

Effects of Rail Pressure, Pilot Scheduling and EGR Rate on Combustion and Emissions in Conventional and PCCI Diesel Engines

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ABSTRACT

In Diesel engines the optimization of engine-out emissions, combustion noise and fuel consumption requires the experimental investigation of the effects of different injection strategies as well as of a large number of engine operating variables, such as scheduling of pilot and after pulses, rail pressure, EGR rate and swirl level. Due to the high number of testing conditions involved full factorial approaches are not viable, whereas Design of Experiment techniques have demonstrated to be a valid methodology. However, the results obtained with such techniques require a subsequent critical analysis, so as to investigate the cause and effect relationships between the set of engine operating variables and the combustion process characteristics that affect pollutant formation, noise of combustion and engine efficiency.

To this purpose, the zero-dimensional multizone diagnostic combustion model developed at ICEAL was applied for the combustion and emission formation analysis in two different diesel engines, for various sets of injection strategies and engine operating parameters. The experimental data were acquired at the highly dynamic test rig of ICEAL, both in a EURO V low compression ratio diesel engine with a twin-stage turbocharger, equipped with piezoelectric injectors, and in a PCCI low compression ratio diesel engine equipped with solenoid injectors. The model results were discussed and reported in the well known ϕ -T diagrams, which give a synthetic representation of the local thermodynamic charge conditions during the mixture formation and premixed-diffusion combustion processes. The rail pressure increase was found to be an effective means to improve fuel-charge premixing and to lower the average local equivalence ratio of

the charge during premixed combustion, so leading to a decrease in soot formation. As regards the effects of cooled high-pressure EGR on combustion, it was shown that an increase of its rate does not significantly affect the average equivalence ratio during premixed combustion, which is associated to the soot formation rate. Finally, a proper calibration of the dwell-time between pilot and main injection, so as to have the main injection pulse center-of-gravity phased in correspondence to the start of pilot burning, resulted to produce a reduction of CO and soot emissions higher than 50% with respect to baseline case, without any deterioration of NO_x emissions.

INTRODUCTION

During the calibration activity of diesel engines, different injection strategies can be tested, in order to investigate their effects on the pollutant emission formation, on the combustion noise and on the fuel consumption. In addition, the optimization of engine-out emissions, combustion noise (CN) and fuel consumption requires the experimental investigation of the effects of a large number of engine operating variables, such as injection parameters, Exhaust Gas Recirculation (EGR) rate, rail pressure and swirl level. In particular, target functions can be identified, which account for the above-mentioned quantities, with proper weight factors depending on which the target of the optimization is. The minimization of the target function is the criterion which is followed for the identification of optimal sets of calibration parameters of the electronic control unit. Due to the high number of testing conditions and variables usually involved, full factorial approaches are not viable, whereas Design of Experiment (DoE) techniques demonstrated to be a valid methodology ([1]¹). However, the experimental results of the

¹Numbers in square brackets designate references at the end of paper.

different calibration sets require an accurate analysis in order to investigate the cause and effect relations between injection and combustion processes. To that end, the application of the multizone premixed-diffusion diagnostic combustion model presented in [2] can be of fundamental importance in order to add complementary information to experimental results.

This paper investigates the effects of rail pressure, pilot injection schedule and EGR rate in a 2.0L GMPT-E EUV diesel engine equipped with piezoelectric injectors as well as of dwell-time between pilot and main injections (DT) in a 1.9L GMPT-E PCCI diesel engine equipped with solenoidal injectors.

Experimental tests were carried out at the highly-dynamic test rig of ICEAL, at Politecnico di Torino, within two different research projects in cooperation with GMPT-E. The multizone premixed-diffusion diagnostic combustion approach will be applied to the in-cylinder pressure traces so as to obtain the time histories of the released chemical energy, Heat Release Rate (HRR), premixed and diffusive zone temperatures, NO, CO and soot. The model outcomes will be also reported in the well-known ϕ -T diagrams, which give a synthetic representation of the local charge thermodynamic conditions during the mixture formation, premixed and diffusive combustion processes, and of their effects on pollutant emission formation. Finally, an insight into the key-factors controlling CN will be given.

