where the highest concentrations of soot formed, maximum of KL peak value correspond on lowest values of PM emissions, and vice versa. These trends are the opposite of those that would be expected if the PM emissions were explained by the amount of formed soot [15]. Gallo et al. have obtained a similar correlation. In their study [16], different operating conditions were measured in an optical engine and the laser extinction technique was used to evaluate the oxidation rates during the expansion stroke. They conclude that the amount of in-cylinder soot formed does not explain the engine-out soot emissions. Considering diesel fuel and operating conditions tested, the oxidation process is mainly responsible for the exhaust PM emissions in a CI diesel engine under real conditions.

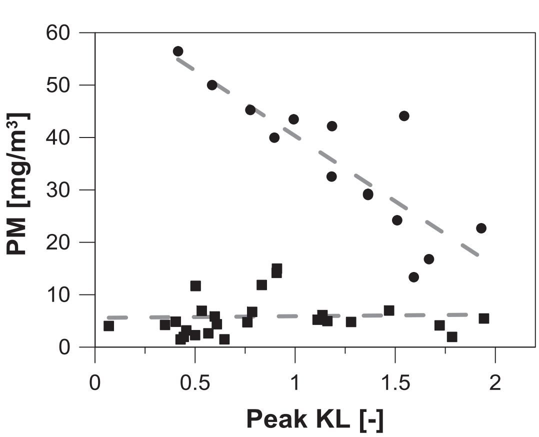

Fig. 1. Concentration of exhaust PM versus the maximum value of KL for the different engine conditions measured in [14].

In literature, many researchers have studied the soot oxidation process. Dembinski et al. [17] studied the impact of swirl ratio and injection pressure on the soot oxidation process. Experimental measurements were made with two different optical techniques (Combustion Image Velocimetry and two-color method) in an optical engine. This research stated that the soot oxidation process improved when the swirl ratio and injection pressure were increased due to an enhancement of in-cylinder turbulence. O'Connor and Musculus [18] studied the effect of different engine parameters on the soot oxidation process, concluding that a post injection can reduce engine-out soot by up to 45% at high swirl ratios and 30% for low swirl ratios. Gallo et al. [16] analyzed the amount of PM emitted by modifying the injection pressure, gas density and temperature at TDC as well as engine speed and nozzle hole size by application of the laser extinction method. These authors concluded that increasing the injection pressure, gas density, and reducing nozzle hole size and the engine speed, the engine-out PM emissions were strongly reduced. Arrègle et al. [19] showed different post-injection strategies for reducing soot emissions in DI diesel engines. In this research, a broad experimental analysis was carried out to explore the behavior of post-injection strategy on exhaust soot emissions under a certain range of operating conditions and with different post-injection timings. These authors concluded that the engine-out soot emissions were reduced when the post-injection event was added. Using a similar optical approach, Lopez et al. [20] also studied the in-cylinder soot oxidation process by means of the two-color method. In particular, the impact of swirl, EGR and injection timing were analyzed. These authors concluded that the soot oxidation process is degraded when swirl is decreased, EGR rate is increased or injection timing is delayed.

Thus, the main objective of this work was to compare different engine strategies to enhance the late cycle mixing controlled combustion process and therefore to improve the soot oxidation process while maintaining similar gross indicated efficiency in a light-duty engine. For this purpose, a simplified methodology defined in [14] was used, which analyzed the effect of mixing process and in-cylinder bulk gas temperature on soot oxidation during the late cycle combustion. Experimental measurements were made in a single-cylinder direct-injection light-duty diesel engine varying the swirl ratio and the injection pattern as injection pressure, Start of Energizing (SoE), Energizing Time (ET) and number of injections events. To analyze soot, the optical thickness (KL) parameter was used, which was measured by an optoelectronic probe based on the two-color pyrometry method. The apparent combustion time (ACT-1) was used as mixing tracer. This parameter is based on the injection rate profile and the experimental heat release. Finally, both strategies (swirl ratio and injection pattern) were evaluated with the goal of getting the maximum benefits in terms of the soot oxidation process.

2. Experimental tools

2.1. Test cell and engine description

The experimental measurements were carried out in a single-cylinder light-duty diesel engine. It was equipped with a