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An investigation on the particulate number and size distributions over the whole engine map from an optimized combustion strategy combining RCCI and dual-fuel diesel-gasoline

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ABSTRACT

Literature demonstrates that, for premixed low temperature combustion concepts, particulate matter cannot be directly extrapolated from soot emissions measurements, as typically done for conventional diesel combustion. This is because the particulate matter from low temperature combustion has low fraction of carbonaceous compounds and great amount of soluble organic fraction, which is not captured by the smoke measurement techniques such as the optical reflectometry. By this reason, the study of the particulate matter characteristics from this combustion techniques requires using specific equipment. The aim of the current work is to gain understanding on the particulate matter characteristics from the dual-mode dual-fuel combustion, which is an optimized combustion strategy that combines fully and highly premixed RCCI regimes at low and medium loads, and switches to dual-fuel diffusion combustion at full load. The study was performed over the whole engine map, using a 15.3:1 compression ratio medium-duty EURO VI diesel engine. In particular, the particulate number and size distributions were sampled using a scanning mobility particle sizer and a condensation particle counter, which allow measuring the size distribution and total number of particles from 5 to 250 nm. Results demonstrate that the fully premixed RCCI combustion is dominated by small particles (less than 30 nm in mobility diameter), the dual-fuel diffusion mode is dominated by larger particles (around 100 nm in mobility diameter) showing more diesel-like particle size distributions, and the highly premixed reactivity controlled compression ignition regime shows a transitional particle size distribution with two peaks of mobility diameters around 20 and 80 nm.

1. Introduction

The nitrogen oxides (NOx) and soot emissions limits imposed by the emissions regulations for diesel engines are becoming more and more restrictive over the years, which represents a major concern for researchers and manufacturers [1]. Alternatively to the aftertreatment systems development, the premixed low temperature combustion (LTC) strategies are being extensively studied nowadays as a way to reduce both pollutants directly during the combustion process [2]. These strategies rely on using high rates of exhaust gas recirculation (EGR) and extended fuel-air mixing times as compared to CDC [3], which leads to lower local flame temperatures [4] and avoids fuel-rich zones during the combustion process [5].

The reactivity controlled compression ignition (RCCI) combustion, initially proposed by Inagaki et al. [6] and later developed by Kokjohn et al. [7], has been demonstrated to be more promising

Abbreviations: AIM, Aerosol Instrument Manager; ASTM, American Society of Testing and Materials; ATDC, after top dead center; BDC, bottom dead center; CAD, crank angle degree; CA10, crank angle of 10% heat release; CA50, crank angle at 50% heat release; CDC, conventional diesel combustion; CO, carbon monoxide; CO_2, carbon dioxide; COV, coefficient of variation; CPC, condensation particle counter; CR, compression ratio; DMA, Differential Mobility Analyzer; DMDF, dual-mode dual-fuel; DOC, diesel oxidation catalyst; DPF, diesel particulate filter; ECU, electronic control unit; EGR, exhaust gas recirculation; EVO, exhaust valve open; FSN, Filter Smoke Number; GF, gasoline fraction; HC, hydrocarbons; HCCI, homogeneous charge compression ignition; IMEP, indicated mean effective pressure; IVC, intake valve close; IVO, intake valve open; LTC, low temperature combustion; MCE, multi cylinder engine; NOx, nitrogen oxides; ON, octane number; PFI, port fuel injection; PPC, partially premixed charge; PSD, particle size distribution; PRR, pressure rise rate; RCCI, reactivity controlled compression ignition; RoHR, Rate of Heat Release; SCE, single cylinder engine; SCR, selective catalytic reduction; SMPS, scanning mobility particle sizer; SOC, start of combustion; SOF, soluble organic fraction.

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than previous LTC strategies such us the homogeneous charge compression ignition (HCCI) [8], diesel partially premixed combustion (PPC) [9], gasoline PPC [10] and gasoline PPC spark assisted [11,12]. The RCCI concept has been extensively studied in different single cylinder engine (SCE) platforms: light- [13], medium- [14] and heavy-duty [15], as well as in multi-cylinder engines [16]. Different strategies have been developed to increase the thermal efficiency of RCCI, such as engine settings optimization: injection settings [17,18], air management conditions [19]; fuel properties modification: fuel variation [20], use of additives [21], use of biofuels [22]; and hardware optimization: piston bowl geometry modification [23], compression ratio optimization [24] or engine cooling reduction [25]. These works have demonstrated that RCCI is able to achieve thermal efficiencies near 50% over a wide range of operating conditions, with NOx emissions under the EURO VI limits and simultaneous ultra-low soot emissions [26]. Nevertheless, a general conclusion form the RCCI literature review is that RCCI operating range is limited to around 8–15 bar IMEP if simultaneous high efficiency, low emissions and low knocking levels are intended [27]. Above this engine load, thermal efficiency or emissions should be compromised at the expense of achieving low pressure rise rates (PRR) [28].

