

Particulates Size Distribution of Reactivity Controlled Compression Ignition (RCCI) on a Medium-Duty Engine Fueled with Diesel and Gasoline at Different Engine Speeds

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ABSTRACT

This work investigates the particulates size distribution of reactivity controlled compression ignition combustion, a dual-fuel concept which combines the port fuel injection of low-reactive/gasoline-like fuels with direct injection of highly reactive/diesel-like fuels. The particulates size distributions from 5-250 nm were measured using a scanning mobility particle sizer at six engine speeds, from 950 to 2200 rpm, and 25% engine load. The same procedure was followed for conventional diesel combustion. The study was performed in a single-cylinder engine derived from a stock medium-duty multi-cylinder diesel engine of 15.3:1 compression ratio. The combustion strategy proposed during the tests campaign was limited to accomplish both mechanical and emissions constraints. The results confirms that reactivity controlled compression ignition promotes ultra-low levels of nitrogen oxides and smoke emissions in the points tested. However, in spite of having similar or lower smoke emissions, the number of particles in some conditions is higher for the reactivity controlled compression ignition than for conventional diesel combustion. Nucleation mode dominates the particle formation for the reactivity controlled compression ignition mode, while accumulation mode dominates the particle formation for conventional diesel combustion. Thus, it is confirmed that the smoke measurement in filter smoke number units cannot be used to correlate the total particle mass for the reactivity controlled compression ignition mode, as typically done for conventional diesel combustion.

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INTRODUCTION

Increasing environmental problems such as global warming and air pollution from vehicles have promoted more stringent emissions regulations in different countries around the world. Vehicle manufacturers have been worked hard for updating the engines to face these new emissions regulations without penalizing the engine performance.

Compression ignition (CI) engines are extensively used in vehicle applications due to its high thermal efficiency. However, the nitrogen oxides (NOx) and smoke emissions still represent a challenge for the research community. To reduce NOx and smoke emissions under the limits imposed by the emissions regulations, CI engines require the addition of aftertreatment systems that increase the cost and complexity of the marketed vehicles. For the NOx reduction, the injection of urea fluid upwards the selective catalytic reduction (SCR) system is required to enhance the conversion reactions, which further increases the costs for the vehicle users.

During last decades, several strategies have been explored trying to maintain the benefits of the conventional diesel combustion (CDC) engines, but reducing the costs related to engine production, urea consumption and fuel consumption increase due to the passive diesel

particulate filter (DPF) regeneration [1]. Among them, the low temperature combustion (LTC) strategies have been found able to provide a reduction of the smoke and NOx emissions and improve the efficiency simultaneously [2][3]. From these, it is worthy to highlight the homogeneous charge compression ignition (HCCI), partially premixed combustion (PPC), reactivity controlled compression ignition (RCCI) or dual-fuel combustion [4,5,6].

HCCI combustion technology was widely investigated by the research community. This strategy characterizes of using fully premixed lean air-fuel mixtures to achieve high thermal efficiency, low smoke and low NOx emissions simultaneously. However, HCCI combustion process is dominated by chemical kinetics, which difficult the concept in terms of ignition control, cold start and produces excessive levels of carbon monoxide (CO) and unburned hydrocarbons (HC) [7]. Hence, HCCI mode is limited to the partial load range [8]. To solve this shortcoming, Bessonette et al. [9] suggested that low loads would require the use of high reactivity fuels and low reactivity fuels should be used at high engine loads.

PCI strategy has been also deeply studied by the research community [10-11]. PCI emerges as a solution for the weaknesses of the HCCI mode by using low reactivity fuels. In this sense, the high volatility of diesel fuel makes it suitable to be used for low load operation.

requiring excessively high exhaust gas recirculation (EGR) rates as load increases [12]. Thus, the use of gasoline improves the heat release rate control and reduces the NO_x and smoke emissions [13-14]. Different octane number (ON) gasolines were tested showing that the use of excessively high research octane number (RON) leads to unburning problems, being critical for gasolines with RON higher than 91. In this sense, gasoline presents a high resistance to ignite, which makes difficult to manage the combustion process at low load [15-16].