EXPERIMENTAL SETUP

The main specifications of the EUV diesel engine (Fig. 1a) are reported in Tab. 1. It was derived from the GMPT-E 2.0 dm³ 16V Twin Stage Turbo engine, equipped with piezoelectric injectors ([1]).

The PCCI (Premixed Charge Compression Ignition) diesel engine (Fig. 1b) is a 16V direct-injection turbocharged one with cooled EGR. Specifications are reported in Table 1. The engine ([3, 4]) was able to run either in conventional combustion mode or in low-temperature highly-premixed combustion one by means of a strong increase in the EGR rate and a reduced geometrical compression ratio (15.5).

With reference to the aftertreatment system, the particulate filter was removed from both engines and the correct exhaust backpressure was set by means of a throttle valve fitted to the exhaust line. The engines were fully instrumented with piezoresistive pressure transducers and K thermocouples (TCK) for the measurement of pressure and temperature levels at various engine locations. An air-fuel ratio 'NGK' UEGO sensor was set within the exhaust system of each engine. As regards the measurement of in-cylinder pressure time-histories, in the PCCI engine a high-frequency KISTLER 6053CCSP piezoelectric transducer was installed on the cylinder head, whereas in the EUV engine a high-

frequency KISTLER 6058A41 piezoelectric transducer was fit to the glow-plug seat. In both engines in-chamber pressure measurements were referenced by means of a high-frequency KISTLER 4075A10 piezoresistive transducer, which was located in the inlet runner of the cylinder equipped with the in-cylinder pressure sensor.

All of the experimental tests on the multi-cylinder engines were carried out at ICEAL highly-dynamic test bed, whereas the injector characterization was made at ICEAL hydraulic test rig. A detailed description of the two test beds is available in [1,5] and is summarized in what follows. The highly-dynamic engine test rig is equipped with: an 'ELIN AVL APA 100' cradle-mounted AC dynamometer, featuring a nominal torque and a power of 525 Nm and 220 kW, respectively, as well as a maximum speed of 12,000 rpm; an 'AVL KMA 4000' for continuously metering fuel consumption. An 'AVL AMAi60' system made up of three analyzer trains is used for measuring engine-out gaseous raw emissions. Two trains are equipped with: two heated flame ionization detectors for the THC/CH₄ analysis; one heated chemiluminescence detector for the analysis of NO_x and NO; three nondispersive infrared analyzers for measuring low as well as high CO concentrations and CO₂ levels; one paramagnetic oxygen detector. The third train is made up of a detector for measuring CO₂ levels in the intake manifold so as to evaluate engine EGR ratio. For particulate matter emission measurement the dynamic test bed is further equipped with: AVL 715S smokemeter, AVL 439S opacimeter and AVL SPC472 Smart Sampler. All of the abovementioned measurement devices are controlled by PUMA OPEN 1.3.2 automation system. The hydraulic test rig is instrumented for a complete fluid-dynamic characterization of Common Rail fuel-injection systems, including an EVI injection-rate meter, an EMI2 device to gauge the oil injected mass as well as thermo-piezo-transducers to measure temperature and pressure traces in the rail and at the injector inlet.

COMBUSTION DIAGNOSTICS

Combustion diagnostics is carried out by means of the multizone approach developed in [2]. It is based on the analysis of measured in-cylinder pressure traces and injection rates through the application of the energy and mass conservation laws to each zone, of the perfect gas law to each gaseous zone and a of a proper fuel evaporation model to the liquid zone. The combustion chamber was split into a liquid fuel zone, an unburned gas zone, a rich mixture of fuel vapor and unburned gas, along with the related premixed burned gas zone, as well as into several diffusive burned gas zones. All of these are internally homogeneous. According to a combustion concept close to the one introduced by J.E. Dec ([6]), an initial fuel rich zone is generated, giving rise to a premixed flame surrounding the fuel-vapor air mixture at the

