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Research Paper

Implementation of two color method to investigate late cycle soot oxidation process in a CI engine under low load conditions

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HIGHLIGHTS

- High uncertainties in flame transparency are obtained for high load conditions.
- The half-life time is a good estimator to characterize the soot oxidation process.
- If injection pressure is reduced, the soot oxidation process is decreased.
- Lower the ambient density and/or temperature, larger the mixing capability.
- The soot oxidation process is explained by the mixing process and bulk temperature.

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ABSTRACT

Soot emissions from diesel engines are an important concern in meeting emissions regulations. Soot emissions are the result of two competing processes: soot formation and soot oxidation. Mechanisms of soot formation are discussed extensively in the literature. Equivalence ratio at lift-off length along with residence time and gas temperature play an important role for soot formation in a diffusion flame. Mixing capability and bulk gas temperature are the most important parameters that influence the in-cylinder soot oxidation process. Normally, research studies of soot formation-oxidation processes have been developed under controlled and not completely representative conditions of engine operation in the field. Therefore, the main objective of this work was to develop a simplified methodology to evaluate in-cylinder soot oxidation under 'real' engine conditions. In particular the impact of mixing process and bulk gas temperature on late cycle soot oxidation was evaluated. The experimental measurements were made in a production light-duty diesel engine varying those parameters that have been demonstrated in the literature as the most relevant in soot formation – oxidation processes; injection pressure, ambient density and intake air temperature. To measure soot, two color method was applied by means of an optoelectronic pyrometer. To evaluate the mixing capability a specific "tracer" Apparent Combustion Time (ACT^{-1}) based on the experimental heat release and injection parameters was defined. The relationship between both parameters was used to explain the soot oxidation process.

1. Introduction

Internal Combustion Engines (ICE) are the most widely used technology in automotive sector. In particular, the Direct-Injection (DI) diesel engine is identified as the most efficient powertrain due to lower fuel consumption compared to Spark Ignition (SI) engines. This benefit has been supported by extensive research in different fields: in-cylinder heat transfer (HT) reduction [1], improvement in thermal management [2], reduction of friction and auxiliaries losses [3], and indicated cycle optimization [4], among others. In spite of its high efficiency, diesel engines have two area of focus: emissions of nitrogen oxides (NOx) and particulate matter (PM), with soot being a major component. These two pollutants are regulated by emissions legislations and thus, engine designers are motivated to develop new combustion strategies for reducing the engine-out pollutant emissions [5,6].

Focusing on soot emissions it is possible to state that soot production in a diesel engine is the result of two competing processes: soot formation and soot oxidation. Thus, spatially the first soot precursors are formed in the fuel-rich premixed burn region in the diffusion flame depending on the local equivalence ratio [7–9]. Once

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Nomenclature

Abbreviations

ACT	Apparent Combustion Time
CA50	Crank Angle at 50% mass fraction burned
EoC	End of Combustion
EoI	End of Injection
EVO	exhaust valve open
FWHM	Full Width al Half Maximun
HT	heat transfer
HRL	heat release law
IVC	inlet valve close
$I_{b,\lambda}$	spectral intensity of black body
I_{soot}	spectral intensity
KL	optical thickness
LOL	lift-off length
P_{in}	intake pressure
P_{inj}	injection pressure
PM	particulate matter
RoHR	rate of heat release
SoI	start of injection
T_{in}	intake temperature
u_0	injection velocity
VGT	variable geometry turbocharger
α	absorptivity
ε	emissivity
λ	wavelength
θ	spray cone angle
ρ_0	density
ϕ_0	equivalence ratio

these precursors appear, particle growth occurs due to high temperature and absence of oxygen in the region covered by the diffusion flame. Now, regarding the soot oxidation process, two different stages in the temporal evolution of the in-cylinder soot concentration need to be considered [10]: in the first stage, from the Start of Injection (SoI) up to the End of Injection (EoI), a quasi-steady state is achieved, and nearly all the soot formed in the spray core is oxidized when reaches the diffusion flame front. In the second stage, from EoI up to the End of Combustion (EoC), the diffusion flame vanishes and soot formation decreases. At these conditions soot oxidation is strongly coupled with the mixing rate and the in-cylinder temperature [8]. It is also worthy to note that only a small fraction of the soot formed in cylinder is emitted in the exhaust [11]. The soot formation process has been studied extensively [12], but now we are going to focus on some studies on in-cylinder soot oxidation that can be highlighted. Pickett and Siebers [7], reported that a reduction in the in-cylinder ambient density causes a large decrease in the peak soot volume fraction due to longer combustion duration and slower combustion development. Measurements were made by using laser extinction under a wide range of operating conditions. Gallo et al. [13], using an optical diesel engine, demonstrated that a reduction in oxygen concentration results in a decrease in in-cylinder soot oxidation. In their study, time resolved extinction measurements have been used to estimate soot oxidation rates during the expansion stroke. Dembinski and Angstrom [14] analyzed the impact of increased turbulence, caused by higher injection pressure and higher swirl number, on in-cylinder soot oxidation. These authors concluded that the soot oxidation process is enhanced with turbulence. Tree and Svensson [9] studied the effect of different engine parameters on the soot oxidation process, concluding that the ambient temperature had the greatest effect by increasing the reaction rates. In addition, Huestis et al. [15] analyzed the in-cylinder processes and exhaust emissions, using two-color pyrometry in combination with soot concentration measurements in the exhaust. Natural luminosity from the flame was collected using three photo diodes with different band pass filters. These authors concluded that a drastic decrease in the oxygen intake concentration (up to 9%) implies a monotonic decrease in the cycle soot oxidation rate [15], which is consistent with the results reported in [13]. Using a similar optical approach, López et al. [16] 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 is to define a simplified methodology to evaluate the in-cylinder soot oxidation under real engine conditions. In particular, the impact of the mixing process and bulk gas temperature on soot oxidation will be evaluated. The experimental measurements will be made in a production light-duty diesel engine varying those parameters that have been demonstrated in the literature as being the most relevant in the soot formation – oxidation processes: injection pressure, ambient density and intake air temperature. To measure soot, the two color method will be applied by means of an optoelectronic pyrometer. To evaluate the mixing capability, a specific "tracer" (ACT^{-1}) based on both the experimental heat release and the injection profiles will be defined. The relationship between both parameters will be used to explain the soot oxidation process.

2. Experimental set up

2.1. Multi-cylinder light duty engine

The engine used in the present research was a production-type GM 1.9L 4-cylinder diesel engine, equipped with a common-rail fuel injection system, a variable geometry turbocharger (VGT), an intake throttle valve able to modify the swirl number (swirl flap) and a high pressure exhaust gas recirculation system. The engine had four valves per cylinder, allowing centrally located injectors, and a re-entrant type piston bowl. The swirl ratio could be varied from 1.4 up to 3 thanks to the dedicated swirl flap mentioned

Table 1
Engine and injection system specifications.

Engine type	DI, 4-cylinder,turbocharged,4-stroke
Displaced volume	1900 cc
Stroke	90.4 mm
Bore	82 mm
Piston bowl	Re-entrant type
Compression ratio	17.5:1
Max. power (kW)	110@4000 rpm
Max. torque (Nm/min^{-1})	320/2000–2750
Injection system	Bosch Common Rail (solenoid)
Max. rail pressure (bar)	1600
Nozzle hole diameter (mm)	0.141
Injector nozzle holes	7