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Parametric study and optimization of the main engine calibration parameters and compression ratio of a methane-diesel dual fuel engine

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ABSTRACT

The increasing energy demand together with the severe emission legislation of the transportation sector requires effective solutions for automotive propulsion systems. Several studies are conducted to further develop the internal combustion engines and they are mainly oriented to the application of alternative combustion concepts combined with the use of alternative fuels. The main concerns are the efficiency, the pollutant, and the carbon dioxide (CO_2) emissions. In this framework, the potential of the Dual Fuel (DF) concept is demonstrated. The methane – diesel DF application permits the reduction of the CO_2 emissions and the diesel fuel usage while improving the NO_x – PM trade-off compared to the conventional diesel combustion (CDC).

The paper investigates the effects of the engine calibration parameters on the DF combustion characteristics, regulated emissions, and global performances. The parametric analysis was performed while varying the compression ratio (CR), the methane substitution ratio, fuel injection pressure, diesel pilot quantity, combustion phasing, Exhaust Gas Recirculation (EGR) and the Air-Fuel ratio (A/F). The tests were conducted utilising a modern combustion system architecture applied on a single cylinder engine.

The analysis is performed at low-medium operating conditions that are more critical for the application of the advanced combustion concepts. In particular, four engine operating test points were selected, two engine speeds (1500, 2000 rpm) and loads (3, 7 bar of imep).

The results show a significant impact of the CR, EGR and A/F ratio variables on the unburned hydrocarbons reduction (up to 40%) compared to the DF baseline. Benefits in terms of CO_2 and particles distributions are shown with respect to the CDC. The CH_4 slip on greenhouses gas (GHG) and the emissions and fuel consumption estimation over the New European Driving Cycle (NEDC) are considered. The information reported in this paper has a relevant impact on the development advanced combustion engines running under natural gas – diesel dual fuel combustion mode and transferable in modern light-duty engines, giving as output the main engine calibration parameters and CR that most influence the efficiency and pollutant emissions formation in a DF engines.

1. Introduction

The engine research and development sectors are strongly focusing on the reduction of the regulated carbon dioxide and pollutant emissions which limits are even more stringent around the world (Euro 6, Tier 3, etc.). In this context, the road transport sector contributes about one-fifth of the CO_2 in Europe and light-duty vehicles (cars and vans) produce around 15% of the total. The current CO_2 target of the average fleet of passenger cars is 130 g/km, in 2021 will be 95 g/km [1].

For these reasons, in the last decade, diesel engines have been favoured due to its higher efficiency and then lower CO_2 compared to the spark ignition engine. However, their nitrogen oxides (NO_x) and

Abbreviations: A/F, Air-fuel ratio; bmep, Brake mean effective pressure; b/c, Bowl/crevices volume ratio; CA50, Combustion phasing; CDC, Conventional diesel combustion; CH_4, Methane; CI, Compression ignition; CO_2, Carbon dioxide; COV_{imep}, Coefficient of variation of imep; CR, Compression ratio; DF, Dual fuel; EC, Energy consumption; EGR, Exhaust gas recirculation; FC, Fuel consumption; GHG, Greenhouses gas; HCCI, Homogeneous charge compression ignition; HR, Heat release; HRR, Heat release rate; HT_{loss}, Heat transfer loss; isfc, Indicated specific fuel consumption; LD, Light duty; LHV, Lower heating values; MCE, Multi-cylinder engine; MHC, Methane unburned hydrocarbon; NEDC, New European driving cycle; imep, Indicated mean effective pressure; NG, Natural gas; NO_x, Nitrogen oxides; PFI, Port fuel injector; P_{ind}, Net indicated power; $P_{pump\text{-}loss}$, Pumping power loss; pfp, Peak firing pressure; PM, Particulate matter; PPC, Partially premixed combustion; PRR_{max}, Peak pressure rise rate; PSDF, Particle size distribution function; $\dot{Q}_{combloss}$, Combustion loss; $\dot{Q}_{EGR}$, EGR heat cooling loss; $\dot{Q}_{Exh}$, Exhaust heat loss; $\dot{Q}_{HT}$, Radiation and convection heat transfer loss; Q_{pil}, Pilot quantity; RCCI, Reactivity controlled compression ignition; r_p, Premixed ratio; SCE, Single cylinder engine; SoI, Start of injection; TDC, Top dead centre; THC, Total unburned hydrocarbon; UDC, Urban driving cycle; WF, Weight factor; λ, Relative air-fuel ratio; η_{comb}, Combustion efficiency; η_{gross}, Gross efficiency; η_{net}, Net indicated efficiency; $\eta_{thermal}$, Thermal conversion efficiency

