Experimental investigations in an optical HCCI Diesel engine. About the influence of fresh charge preparation and composition on auto-ignition delays and combustion development.

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Key Words

Diesel HCCI combustion, direct injection, optical engine, optical diagnostics, LIEF.

Introduction

Due to growing environmental concern and more and more stringent regulations, reducing pollutant emissions from Diesel engine needs further research efforts. While post treatment techniques such as particulate filters or catalytic converters may provide a solution to this major problem, a more efficient and cheaper solution would consist in operating the Diesel engine in a clean combustion mode avoiding in-cylinder NO_x and soot production. The Homogeneous Charge Compression Ignition mode (HCCI) where Diesel fuel is premixed with air, and burnt at lower temperatures than in the conventional diffusion mode, is intended for this purpose. So far, the best Diesel engine configurations spread in the European automotive market are based on direct fuel injection, which allowed to reduce fuel consumption and to increase power density. While HCCI should ideally be used over the complete engine operating range, preliminary tests have shown that it is difficult to achieve full load conditions in such a mode. A combination between HCCI at low or part load, and conventional direct injection (diffusion mode) at full load, is therefore considered as suggested in Refs [Thring-1989,Walter-2002]. As a result, this article investigates the fuel/air mixture homogeneity that may be achieved using a conventional common rail injector. The resulting combustion process is also observed and analyzed. While the rate of combustion is essentially controlled in HCCI combustion using very diluted mixtures achieved with Exhaust Gas Recirculation (EGR), the influence of mixture homogeneity on the onset of auto-ignition is also investigated here. Indeed, the latter should carefully be controlled under HCCI conditions to preserve cycle efficiency and limit combustion noise. Finally, the influence of EGR minor species on combustion phasing is approached through experiments carried out with EGR simulated with nitrogen and containing small concentrations of NO.

The experiments are carried out in an optical single cylinder Diesel engine equipped with a 6 hole, narrow angle, common rail injector and a bowl shaped piston. Mixing between air and fuel is achieved using several multiple injection strategies. On the one hand, mixture homogeneity corresponding to these strategies is assessed using 2D Laser Induced Exciplex Fluorescence images, while auto-ignition and combustion are monitored using direct light emission observation. On the other hand, the effect of EGR rate and NO content is investigated using OD thermodynamical analysis of cylinder pressure recordings.

Experimental setup

Experiments were carried out with a 4-stroke, single cylinder (85 mm bore, 88 mm stroke, 0.5 l displacement), Direct Injection Diesel (DID) engine based on a DW10 (*PSA*) motor. It is equipped with a production cylinder head (4 valves per cylinder) and an elongated piston with piston-crown quartz window and tilted (45°) static mirror provides the optical access to the combustion chamber (46 mm diameter, 5 mm depth) as presented in Fig. 1. To limit the rate of combustion, compression ratio was set to 14:1, and the swirl valve of the cylinder head was adjusted so as to minimize the swirl motion in the chamber (2.2 swirl number) and therefore limit fuel droplets centrifugation and wall wetting. Direct fuel injection is performed with a central common rail *Bosch* CR1 injector unit mounted with a 6 hole, reduced angle (80°) nozzle with nominal hole diameter/length of 0.120 mm/1 mm. Fuel was pressurized at 650 bar using a hydro-pneumatic pump. EGR was simulated with pure nitrogen. To specifically investigate the influence of NO on auto-ignition delay, it was mixed together with EGR and air at the engine intake channel and a chemiluminescence NO analyzer was set to continuously monitor the air/EGR/NO supplied to the engine.

