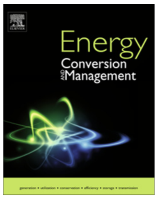
Energy Conversion and Management 136 (2017) 142–151

Contents lists available at ScienceDirect

Energy Conversion and Management

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



Achieving clean and efficient engine operation up to full load by combining optimized RCCI and dual-fuel diesel-gasoline combustion strategies

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ARTICLE INFO

Article history:
Received 7 November 2016
Received in revised form 2 January 2017
Accepted 5 January 2017

Keywords:
Reactivity controlled compression ignition
Dual-fuel combustion
Engine map
EURO VI emissions
Efficiency

ABSTRACT

This experimental work investigates the capabilities of the reactivity controlled compression ignition combustion concept to be operated in the whole engine map and discusses its benefits when compared to conventional diesel combustion. The experiments were conducted using a single-cylinder medium-duty diesel engine fueled with regular gasoline and diesel fuels. The main modification on the stock engine architecture was the addition of a port fuel injector in the intake manifold. In addition, with the aim of extending the reactivity controlled compression ignition operating range towards higher loads, the piston bowl volume was increased to reduce the compression ratio of the engine from 17.5:1 (stock) down to 15.3:1.

To allow the dual-fuel operation over the whole engine map without exceeding the mechanical limitations of the engine, an optimized dual-fuel combustion strategy is proposed in this research. The combustion strategy changes as the engine load increases, starting from a fully premixed reactivity controlled compression ignition combustion up to around 8 bar IMEP, then switching to a highly premixed reactivity controlled compression ignition combustion up to 15 bar IMEP, and finally moving to a mainly diffusive dual-fuel combustion to reach the full load operation. The engine mapping results obtained using this combustion strategy show that reactivity controlled compression ignition combustion allows fulfilling the EURO VI NOx limit up to 14 bar IMEP. Ultra-low soot emissions are also achieved when the fully premixed combustion is promoted, however, the soot levels rise notably as the combustion strategy moves to a less premixed pattern. Finally, the direct comparison of reactivity controlled compression ignition versus conventional diesel combustion using the nominal engine settings, reveals that reactivity controlled compression ignition can be a potential solution to reduce the selective catalyst reduction and diesel particulate filter aftertreatment necessities with a simultaneous improving of the thermal efficiency.

1. Introduction

The stringent emissions standards introduced for internal combustion engines suppose a major challenge for the research community. The technological solution adopted by the manufactures of diesel engines to meet the NOx and particulate matter values imposed in the EURO VI regulation relies on using selective catalyst reduction (SCR) [1] and diesel particulate filter (DPF) systems [2], which increases the complexity and cost of the engine. Alternatively, several new combustion modes aimed at avoiding the formation of these two pollutants by promoting low temperature combustion (LTC) reactions, are in focus of study nowadays [3]. In this sense, homogeneous charge compression ignition (HCCI) has demonstrated great potential to inhibit the emission of these two pollutants while maintaining high efficiency [4,5]. However,

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Abbreviations: ASTM, American Society for Testing and Materials; ATDC, After Top Dead Center; CAD, Crank Angle Degree; CA50, crank angle at 50% mass fraction burned; CDC, conventional diesel combustion; CO, carbon monoxide; CR, compression ratio; DI, direct injection; DPF, diesel particulate filter; ECU, electronic control unit; EGR, exhaust gas recirculation; EVO, exhaust valve open; FSN, Filter Smoke Number; HC, hydro carbons; 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; OEM, original equipment manufacturer; ON, octane number; PFI, port fuel injection; PPC, partially premixed charge; PRR, pressure rise rate; RCCI, reactivity controlled compression ignition; RoHR, rate of heat release; SOC, start of combustion; SCE, single cylinder engine; SCR, selective catalytic reduction.

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http://dx.doi.org/10.1016/j.enconman.2017.01.010
0196-8904/

low combustion control, high mechanical engine stress and excessive unburned products were identified with HCCI [6]. Some researchers suggested that to promote a proper HCCI operation, the in-cylinder reactivity must vary depending on the engine operating conditions, which could be achieved using high cetane fuels at low load and low cetane fuels at medium-high load [7]. Moreover, several other techniques aimed at modulating the in-cylinder reactivity such as the residual gas trapping [8], valve lift optimization [9], variable valve timing [10] and fuel modification [11] were studied. These methods were found to be beneficial for reducing the HCCI shortcomings, but were not enough to enable a wide HCCI operating range. By this reason, the use of gasoline-like fuels under partially premixed combustion (PPC) strategies gained interest to be studied [12]. In this sense, several researchers confirmed the gasoline PPC as a promising strategy to improve the heat release control while reducing the NOx and soot emissions simultaneously [13,14]. However, the low load PPC operation using gasolines of octane number (ON) greater than 90 was found to be inadequate due to the excessive combustion instability [15,16]. Trying to solve this problem, some researchers investigated the use of a spark plug to assist the low load PPC operation. It was found that the spark discharge improves the control of the PPC combustion process, temporal [17] and spatially [18], over the low load gasoline PPC combustion process, but led to excessive NOx and soot emissions [19], even using double injection strategies [20,21].

