Energy Conversion and Management 176 (2018) 1–10

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

Experimental investigation on the efficiency of a diesel oxidation catalyst in a medium-duty multi-cylinder RCCI engine

Jesús Benajes, Antonio García*, Javier Monsalve-Serrano, Rafael Lago Sari

CMT – Motores Térmicos, Universitat Politècnica de València, Camino de Vera s/n, 46022 Valencia, Spain

ARTICLE INFO

Keywords:
Reactivity controlled compression ignition
Dual-fuel combustion
Aftertreatment
Catalyst
Emissions

ABSTRACT

Reactivity controlled compression ignition (RCCI) combustion is one of the most promising low temperature combustion (LTC) techniques, as it is able to provide ultra-low NOx and soot emissions together with higher thermal efficiency than conventional diesel combustion (CDC) in a wide range of operating conditions. However, the unburned hydrocarbon (UHC) and carbon monoxide (CO) emission levels are orders of magnitude higher than CDC, which can result in a major problem for implementing the RCCI concept in real engines. In this sense, the high levels of UHC and CO emissions together with the low exhaust temperatures during RCCI operation could compromise the diesel oxidation catalyst (DOC) conversion efficiency.

The objective of this work is to evaluate the efficiency of a conventional DOC in oxidizing the UHC and CO emissions from RCCI combustion. To do this, a medium-duty multi-cylinder diesel engine equipped with its original after treatment system has been used. First, the DOC conversion efficiency is evaluated under some steady-state conditions. Later, the influence of the thermal inertia on the DOC response has been evaluated by means of transient tests. In this sense, different engine load-speed steps as well some simplified conditions from the worldwide harmonized vehicle cycle (WHVC) and the supplemental engine transient cycle (SET) are evaluated. In steady-state conditions, with DOC-inlet temperatures of 200–300 °C, the results show conversion efficiencies of 100% for CO and 85–95% for HC. At 10% and 25% load, the DOC-outlet UHC levels are unacceptable considering the EURO VI regulation, while at 50% load the tailpipe emissions fulfill the emissions standard. The results in transient conditions are more promising thanks to effect of the thermal inertia, showing 100% conversion efficiency for CO and greater than 90% for UHC during large periods of engine operation.

1. Introduction

During the last years, the emissions regulations for internal combustion engines (ICE) are being more and more stringent with the aim of reducing the levels of pollutants emitted to the atmosphere [1,2]. In the transport sector, compression ignition (CI) engines are the most widely used ICE type because they provide high efficiency with moderate engine-out emissions [3]. The most harmful emissions from CI engines operating with diesel fuel are the nitrogen oxides (NOx) and soot. Between both pollutants exists a trade-off by which reducing one, the other increases [4]. To reduce both pollutants simultaneously, the current CI are equipped with aftertreatment devices that reduce the emissions before being emitted to the atmosphere. The most used technologies in the CI used for transport sector are the selective catalyst reduction (SCR) to reduce NOx, and the diesel particulate filter (DPF) for soot emissions [5,6]. The use of these devices increases both the acquisition and operation costs for the customer. The operation costs increase due to several reasons, as are the necessary maintenance, exhaust fluids consumption, an extra back pressure in the exhaust line [7,8].

The aftertreatment systems are being continuously improved to increase their efficiency and reduce their associated costs [9]. In parallel

Abbreviations: ATDC, After Top Dead Center; ATS, Aftertreatment System; BSFC, Brake Specific Fuel Consumption; CAD, Crank Angle Degree; CDC, Conventional Diesel Combustion; CI, Compression Ignition; CO, Carbon Monoxide; CR, Compression Ratio; DI, Direct Injection; DMDF, Dual-Mode Dual-Fuel; DPF, Diesel Particulate Filter; EGR, Exhaust Gas Recirculation; FSN, Filter Smoke Number; GF, Gasoline Fraction; HCCI, Homogeneous Charge Compression Ignition; HRF, High Reactivity Fuel; ICE, Internal Combustion Engine; IMEP, Indicated Mean Effective Pressure; LRF, Low Reactivity Fuel; LTC, Low Temperature Combustion; MCE, Multi-Cylinder Engine; NOx, Nitrogen Oxides; ON, Octane Number; PFI, Port Fuel Injection; PRR, Pressure Rise Rate; RCCI, Reactivity Controlled Compression Ignition; RON, Research Octane Number; SCE, Single Cylinder Engine; SCR, Selective Catalytic Reduction; SET, Supplemental Engine Transient Cycle; TDC, Top Dead Center; UHC, Unburned Hydro Carbons; WHVC, Worldwide Harmonized Vehicle Cycle

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

https://doi.org/10.1016/j.enconman.2018.09.016
Received 23 July 2018; Received in revised form 3 September 2018; Accepted 5 September 2018
0196-8904/

to this, the research community is working on developing new combustion strategies to reduce the generation of pollutant emissions during the combustion process. This allows minimizing the aftertreatment necessities to meet the current standards [10]. The low temperature combustion (LTC) strategies have been confirmed as able to provide ultra-low engine-out NOx and soot emissions and similar efficiency than CDC [11,12]. The formation of both pollutants is reduced simultaneously by using high amounts of EGR rates together with highly advanced injection strategies, which improves the fuel-air mixing before the start of combustion [13,14]. Moreover, the thermodynamic efficiency of the engine cycle increases due to the heat transfer reduction and the lower combustion duration [15].