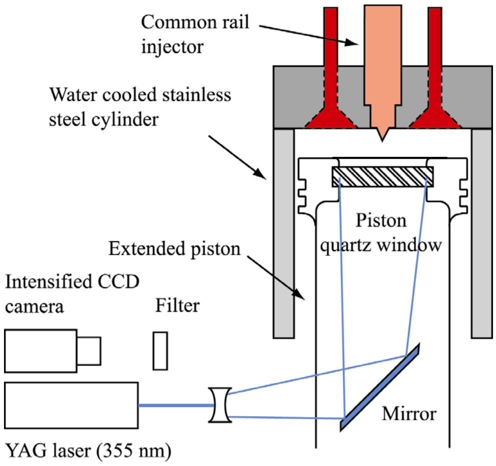

Fig. 1 : Engine setup for fuel and combustion monitoring

The propagation and mixing of the fuel in the chamber was investigated using Laser Induced Exciplex Fluorescence (LIEF). In this technique, the base fuel (N-Decane, 89.64%mass) is doped with a small quantity of organic dopants (mixture of a partner α-methyl-naphtalene, 9.96%mass, and a fluorescent monomer, tetramethyl-phenylene diamine, 0.4% mass). After global excitation with a frequency tripled Nd:YAG laser at 355 nm as shown in Fig. 1, the dopants fluoresce at different wavelengths depending whether they exist in the liquid or vapor phases. Due to oxygen induced quenching, visualizations of the fuel jets were carried out in an oxygen-free nitrogen environment to ensure sufficient vapor phase emission intensity. The fluorescence signal was collected backward with an intensified CCD camera associated to a high-pass filter for liquid phase monitoring (λ>500 nm) or a band-pass filter for vapor phase monitoring (λ_{nom}=400 nm). Additional information about the LIEF technique and the setup may be found in Refs [Melton-1984,Docquier-2002]. To monitor combustion, the light naturally emitted by the engine was directly monitored with an intensified CCD camera, and the nature of this light was also analyzed using a grating spectrometer.

Results

Five test cases corresponding to three consecutive injections of 5 mm^3 of N-Decane, were chosen to analyze the influence of injection timing on stratification at a constant EGR rate of 50% in mass. The first two injections were performed during the intake stroke, the third one during the compression stroke.

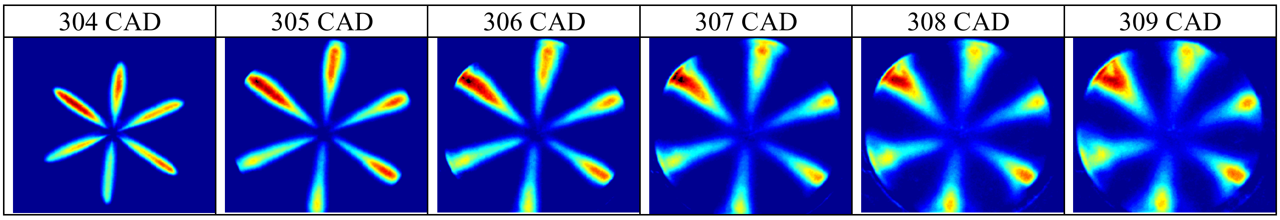

Fig. 2 : Vapor phase of the fuel jets. Inj 3 @300 CAD, energizing time = 325 µs, inj. pressure = 650 bar.

From the fuel visualizations, it arises first that for the injections carried out in this study (up to 60 CAD BTDC) fuel vaporization is weak as presented in Fig 2 and liquid fuel penetration is high due to low temperatures and counter-pressures encountered at the time of injection. This phenomenon is further reduced by the low engine compression ratio (14:1) set to retard auto-ignition as much as possible. As a result, wall wettings occur inducing large HC emissions in comparison with a standard direct injection Diesel engine.

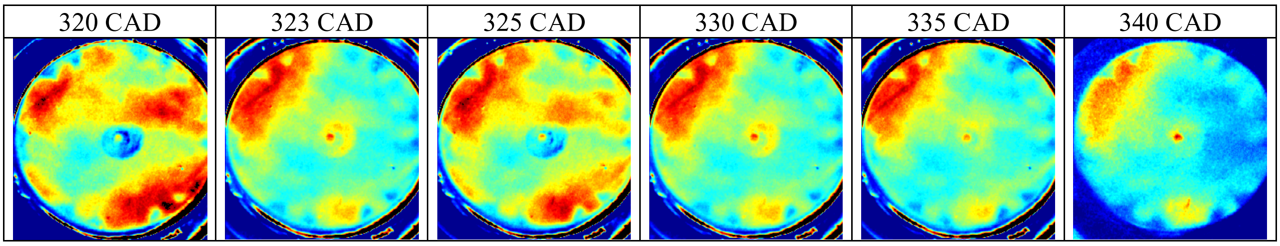

Fig. 3 : Fuel/N_2 mixture homogeneity. Case 1 : Inj 1 @40 CAD, Inj 2 @ 150 CAD and Inj 3 @290 CAD.