Trying to extend the operation towards higher loads, Benajes et al. [29] developed an optimized dual-mode dual-fuel (DMDF) combustion strategy that combines fully and highly premixed RCCI regimes at low and medium loads, and switches to dual-fuel diffusion combustion at full load. The authors found that this strategy allows to cover the whole engine map with PRR and in-cylinder pressure peaks below 15 bar/CAD and 190 bar, respectively. NOx emissions were below 0.4 g/kW h (EURO VI limit) up to 14 bar IMEP and soot emissions were below 0.8 FSN in the major portion of the engine map, with soot levels equal than or below 0.02 FSN in the region below 7 bar IMEP. In spite of these low soot values, literature demonstrates that, particulate matter (PM) from premixed LTC concepts cannot be directly extrapolated from soot emissions measurements [30], as typically done for CDC [31].

In the past, some researchers have performed studies to characterize the particles emitted during CDC to understand the particle size distribution (PSD) [32] and composition. The different studies agree that PSD for CDC present a bimodal shape, with nucleation (mobility diameter < 50 nm) and accumulation mode (diameter > 50 nm) particles. In this sense, Kittelson et al. [33] stated that nucleation mode particles might contain up to the 90% of the number of the particles but less than the 20% of the PM mass emissions. More recently, Storey et al. [34] carried out a speciation about the particles emitted under RCCI operation. The most important results indicate that high boiling range of diesel hydrocarbons was responsible for the PM mass captured on the filter media. Northrop et al. [35] and Glenn et al. [36] demonstrated that RCCI produces lower quantity of particles compared to other LTC strategies. These findings agree with the work performed by Prikhodko et al. [37], which stated that RCCI was highly dominated by nucleation mode particles. These authors also compared the smoke results in terms of filter smoke number (FSN) and PM filter mass measurements. The main conclusions were that RCCI PM is mainly composed of soluble organic fraction (SOF) with almost no elemental carbon [38]. This makes not possible to convert FSN in PM [39], because the smoke meter do not capture the SOF present in the PM of RCCI mode.

The dual-mode dual-fuel (DMDF) combustion concept proposed by Benajes et al. [29] switches between premixed and diffusive combustion strategies to complete the operation over the whole engine map. Thus, considering previous LTC PM findings, a dedicated study is necessary to gain understanding on the PM characteristics from this combustion strategy. In the current research, the particulate number and size distributions from this combustion mode are studied over the whole engine map, using a 15.3:1 compression ratio (CR) medium-duty EURO VI diesel engine. For this purpose, a scanning mobility particle sizer (SMPS), with a condensation particle counter (CDC), has been used to measure the size distribution and total number of particles between 5 and 250 nm in mobility diameter. Before analyzing the PM results, the main fundamentals of the combustion strategy under investigation is explained to better understand the results extracted from the PM measurements. Later, the smoke emissions and particle number measurements over the whole engine map are presented. Finally the particle size distributions for the different combustion regimes at different loads and speeds, are studied in detail.

2. Materials and methods

2.1. Test cell and engine description

The single-cylinder engine used in this work derives from a state-of-the-art in-line four-cylinder EURO VI diesel engine of 5.1 L displacement. Their main specifications are shown in Table 1. Fig. 1 shows the test cell layout and the instrumentation used to acquire the data during the engine tests. From the figure, it is seen that the dual-fuel studies are only performed in the first cylinder, while the other three cylinders work under conventional diesel combustion (CDC) governed by the electronic control unit (ECU). For controlling purposes, the in-cylinder pressure signal is measured in the first and fourth cylinder every 0.2 CAD using a Kistler 6125C pressure sensor coupled with a Kistler 5011B10 charge amplifier. This also allows balancing the engine load and pressure peaks between the different cylinders. Finally, it is interesting to note that the dual-fuel combustion process must be studied using indicated values, because all the cylinders share the crankshaft and the dynamometer.

Fully independent intake air, exhaust gas and the EGR lines were used for the dual-fuel cylinder (i.e. first cylinder). A screw compressor was installed at the beginning of the intake line to provide a stable supply of air at a desired pressure and with ambient properties. To condition the intake air before reaching the cylinder, it passes through an air drier and heater. Pressure and temperature of the fresh air are controlled in the intake settling chamber before mixing with the EGR. After that, pressure and temperature are measured in the intake manifold. Later, the charge temperature is measured again after the gasoline injection. In the exhaust line, temperature and pressure are measured in the exhaust manifold as well as in the settling chamber. The next element found is a valve, which is used to reproduce the exhaust backpressure introduced by the turbine in the serial engine. After that, the sample probes from the emissions measurement devices are found. Before the exhaust backpressure, part of the exhaust gases are taken to perform EGR. First of all, the exhaust gas passes through a DPF to eliminate particles from the exhaust stream and the temperature is reduced by means of a water-gas heat exchanger. Due to the

Table 1
Engine characteristics.

Style	4 Stroke, 4 valves, DI diesel engine
Manufacturer/model	VOLVO/D5K240
ECU calibration	EURO VI
Maximum power	177 kW @ 2200 rpm
Maximum brake torque	900 Nm @ 1200–1600 rpm
Maximum in-cylinder pressure	190 bar
Bore × Stroke	110 mm × 135 mm
Connecting rod length	212.5 mm
Crank length	67.5 mm
Total displaced volume	5.1 L
Number of cylinders	4
Compression ratio	15.3:1