Among the LTC combustion concepts, the dual-fuel strategy commonly known as reactivity controlled compression ignition (RCCI) has the major scientific interest nowadays [22]. This strategy relies on injecting a low reactivity fuel in the intake port and a high reactivity fuel directly in-cylinder [23]. The RCCI combustion mode differs from the conventional dual-fuel combustion in that RCCI relies on decoupling the end of injection of the direct injected fuel and the start of combustion [24]. This promotes a well-mixed and dilute charge, which provides ultra-low NOx and soot emissions together with high efficiency over a wide range of engine speeds and loads [25]. In addition, RCCI concept allows better control of the combustion process than the single-fuel LTC strategies thanks to the capacity of modulating the fuel reactivity depending on the engine operating conditions [26]. The literature demonstrates that to attain these combustion characteristics, a highly premixed combustion strategy is necessary [27]. This is typically done using a double injection diesel pulse, with the first injection at around −60 to −40 CAD ATDC and the second one at around −35 CAD ATDC [28]. The first injection was found to be necessary to improve the in-cylinder reactivity in the crevices zones, where high amount of gasoline gets trapped [29]. The second diesel injection is needed to act as an ignition source, and should be relatively advanced to have enough mixing time to avoid soot formation [30]. In spite of these benefits, this type of injection strategy results in excessive maximum pressure rise rate (PRR) and maximum in-cylinder pressure (P_{max}) when increasing the engine load, which limits the maximum engine load achievable with RCCI operation [31]. This occurs because the in-cylinder charge composed of homogeneously mixed gasoline and highly premixed diesel (from the first injection) autoignites abruptly when the main diesel pulse is injected [32].

In order to extend the engine operation up to full load without exceeding the engine mechanical limits, a switch to conventional diesel combustion (CDC) can be done [33]. This solution, commonly known as dual-mode engine operation, showed a promising potential for reducing the aftertreatment necessities in terms of exhaust fluids (urea and diesel) consumption. However, the need for a high compression ratio to ensure high efficiency when running in CDC mode, resulted in a dramatic reduction of the effective RCCI operating range [34]. This fact rests potential to the concept and questions the advantages of moving from CDC to a dual-fuel architecture. Another possible solution to allow the operation in all the engine map could be the modification of the dual-fuel injection/combustion strategy to avoid the excessive PRR and P_{max} as engine load increases, which can be done moving from a highly premixed dual-fuel strategy (RCCI) to a less premixed strategy progressively. Although this method entails penalizing the NOx and soot emissions as compared to a highly premixed RCCI strategy, the capabilities of this alternative versus CDC must be studied in detail. Thus, the present investigation aims at evaluating the potential of this solution, in which dual-fuel operation is achieved over the whole engine map using different injection strategies. To do this, firstly, a dedicated testing procedure is defined to obtain engine maps that are used to analyze the performance and engine-out emissions of the dual-fuel combustion strategy proposed. Later, a direct comparison between dual-fuel and conventional diesel combustion operation is presented by means of engine maps differences, which allows to extract the main advantages and drawbacks of the combustion mode under investigation.

2. Materials and methods

2.1. Test cell characteristics and engine description

The tests performed in this study were carried out in a single-cylinder engine which comes from a medium-duty stock engine. In addition, the engine satisfies the newest EURO VI limitations and was specially developed for urban freight distribution purposes. As shown in Table 1, the nominal compression ratio (CR) of the production engine is 17.5:1. Previous studies showed that, with this CR, the RCCI operation is limited to a narrow region between 25% and 35% load, even using a mid-level ethanol blend (E20-95) as a low reactivity fuel [35]. In a further study, it was found that the RCCI operating range can be extended up to 80% load by reducing the CR to 12.75, however the region below 25% load showed lower efficiency than CDC [36]. Thus, in the present study, an intermediate CR of 15.3:1 was set in the engine by increasing the bowl volume as compared to the stock piston (Fig. 1). The bowl geometry for the RCCI piston was defined following the guidelines provided in literature [37,38], which suggests that wider bowl geometries with lower surface areas are beneficial to increase the efficiency of the RCCI concept [39]. This is explained due to both, the lower heat transfer and the enhanced burning of the gasoline located at the crevice region. The lower heat transfer is consequence of the lower area-to-volume ratio and the enhanced gasoline burning results from the better flow of the high temperature gas until the crevice zone [29].

In order to operate the engine under RCCI mode, the engine was modified by adding an additional injection system, as it is observed in Fig. 2. Therefore, it is possible to modify the properties of the fuel

Table 1
Engine characteristics.

Style	4 Stroke, 4 valves, DI diesel engine
Manufacturer/model	VOLVO/D5K240
OEM 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	5100 cm^3
Number of cylinders	4
Compression ratio (nominal)	17.5:1
Compression ratio for RCCI	15.3:1