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particulate matter (PM) emissions represent the main concerns considering the very low NO_x emission limits reduced in Europe by 50% in the transition from Euro 5 to Euro 6 at constant PM.

For these reasons, advanced technological solutions combined with new combustion concepts and alternative fuels are crucial. Advanced combustion concepts like Homogeneous Charge Compression Ignition (HCCI) [2,3], Partially Premixed Combustion (PPC) [4–6], Dual Fuel combustion (DF) [7–9] and Reactivity Controlled Compression Ignition (RCCI) [10,11] require specifically designed fuels [12].

Low cetane number fuels like ethanol, methanol, methane, etc., are appropriate to accomplish the requested characteristics and to meet the pollutant and CO_2 targets as proved by literature results [13–17]. Many research projects are focussed on the use of alternative "cleaner" fuels, pure (alcohols, methane, etc.) or blended (natural gas, alcohol in diesel, biodiesels, etc.) in order to get advantages in terms of emissions and CO_2. Recent results obtained by the authors have shown significant advantages in terms of efficiency (up to 5%) adopting different blending ratios (up to 30%) of gasoline and ethanol in diesel [18]. Rakopoulos et. al. (2015) performed experiments using different biodiesel, ethanol and n-butanol in various proportions with diesel fuel, showing significant NO_x-soot trade-off reduction proportional function of the percentage of bio-fuels with the diesel fuels [19,20].

In the field of compression ignition engines, the dual fuel combustion concept using natural gas as additional fuel has the potential to couple the theoretical benefits of the higher cycle conversion efficiency, typical for compression ignition (CI) engines, and the lower CO_2 production related to the higher intrinsic H/C ratio (~4) respect to the diesel fuel (~1.87). The considered Dual Fuel combustion concept is based on using methane (CH_4), due to its fixed characteristics, as the main energy carrier, while the diesel fuel is injected to ignite the mixture of CH_4 and air. CH_4 is fed by the means of a port fuel injection and then mixed and compressed with air. Most of the DF studies employ the use of a single pilot pulse injection of diesel; other few cases with double pulse injection strategies, identified as "pilot" plus "main", have demonstrated better potential in terms of combustion control and efficiency [21,22].

Previous authors results show significant improvements in terms of CO_2 reduction (13% averaged on the NEDC) and NO_x-PM trade-off, while significantly higher Total Unburned Hydrocarbon (THC) and Carbon Monoxides (CO) have been detected. The unburnt are mainly linked to the fuel trapped in the crevice and squish volumes and not involved by the combustion flame [22,23]. In this sense, a properly optimized combustion chamber is required [23,24].

According to research results, diesel injection timing and pilot quantity [25], compression ratio and equivalence ratio are the most important variables controlling the DF combustion and emissions. A higher pilot diesel fuel quantity produces a higher heat release (HR) before the top dead centre (TDC) penalizing the efficiency. The CR reduction has a significant impact on the methane unburned hydrocarbon (MHC) emissions since they reduce proportionally with the fuel mass concentration in the crevice volumes and then with the bowl/crevices volume ratio [26]. Results on the equivalence ratio show that higher values and possibly near to the stoichiometric condition, increase the flame front speed by reducing the combustion duration and the unburnt [23].