liquid-jet tip. Later on, this zone completes its oxidation in the nearly stoichiometric diffusion flame at the periphery of plume, where it entrains the oxygen required to oxidize the combustion products of the rich phase, consequently to an unburned gas induced mass dilution. Within such an approach, combustion is treated like a two-stage quasi-steady process made up of a premixed and a diffusive phase. Premixed burning involves a fuel-rich mixture of fuel vapor and unburned gas surrounding the liquid jet. Diffusive combustion occurs at the jet periphery, where the combustion products of the previous rich premixed burned mass complete their oxidation in an environment close to stoichiometric conditions. The implementation of such a two-stage quasi-steady combustion process in a diagnostic model is innovative with respect to previously developed different multizone models of the zero- and quasi-dimensional type ([7,8,9]). The proposed multizone model is zero dimensional, so that it does not require a geometric characterization of the combustion process. Thus, for example, the modeling of the influence of air turbulence and of the dynamics of each injected fuel spray in the combustion chamber is not necessary. However, the proposed diagnostic approach does account for these effects since it is based on the experimental pressure traces. In addition, the model is capable of taking the non-uniform spatial distribution of in-cylinder burned gas thermodynamic and chemical properties into account, thus allowing the implementation of specific sub-models for an accurate calculation of pollutant emissions.

RESULTS AND DISCUSSION

EUV DIESEL ENGINE: EFFECTS OF RAIL PRESSURE (P_{RAIL}) LEVEL, INJECTION SCHEDULE AND EGR RATE

Description of the Experimental Activity: Objectives and Methodologies

The experimental data were acquired in the frame of a research project financially supported by GMPT-E, and detailed in [1]. The ultimate goal of the activity was to assess the potentialities of innovative piezo- and solenoid-driven Common Rail injection systems on engine performance, emissions, fuel consumption and combustion. Particular attention was paid to the effects of the advanced injection patterns enabled by each Common Rail system.

With reference to the engine configuration considered in this paper (Tab. 1), a standard calibration set featuring an injection schedule with a pilot shot and a main pulse was used as baseline, whereas three advanced injection patterns were taken into account, namely:

- PPM: two pilot pulses and a main injection;

- PMA: a pilot pulse and a main injection followed by an after pulse;

- PPMA: two pilot pulses and a main injection followed by an after pulse.

Injection strategies were optimized in 7 key-points, which were identified so as to characterize engine operation for a middle-size passenger car during NEDC cycle (idle, 1500×2, 1500×5, 2000×2, 2000×5, 2500×8, 2750×12). For each key-point and each considered injection strategy, different calibration sets were identified by means of a specifically developed DoE approach ([1]).

In this paper, the study will be focused on the ‘2000×5’ key point, where PPM injection strategy has shown to give better results. As a matter of fact, in the considered engine it was found that double pilot strategies feature the best potential to reduce CN with limited penalties in soot emissions at low and medium engine loads, whereas after injection should be enabled mainly at higher engine loads (‘2500×8’ key point) to control soot oxidation ([1]).

Three different calibration sets (Cal. #1, Cal. #2, Cal. #3) were analyzed. For each calibration set two test cases are considered: the ‘optimal’ case, which was identified as a result of the DoE methodology, and the ‘constant trapped mass’ case. This latter features the same engine variables of ‘optimal’ case except the EGR rate, which was changed so as to obtain the same trapped air mass of baseline case. Numbers in Tab. 2 express the difference (p_{rail} , SOI_{main} , DT_{pil1} , DT_{pil2}) or the ratio (all other operating variables) between the value of a specific engine variable in the considered calibration set and the correspondent baseline value. As regards pilot pulses, “pil 1” and “pil 2” subscripts indicate shots closer to and farther from the main injection, respectively. The injected fuel and DT of each pilot shot are referred to the pilot fuel and DT of the single pilot in the baseline case, respectively. Tab. 3 shows the experimental values of bsNOx, bsSoot, bsHC, bsCO, bsfc and CN for each test case listed in Tab. 2. Values in Tab. 3 are usually normalized with respect to the correspondent value measured in the Ref. Case, except CN values that indicate the difference vs. baseline.

Basically, all calibrations aim at minimizing bsNOx. Cal. #1 requires that bsSoot and bsHC do not exceed the levels measured for baseline, whereas Cal. #2 also imposes a reduction of bsfc. Finally, Cal. #3 stresses the data set in order to reach lower levels of CN without bsfc and bsSoot penalties. Even though the identification of optimal operating conditions was carried out by accounting for the effects of all influencing engine variables, Tab. 2 shows that the three engine calibration sets are characterized by different rail-pressure levels and pilot-shot schedule, at constant SOI_{main} and swirl level. Therefore, the multizone analysis will be

mainly focused on rail pressure and pilot injection effects. In addition, the effects of a change in EGR rate will be studied for Cal. #3 test case.