Then, it turns out that the fuel/air mixture is quite inhomogeneous in every cases, even when the first injection is carried out 320 CAD BTDC as shown in Fig. 3. This result is not really surprising as a regular common rail injector with a 6-hole nozzle was used. Indeed, with such a device, the mixing essentially depends on the entrainment induced by the fuel jets and in this study, as fuel vaporization is weak at the time of injection, this results in poor mixing. Moreover, the latter cannot be enhanced by the bulk motion of the fresh charge due to the low swirl number of the cylinder head. Although the influence of fuel stratification on combustion was weak in the framework of this study, it seemed that the most stratified cases (in terms of fuel vapor distribution) lead to the shortest auto-ignition delays likely related to local equivalence ratio and/or temperature patterns more favorable to auto-ignition.

335CA,I_{max}=150	340CA,I_{max}=150	342CA,I_{max}=150	345CA,I_{max}=250	350CA,I_{max}=7.10^3	370CA,I_{max}=3.10^5

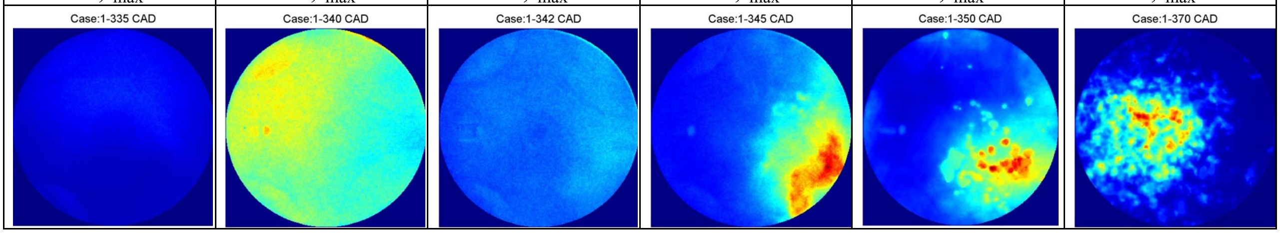

Fig. 4 : Combustion monitoring. Case 1 : Inj 1 @40 CAD, Inj 2 @ 150 CAD and Inj 3 @290 CAD.

From the direct observation of combustion, it was found that HCCI combustion could be divided into three stages (see Fig. 4). First, a cool flame, associated to a low and homogeneous signal (formaldehyde chemiluminescence, see Fig. 5), could be detected around 20 CAD BTDC. Then a "hot" and luminous flame stage could be monitored around 15 CAD BTDC. Most of the energy is released during this stage which lasts about 10 CAD. Finally soot kernels that developed during the previous stages due to fuel/air mixture inhomogeneities start to radiate (see black body signal in Fig. 5), emitting an intense signal but participating weakly to the heat release.

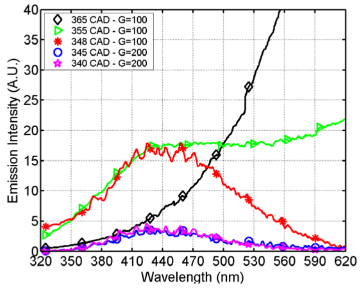

Fig. 5 : Emission spectra at different crank angle. Case 1.

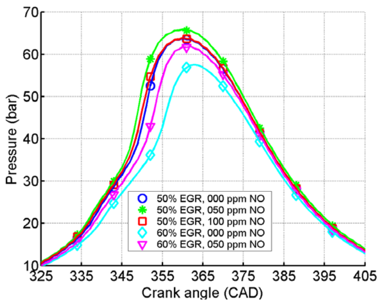

Fig. 6 : Pressure signals at different EGR and NO levels.

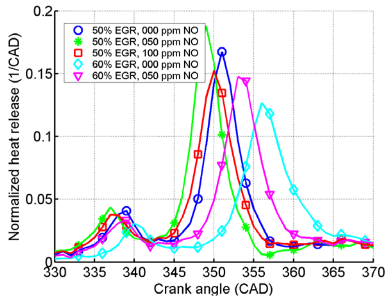

Fig. 7 : Calculated heat release at different EGR and NO levels.

Finally, it was checked that the most prevalent parameters for HCCI combustion control was EGR rate (see Fig. 6 and 7). We also observed that the amount of NO in the intake gases had a clear influence on the low temperature chemistry, inducing an advanced auto-ignition when supplied to the engine in small quantity (50 ppm, see Fig. 7). Higher levels of NO seem not to affect ignition delays and heat release rates.

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