Park et al. [17] studied the effects of the fuel blends formed with diesel and gasolines. Inagaki et al. [18] proposed the dual-fuel PCI combustion concept feeding the engine with two fuels of different reactivity by means of separated injection systems. The different reactivity of the fuels was found to be a key factor for triggering the combustion phasing, also showing very promising results in terms of performance and emissions. Kokjohn et al. [19] continued this investigation and referred the combustion concept as reactivity controlled compression ignition (RCCI). This concept is the most promising LTC, achieving simultaneously low NO_x and smoke emissions and high thermal efficiency under different fueling strategies [20][21] and hardware conditions [22][23]. RCCI presents excellent capabilities in order to overcome the challenges found with traditional LTC strategies. RCCI provides simultaneously low NO_x and smoke emissions and high thermal efficiency. This strategy allows to reach high engine load while the combustion timing is under control [24].

From [25,26,27] is known that RCCI is capable enough to meet EU VI in terms of NO_x at steady state operation points with low levels of smoke for heavy-duty engines. However, current emission regulations also limit the number of particles as well as the particle matter (PM). CI diesel engines usually form carbonaceous particles and their measurement is often mass-based. CI particle characterization studies have been widely carried out [28-29] in order to obtain the particle size distribution (PSD). These studies suggest that CI PSD present a bimodal shape, presenting both nucleation and accumulation modes, depending on the mobility diameter. For CDC operation mode, the cutoff diameter is typically located at 50 nm. Therefore, nucleation mode particles would have mobility diameters lower than 50 nm and accumulation mode particles would contain particles with diameter larger than 50 nm. For the traditional CI engines, Kittelson et al. [28] stated that nucleation mode particles might contain up to the 90% of the number of the particles but less than 20% of the PM mass emissions.

Storey et al. [30] carried out a speciation about the particles emitted under RCCI operation. The most important results indicate that the high boiling range of diesel hydrocarbons was surely responsible for the PM mass captured on the filter media. Additional studies showed that RCCI produces lower quantity of particles compared to other LTC strategies [31-32]. In this sense, Prikhodko et al. [33] carried out a PM study in a light-duty engine and stated that RCCI was highly dominated by nucleation mode particles and 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 organic carbon with almost no elemental carbon. Thus, implies that it is not possible to convert FSN in PM because of the low values of FSN measured at RCCI mode [34] due to the organic fraction.

The present study shows the results of the gaseous and PM emissions of a medium-duty engine operating under RCCI mode at 25% engine load. These results are also compared to the results of the same engine operated under CDC mode. The novelty of the study is to study the impact of varying the engine speed from 950 rpm to 2200 rpm in a medium-duty engine. The study will focus on particles emission with a scanning mobility diameter between 5-250 nm by carrying out a PSD analysis.

EXPERIMENTAL SETUP

Test Cell and Engine Description

RCCI operation mode has been implemented in a single-cylinder engine (SCE) adapted from a multi-cylinder engine (MCE). The MCE is a four-stroke, four in-line cylinders, medium-duty diesel engine that meets the EURO VI regulation. Main engine properties are shown in the table below.

Table 1. Main characteristics of the engine used.

Style	4 Stroke, DI diesel engine
Manufacturer / model	VOLVO / D5K240
OEM ECU calibration	EURO VI
Piston bowl geometry	Re-entrant
Maximum power	177 kW @ 2200 rpm
Maximum brake torque	900Nm @1200-1600 rpm
Maximum in-cylinder pressure	190 bar
Bore x Stroke	110 mm x 135 mm
Connecting rod length	212.5 mm
Crank length	67.5 mm
Total displaced volume	5100 cm ³
Number of cylinders	4
Compression ratio	15.3: 1

The adaptation to operate the engine as a SCE was carried out at CMT facilities and consists of removing the after-treatment elements as well as modifying the intake and exhaust manifolds to isolate the air management of one of the cylinders. Thus, one of the cylinders can be operated under RCCI regime while the other three cylinders run under CDC mode to balance the cylinder-to-cylinder pressure peaks. To allow this, an in-house control system was developed to manage the injection settings for the RCCI cylinder, while the ECU was in charge of the other three cylinders.

As can be observed in [Figure 1](#), the test cell is fully instrumented and the engine is monitored in real time. The air management for the SCE has been redesigned and new elements such as an intake and exhaust

air conditioners have been incorporated to the test bench. Intake air conditioner is formed by a screw compressor and an air dryer stage, controlling the humidity and a heater in order to adjust the temperature. Exhaust air management is in charge of the exhaust gases, controlling the back pressure, and the EGR supply. The low pressure (LP) EGR loop is formed by a screw compressor, a diesel particulate filter (DPF), a dryer to control the humidity and a heater to adequate the temperature. Additional equipment such as the instrumentation and the injection system is also needed for the SCE. As can be observed in Figure 1, CDC side engine has a cooler for the boosted air and the corresponding instrumentation required for the correct operating and safety of the engine.

