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Effects on performances, emissions and particle size distributions of a dual fuel (methane-diesel) light-duty engine varying the compression ratio

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HIGHLIGHTS

- MHC reduction and combustion efficiency improvement by reducing the compression ratio.
- Compression ratio and Air-throttling impact on emissions and particles in dual-fuel mode.
- CO_2 reduction and GHG impact over the NEDC test in dual fuel mode.

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ABSTRACT

Economic and technological issues related to meet the future harmful emissions and greenhouse gases (GHG) standards are pushing the scientific community to consider studying alternative routes for low emissions and high efficient propulsion systems. A possible approach is represented by the dual-fuel (DF) concept applied to high efficient compression ignition engines.

In this context, the results of a wide experimental campaign performed on a single-cylinder engine platform equipped with modern combustion and injection systems operated in dual-fuel diesel/methane mode are presented. The effects of the compression ratio, injection parameters and air-throttling on the global performances and emissions, also in terms of particle size spectrum, are assessed.

The tests were performed in several operating points representative of real working conditions of an automotive light-duty (LD) diesel engine in order to carry out the fuel consumption (FC), the GHG and the pollutant emissions estimation on the New European Driving Cycle (NEDC) test procedure. A proper DF engine parameter calibration was set-up observing constraints in terms of in-cylinder peak firing pressure, pressure rise rate, cycle-to-cycle variation and engine-out emissions.

A significant impact of the CR variation and injection parameters on the combustion characteristics and emissions is revealed in DF mode (MHC). In particular, benefits on methane unburnt (MHC) and combustion noise can be attained reducing the CR. A global CO_2 reduction of about 12%, over the NEDC, can be definitely obtained with an average CH_4 substitution rate of about 50% and independently of the CR at the expense of the DF- CO_2 equivalent that is higher (22%) compared to D mode. The DF particles concentration in the accumulation mode is generally reduced as well as the estimated particle number on the NEDC. Moreover, within the tested engine class, a CR of 15.5 appears to be the best compromise among the global efficiency and pollutant emissions outputs to operate in DF mode.

Abbreviations: AFR, Air to Fuel Ratio; b/c, bowl/crevices Volume Ratio; BMEP, Brake Mean Effective Pressure; BTDC, Before Top Dead Centre; CAD, Crank Angle Degree; CI, Compression Ignition; CN, Cetane Number; CO_2, Carbon dioxide; COV, Coefficient of Variation; CR, Compression Ratio; D, Diesel; DF, Dual Fuel; DI, Direct Injection; EC, Energy Consumption; EGR, Exhaust Gas Recirculation; FC, Fuel Consumption; h_d, Lower Heating Value of diesel; h_{CH4}, Lower Heating Value of methane; HRR, Heat Release Rate; HR, Heat Release; IMEP, Indicated Mean Effective Pressure; ISEC, Indicated Specific Energy Consumption; λ, Relative air/fuel ratio; LD, Light Duty; LHV, Lower Heating Value; LNT, Lean NO_x Trap; md, Mass of diesel; m_{CH4}, Mass of methane; m_{tot}, Total fuel mass; MHC, Methane Hydrocarbon; MBF50%, 50% of Burned Mass Fraction; NEDC, New European Driving Cycle; NG, Natural Gas; NMHC, Non methane hydrocarbon; N/cc, Particle number concentration; ON, Octane number; P_{ind}, Indicated power; p_{rail}, Rail pressure; PFI, Port Fuel Injection; pfp, Peak firing pressure; PM, Particulate Matter; PRR, Pressure Rise Rate; PSDF, Particle Size Distribution Function; r_{pe}, Premixed ration on energy basis; r_p, Premixed ration on mass basis; SCE, Single Cylinder Engine; SCR, Selective catalytic reduction; SR, Swirl Ratio; SOI, Start of Injection; THC, Total Hydrocarbons; UDC, Urban Driving Cycle; WLTC, Worldwide harmonized light vehicles test procedures; WF, Weight Factors

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1. Introduction

The rapid extinction of fossil fuels, the fuel price increase and the stringent emissions regulation, push the interest of the scientific community in the field of internal combustion engines towards alternative fuels and advanced combustion concepts. Special attention is also paid to the greenhouse gases (GHG) and in particular on the CO_2 emission limitation of the vehicles. In this regard, the CO_2 limit in Europe for passenger cars will be cut from the current 130 g/km value for the average fleet, to 95 g/km by 2021 [1]. Within this framework, alternative fuels (e.g. natural gas, ethanol and methanol etc.) [2,3,4,5] combined with alternative combustion concepts (e.g. Dual Fuel, HCCI, RCCI and PPC) [6,7,8,9,10,11,12] and new engine technology routes (downsizing, friction reduction, electrification, etc.) [13,14] represent a possible approach to meet the emissions and efficiency targets.

The Dual-Fuel (DF) approach on compression ignition engines combines alternative fuels and advanced combustion concept. It usually consists in injecting a fuel with low reactivity, like natural gas, alcohols, etc., into the intake manifold by means of a port fuel injector (PFI). Then, the air -fuel charge is inducted and mixed into the cylinder. Subsequently, high cetane diesel fuel is direct injected and auto-ignited when the piston approaches the Top Dead Centre (TDC) involving also the premixed air-fuel that burns by means of a flame propagation [15,16].