Among the different LTC concepts, the reactivity controlled compression ignition (RCCI) combustion is the most widely studied strategy nowadays because it offers high efficiency and low NOx and soot emissions in a wide engine operating range [16]. RCCI is implemented by feeding the engine with two fuels of different reactivity, as diesel (high reactivity fuel, HRF) and gasoline (low reactivity fuel, LRF), using independent injection systems [17]. The diesel fuel is injected directly into the cylinder, while the gasoline is fumigated in the intake port [18]. This allows modifying the percentage of each fuel injected according to the engine operating conditions. As described in literature, a highly efficient operation can be promoted using a major portion of LRF, and using the HRF to trigger the combustion [19,20]. After the start of combustion, its progression strongly depends on the in-cylinder reactivity stratification, mainly driven by the HRF injection conditions [21]. The reactivity gradient leads to a more sequential autoignition than other LTC concepts [22], reducing the maximum pressure rise rate (PRR) at high loads.

Recent works performed on different engine platforms confirm the potential of RCCI on reaching engine-out NOx and soot levels below the limits imposed by the EURO VI regulation in steady-state conditions [23,24]. Nevertheless, RCCI still has several challenges that limit its practical application [25,26], as are the high EGR rate levels needed to enable operation at high load [27,28] and the high amount of UHC and CO emitted at low load [29,30]. An alternative to apply RCCI in all the engine map is the dual-mode concept, which consists of switching to another combustion regime in the regions of the map in which the RCCI has limitations [31]. Depending on the engine compression ratio (CR), the secondary combustion mode used to complete the engine map can change, e.g. switching to diffusive dual-fuel [32] or to CDC [33].

The dual-mode dual-fuel (DMDF) strategy can be implemented with lower CR than the dual-mode RCCI/CDC concept. This allows extending the operating region of RCCI towards higher loads in the global map before the PRR problems start to appear. However, the UHC and CO emissions levels at low and medium loads with DMDF are higher than with dual-mode RCCI/CDC, and much higher than with CDC [34]. This occurs because the majority of engine operating conditions found during a real driving cycle fall in the low-medium load portion of the map, where RCCI operation is promoted. This fact can cause difficulties for the DOC to operate in a high efficient region, even more considering the low exhaust temperatures with RCCI. Additionally, the chemical composition of the exhaust gas has a great dependence on the engine operating condition since the gasoline fraction (GF) varies substantially along the RCCI map.

In a preliminary work [35], the authors developed a DOC model for RCCI combustion using data coming from experimental measurements in a single-cylinder light-duty engine equipped with a conventional DOC (sized for four cylinders). Under these conditions, the results suggested that the DOC volume needed to fulfill the type approval regulation limits for different driving cycles ranges from four to six times the original volume, mainly because of the low UHC conversion efficiency. However, some effects such as the thermal inertia were not perfectly characterized due to using a single-cylinder engine, which may have a great influence in the DOC sizing.

The objective of this work is to evaluate the efficiency of a conventional DOC in oxidizing the UHC and CO emissions from RCCI combustion in a series-production engine architecture working in steady-state and transient conditions. To do this, a medium-duty multi-cylinder diesel engine equipped with its original aftertreatment system has been used. First, the DOC conversion efficiency is evaluated under some steady-state conditions. Later, the influence of the thermal inertia on the DOC response has been assessed by means of transient tests. In this sense, different engine load-speed steps as well some simplified conditions from the worldwide harmonized vehicle cycle (WHVC) and the supplemental engine transient cycle (SET) are evaluated.

Table 1
Engine characteristics.

Engine type	4 stroke, 4 valves, direct injection
Number of cylinders [–]	6
Displaced volume [cm^3]	7700
Stroke [mm]	135
Bore [mm]	110
Piston bowl geometry [–]	Bathtub
Compression ratio [–]	12.75:1
Rated power [kW]	235 @ 2100 rpm
Rated torque [Nm]	1200 @ 1050–1600 rpm

2. Materials and methods

2.1. Engine characteristics

The experimental tests were carried out on a medium-duty, four stroke, serial production 8 L multi-cylinder diesel engine (MCE). The engine has a dedicated piston with bathtub bowl shape, optimized for RCCI combustion [24]. The geometric compression ratio is 12.75:1. Table 1 shows the main characteristics of the engine.

2.2. Test cell description

A scheme of the test cell in which the multi-cylinder engine was installed is shown in Fig. 1. The engine speed and load were governed through an electric dynamometer. The pressure and temperature of the intake charge was monitored before and after the high-pressure exhaust gas recirculation (EGR) line. The original exhaust line was modified to include a low-pressure EGR line, including a cooler and a filter. Moreover, a pneumatic valve was installed downstream the turbine to regulate the low-pressure EGR flow. The exhaust temperature and pressure were controlled at the exhaust manifold as well as at different points of the exhaust line. The original aftertreatment system (ATS) box, composed of a DOC, DPF and SCR, was installed after the pneumatic valve, 1300 mm far from the exhaust manifold. As shown in Fig. 1, pressure and temperature transducers were instrumented at different points of the ATS. The geometrical parameters of the DOC used in this work are listed in Table 2. The gaseous engine-out emissions were measured before and after the DOC using a five-gas Horiba MEXA-7100 DEGR analyzer. The data of each condition was recorded along a period of 60 s, and repeated three times. The three repetitions were recorded first with the emissions probe set upwards the DOC. After that, the three measurements were carried out with the emissions probe placed downwards the DOC. Then, the combustion efficiency can be estimated as shown in Eq. (1) [36].

$$Comb.\quad Eff. = \left(1 - \frac{HC}{m_f} - \frac{CO}{4 \cdot m_f}\right) \cdot 100 \tag{1}$$

An AVL 415S smoke meter was used to measure the black carbon content in the exhaust stream, providing the results in filter smoke number (FSN) units. Each operating condition was measured three times, with a sample volume of 1 L and paper-saving mode off [37]. An in-house developed acquisition system (SAMARUC) was used to record