Engine-raw gas emissions were sampled with a five gas Horiba MEXA-ONE-D1-EGR analyzer. Measurements were carried out by averaging 40 s after attaining steady state operation. An AVL 415 smoke meter was used for the smoke emissions measurements. Measurements were performed by averaging three samples of 1 liter volume each with paper-saving mode off. Results of these measurements are presented in filter smoke number (FSN) units.

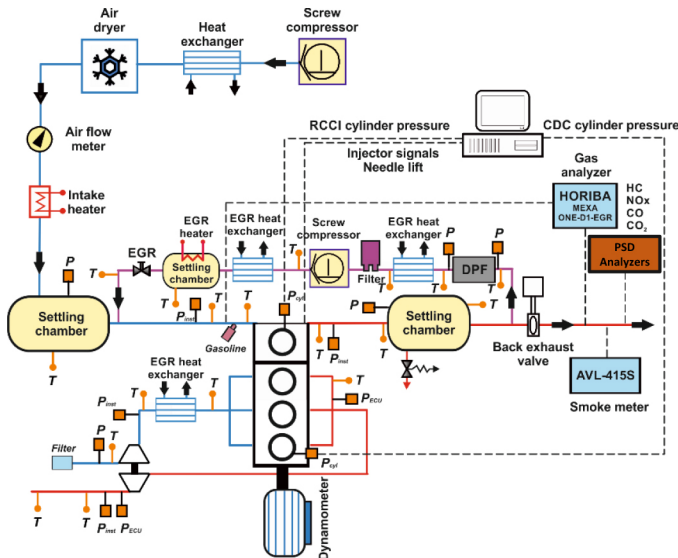


Figure 1. Test cell scheme.

In-cylinder pressure was measured with a Kistler 6125C pressure transducer coupled with a Kistler 5011B10 charge amplifier. A shaft encoder with 1800 pulses per revolution is used to obtain a crank angle degree (CAD) with 0.2 CAD resolution.

From the injection system standpoint, the stock diesel injector is used to supply diesel fuel into the combustion chamber and a port fuel injector (PFI) is installed at the intake manifold to supply the gasoline fuel. Main characteristics of the injectors are presented in table 2. Both injection systems are completed with two AVL 733S in order to measure the fuel mass flow. Both injectors are driven using a National Instruments (NI) DRIVEN control system. The in-house

developed control allows to operate the engine between different engine points automatically, being able to carry out transitions between engine speeds for instance.

Table 2. Main properties of the diesel and gasoline injector.

Diesel injector	
Actuation Type	Solenoid
Steady flow rate @ 100 bar [cm ³ /min]	1300
Number of Holes	7
Hole diameter [μm]	177
Included Spray Angle [°]	150
Maximum injection pressure (bar)	1200
Gasoline injector	
Injector Driver	Saturated
Steady flow rate @ 3 bar [cm ³ /min]	980
Included Spray Angle [°]	30
Injection Pressure [bar]	5.5
Injection Strategy	Single
Start of Injection Timing	340 CAD ATDC

The low reactivity fuel selected has been gasoline with 95 RON (EN 228) and the high reactivity fuel used is the regular diesel (EN 590). The main characteristics are presented in table 3.

Table 3. Physical and chemical properties of the fuels used.

	Diesel EN590	Gasoline
Density [kg/m ³] (T= 15 °C)	820	720
Viscosity [mm ² /s] (T= 40 °C)	2.8	-
RON [-]	-	95.0
MON [-]	-	85.0
Cetane number [-]	>51	-
Lower heating value [MJ/kg]	42.97	42.4

As shown in Figure 2, particle size distribution measurements has been carried out by using a diluter, a scanning mobility particle size (SMPS) and a condensation particle counter (CPC). The measurement equipment is located after the exhaust backpressure, which is located immediately before the exhaust settling chamber. The diluter chosen is a TSI Rotating Disk thermodiluter, which dilutes the sample by means of a rotating disk method. Every measurement unit is provided by two disks in order to obtain different number of cavities. The next step consist of a raw portion of the exhaust flow captured by the cavities driven into the mixer with particle-free air. This step ensures good stability and accuracy. Due to the volatiles could cause condensates, air sample must be heated and, hence the equipment will not confuse nanodroplets with particles. This step adapt the inlet concentration of the particles, which is required by the SMPS equipment.