Combustion Analysis: Combined Effects of p_{rail} and Pilot Injection Scheduling

Firstly the outcomes of the test cases featuring ‘constant trapped mass’ are discussed and compared to those of the baseline case. Figs. 2,3,4 present both experimental results and data computed by means of multizone diagnostic approach. As regards experimental results, Fig. 2a and Fig. 4a show in-chamber pressure and its derivative with respect to Crank Angle (CA), respectively, whereas Fig. 2b reports injection rate profiles. As regards quantities computed by means of the multizone diagnostic approach, Fig. 2 shows the released chemical energy (Fig. 2c) as well as global and premixed HRR (Fig. 2d), whereas Fig. 3 reports the temperatures (Fig. 3a) of unburned, premixed and diffusive zones, NO (Fig. 3b), CO (Fig. 3c) and soot (Fig. 3d) curves. The diffusive temperatures in Fig. 3a represent the average temperature of all the diffusive zones. In Figs. 3b-d, arrows indicate experimental values of emissions measured at engine exhaust. Finally, Fig. 4b plots the computed local thermodynamic conditions of fuel-air mixture during the mixing process and of burned gas in both premixed and diffusive combustion phases on the ϕ -T diagram. Values of each time-history (except temperature time histories) are normalized with respect to the peak value of the same quantity obtained in the baseline case.

In the considered tests, p_{rail} values of Cal #1, Cal #2 and Cal. #3 are 249 bar, 286 bar and 102 bar higher than baseline, respectively, whereas SOI_{main} is constant. Fig. 2b shows that main pulse starts earlier as p_{rail} increases, as a consequence of the reduction of Nozzle Opening Delay (NOD) when rail pressure augments ([5]). This produces higher rates of injection at the beginning of main pulse, which in turn affects the in-cylinder pressure rise (Fig. 2a) and thus determines both higher values of the peak firing pressure and a steeper and more advanced HRR (Fig. 2d). As a matter of fact, higher rates of injection improve fuel spray atomization, which increases the fuel/air contact surface, thus improving fuel evaporation rate and, consequently, shortening the physical contribution to the ignition delay. In addition, as p_{rail} increases, premixed HRR is more pronounced (Fig. 2d) and ϕ values reduce during premixed combustion (Fig. 4b). This latter result is consistent with the findings in [10], where an increase of lift-off length and a decrease of ϕ at lift-off were ascertained as the pressure drop across injector orifices became larger.

As regards CN, Cal. #3 shows a significant advantage with respect to baseline (-1.42 dBA in Tab. 3), whereas Cal. #1 and Cal. #2 feature much higher values. It is well known that

CN can be correlated to the peak value of $dp/d\theta$ time-histories ([11]). As a matter of fact, with reference to the results shown in Tab. 3 and Fig. 4a, both CN levels and $dp/d\theta$ peak values are lower for Cal. #3 and progressively increase for baseline, Cal. #1 and Cal. #2. The peak values of $dp/d\theta$ for the different calibration sets can be explained based on pilot injection quantities and timings as well as on p_{rail} values, thus supporting the CN results. As regards Cal. #3, the total injected quantity for the two pilot shots is 61% higher than for baseline case (Tab. 2), but a proper pulse-splitting enables a better control of the HRR of the pilot fuel (Fig. 2d), of $dp/d\theta$ peak value (Fig. 4a) and of CN (Tab. 3). Cal. #2 is characterized by the highest fuel quantity globally injected during pilot shots (+117% with respect to baseline), thus featuring the highest values of HRR (Fig. 2d) and of $dp/d\theta$ peak (Fig. 4a) related to pilot shots, as well as of CN (Tab. 3). With reference to Cal. #1, CN is higher with respect to Cal. #3, even though the total mass of pilot fuel in Cal. #1 (+48% higher than baseline) is lower than that in Cal. #3 (+61% higher than baseline). However, Cal. #1 features a larger q_{pil2} with respect to Cal. #3 (Tab. 2), thus producing a higher $dp/d\theta$ value. In addition, Cal. #1 is also characterized by a higher value of p_{rail} (Tab. 2), which leads to a more pronounced HRR (Fig. 2d).