Based on these considerations, in order to extend previous authors and literature findings, the present experimental work, conducted on a Light Duty (LD) Single Cylinder Engine (SCE) assesses the single effects of the parameters like injection parameters, Exhaust Gas Recirculation (EGR), relative air-fuel ratio (λ) and Compression Ratio (CR) on the engine-out emissions, particle size distribution function (PSDF) and indicated performance.

2. Experimental setup and test methodology

2.1. Engine test cell

A single cylinder compression ignition engine, representative of the Euro 5 light-duty diesel technology, is employed to carry out the experimental campaign. The combustion architecture (connecting rod, piston, cylinder head, etc.) derives from production series engines and has been modified to run in single-cylinder mode. Fuel, cooling, and lubrication systems are decoupled from the engine allowing a greater flexibility of their control parameter compared to the equivalent multi-cylinder one, while the intake and exhaust gas lines are properly designed to realise accurate controls of the boost and backpressure variables. In order to make the results representative of the reference multi-cylinder engine (MCE), the control variables of the auxiliary systems (boost, EGR, oil cooling, water cooling, fuel cooling) are set as those of the reference multi-cylinder engine.

The engine calibration parameters (DI and PFI injections, intake throttle valve, EGR valve, VGT, etc.), pressure, temperature and emissions are monitored, controlled and acquired by means of National Instruments HW platform and LabvVIEW® software. The methane port fuel injector (PFI) is fed by a low-pressure line operating at pressures of 8 bar. The diesel and methane fuel measurements are realised by means of a gravimetric balance (AVL 733) and a thermal mass flow meters (Brooks SLA 5860) respectively. For the air measurement, two different air mass flow meters are installed in order to have higher accuracy, depending on the flow range. Emerson Coriolis sensor for the range 0–150 kg/h and ABB thermal sensor for 0–400 kg/h. The test cell layout is depicted in Fig. 1, while Table 1 describes the main engine characteristics.

The indicated pressures are measured by means of a Kistler 6125B flush mounted piezo-quartz transducer, fitted inside the head glow plug hole, and acquired with a resolution of 0.1 CAD. The averaged pressure signal, for the calculation of the indicated mean effective pressure (imep) and the apparent heat release (HR) and heat release rate (HRR), are averaged over 128 consecutive cycles. The number of acquired cycles are considered sufficient for the scope of the presented analysis. However, for a more accurate statistical analysis at least about 400 consecutive cycles are necessary [27]. At least three repetitions for each test point were executed. In the following, are reported the limitation of the COV_{imep} and the test to test variation of the measured results.

The emitted smoke is measured by means of the AVL 415S smokemeter while the Particle Size Distribution Function (PSDF) is detected by means of a Differential Mobility Spectrometer (Cambustion DMS500) in the measuring range 5–1000 nm at a sampling frequency of 10 Hz. The engine-out gaseous emissions in terms of THC, MHC, NO_x, CO, CO_2 and O_2 are measured using an integrated emissions test bench. In particular, the THC and MHC are detected by means of flame ionization detectors (ABB and Emerson respectively), the NO_x by means of a chemiluminescence detector (Ecophysics CLD700), CO and CO_2 by means of nondispersive infrared detectors (Emerson) and the O_2 through a paramagnetic sensor (Emerson). Measurement range and accuracy for the used sensors are listed in Tables 9 and 10, in Appendix A.

2.2. Fuels

Commercial EN590 compliant diesel fuel and methane (CH_4) were used as direct and port injected fuel respectively and their characteristics are listed in Table 2. Since natural gas is constituted by a mix of hydrocarbons, the composition and consequently its specifics are variable and dependent on the source of supply. For this reason, the CH_4 was used as premixed fuel because of its fixed physical-hemical characteristics.

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