The use of natural gas (NG), composed mainly of methane (higher $H/C = 4$), could theoretically reduce the CO_2 of about 25% on the Well to Wheel (WTW) life cycle compared to diesel fuel ($H/C \approx 1.87$) and even more if it comes from a renewable source like biogas (75%) [17]. On the engine side, its use in compression-ignition (CI) engines allows higher thermodynamic conversion efficiencies compared to the Spark Ignition (SI) ones. Additionally, the high octane number of methane reduces the risk of engine knock for higher compression ratio (CR) CI engines.

Several DF literature studies face with issues related to the combustion controllability, unburnt emissions, etc. especially for high substitution rates of diesel with NG. The results indicate that higher substitution rates, compatibly with acceptable engine working conditions, are likely for higher engine loads. About the emissions, global results show lower CO_2, NO_x and PM emissions, and higher levels of total unburned hydrocarbon (THC) compared to D [18,19]. The higher DF – THCs are demonstrated to be mainly linked to the premixed methane trapped into the crevices volumes and not involved in the combustion process, and to the locally lean air-fuel regions in the combustion chamber not able to sustain the flame front propagation [3,6].

Typically, DF combustion employs a single pulse diesel injection but, as already reported by the authors in a previously published paper, the double pulse injection strategy can improve the combustion stability and the combustion noise [18]. Other results identify the injection timing, pilot diesel fuel quantity, compression ratio and equivalence ratio as effective variables to control performances and emissions especially in terms of THC [18,20].

However, among the literature studies on light duty (LD) engines, there is a lack of results in terms of compression ratio (CR) impact on the DF engine outputs. In the case, the results are limited to the knock and noise assessment for dated indirect injection (pre-chamber) engine and in a CR range not applied in current powertrains [21]. Moreover, since the development of new high efficient and low emission diesel engines accounts for even lower CR values [22], to reduce the NO_x and soot emissions, the assessment of the CR effect is valuable [23,24].

Within this framework, the present study was aimed to a comprehensive analysis of the CR impact, in a range compatible with the up-to-date trends [22], on the global performances such as efficiencies, noise, combustion stability and pollutant emissions, including the particle size distribution function (PSDF). The experimental analysis was performed by means of a single cylinder engine (SCE) setup with a modern combustion system representative of the automotive engine technology.

The SCE outputs to the CR variation were analysed starting from a pre-defined engine calibration, acting on the diesel substitution ratio, diesel 1st injection pulse quantity, and intake air throttling observing the specific engine functional limits in terms of noise, combustion stability, gaseous emissions, and thermo-mechanical stress of the engine combustion system components.

The operating test points were selected in order to assess the combustion outputs over a wide engine operating map including the emission estimation over the NEDC emission homologation cycle test of the real four-cylinder automotive engine from which the engine is derived. The experimental apparatus, the test methodology and the results are thoroughly described.

2. Experimental apparatus and procedure

2.1. Single cylinder engine

A single cylinder compression ignition engine, with an up-to-date Eu5 combustion architecture, was employed for the test campaign. The main combustion components (conrod, piston, cylinder head, etc.) of the SCE come from a four-cylinder production series engine. The crankcase and cylinder block were designed to adapt all the components. Fuel, cooling, and lubrication systems are decoupled from the engine allowing a greater flexibility of their control parameters, independently of the engine operating conditions. The control of the intake and exhaust parameters (pressure and temperatures) were realised through proper boost and back pressures control valves) and an intake heater (temperature). In general, to make the results as representative as possible of the reference multi-cylinder engine (MCE) one, the setting of all the boundary conditions (EGR, oil cooling, water cooling, fuel cooling, etc.) were equivalent.

The control of the equivalence ratio was carried out through a throttle-valve located in the intake manifold. For the direct injection of the diesel fuel a production series 7-hole injector for common rail system was used, while the indirect injection of the methane fuel was realised through a proper multi-hole port fuel injector, placed in the non-swirl intake runner, fed by a pressure of 8 bar. The diesel and methane fuel measurement were carried out by means of a gravimetric balance (AVL 733) and a thermal mass flow meters (Brooks SLA 5860) respectively. The engine and auxiliary control systems were realised by means of an in-house electronic control unit developed on the National Instrument platform (CRio 9081 and Single-Board Rio). The test cell layout is depicted in Fig. 1, while Table 1 describes the main engine characteristics.

The indicated pressures were measured by means of a Kistler 6125B piezo-quartz transducer fitted inside the combustion chamber and acquired by means of a high-frequency acquisition system (AVL-Indimicro) with a resolution of 0.1 crank angle degree (CAD). The pressure signals were averaged over 128 consecutive cycles and then elaborated by means of the AVL Indicom software for the calculation of the apparent heat release (HR) and heat release rate (HRR) through the first law of thermodynamic. The emitted smoke in FSN unit was measured by means of the AVL 415S smoke meter and converted in mg/m^3 unit through a consolidated correlation [25]. The measurement of the emitted particles, presented in form of Particle Size Distribution Function (PSDF), was done by means of a Differential Mobility Spectrometer (Cambustion DMS500). The measuring interval was 5–1000 nm with a sampling frequency of 10 Hz. The engine-out gaseous emissions (THC, MHC, NO_x, CO, CO_2) were measured using an integrated emissions test bench.

Commercial EN590 compliant diesel fuel and pure methane (CH_4) were used as direct and port injected fuel respectively. The main fuels characteristics are listed in Table 2. Since natural gas (NG) is constituted by a mix of hydrocarbons, the composition and then its characteristics are variable and dependent on the source of supply. For this reason, instead of NG, CH_4 was used as premixed fuel because of its