With reference to bsfc, Cal. #1, Cal. #2 and Cal. #3 feature slightly improved values with respect to baseline. This can be ascribed to more advanced values of SOI_{main} (+1.13 deg, Tab. 2).

The diffusive burned gas temperatures (Fig. 3a) are almost overlapping for the different engine calibrations, except in the interval around 370 CA deg, where they are higher for Cal. #1 and Cal. #2 as a consequence of the steeper and more advanced start of HRR for main injection (Fig. 2d). This supports higher NO levels in Fig. 3b for these calibration sets. Premixed combustion temperatures (Fig. 3a) are also higher for Cal. #1 and Cal. #2. This can be ascribed to the higher premixed HRR (Fig. 2d) with respect to the other test cases.

With reference to CO (Fig. 3c), Cal. #1 and Cal. #2 show the highest peak values, which occur around 370 deg where higher diffusive temperatures (Fig. 3a) determine more significant dissociation phenomena; nevertheless, CO values at the end of combustion are very close to each other for all calibrations, because oxidation rates are fast during the expansion phase and CO conversion to CO_2 is almost complete.

As regards the soot mass, Fig. 3d shows that both peak and end-of-combustion values are strongly influenced by engine calibration. More in detail, soot formation is mainly affected by rail pressure, being higher at lower p_{rail} values (i.e., baseline and Cal. #3) as a consequence of a poor fuel/air premixing. This latter is highlighted by the higher ϕ values

during premixed combustion in the ϕ -T diagram of Fig. 4b. However, peak and end-of-combustion values of soot mass are slightly higher with Cal. #2 set than for Cal. #1 set, even though Cal. #2 features higher values of p_{rail} (Tab. 2). In fact, a higher ϕ value during premixed combustion (Fig. 4b) and a lower value of premixed HRR (Fig. 2d) counterbalance the positive effect of p_{rail} increase on soot formation. It can be speculated that the interaction between burned gases from pilot shots and the injected fuel of the main pulse plays a significant role in soot production. As a matter of fact, Cal. #2 features the highest quantity of pilot fuel, therefore the mass of burned gases obtained from the pilot shots is greater with respect to Cal. #1. This leads to a more severe reduction of oxygen concentration in the environment where the first fuel particles of the main pulse are injected. Hence, higher values of ϕ are obtained during mixture formation process and premixed combustion (Fig. 4b) and higher soot formation rates are then estimated (Fig. 3d). This effect will be also evidenced for the PCCI engine.

For all calibrations sets, Tab. 3 shows that the proposed injection strategies determine reduced soot emissions with respect to the reference case when the trapped air mass is kept equal to baseline. This confirms that an increased tolerance to EGR rate has been achieved. Therefore, with Cal. #1, #2 and #3 the EGR rate can be increased so as to obtain the 'optimal' operating points reported in Tab. 2.

Combustion Analysis: Effects of EGR Rate

In this section the EGR rate effect has been studied with reference to Cal. #3 only. All engine variables were kept fixed at the 'optimal' values listed in Tab. 2 except the EGR rate, which was changed so as to vary the normalized trapped charge mass in the range 0.86 (higher EGR rate) to 0.91 (lower EGR rate), with reference to the baseline case. Experimental results and quantities calculated by means of the multizone diagnostic approach are shown in Figs. 5,6 as a function of CA. Fig. 5a reports experimental data, namely the acquired in-chamber pressure and the injection rate. All the other plots (Figs 5b,c,d and Fig. 6) reports diagnosed quantities: the HRR of the pilot shot (Fig. 5b), the global HRR associated to the main injection and the correspondent premixed contribution (Fig. 5c), the unburned gas and premixed burned gas temperatures, the average temperature of the diffusive gas zones (Fig. 5d), the time histories of NO concentrations (Fig. 6a), CO concentrations (Fig. 6b), mass of soot (Fig. 6c) as well as of local thermodynamic conditions of the charge (Fig. 6d) on the ϕ -T diagram. Values of each time-history (except temperature time histories) are normalized with respect to the peak value of the same quantity obtained in the test case featuring the lowest trapped air mass.

Figure 5a shows that values of in-chamber pressure decrease as EGR rate increases (i.e., trapped air mass reduces). This can be ascribed to the reduction of boost pressure, which

determines lower in-cylinder pressure values throughout compression, as well as to the slowdown of the chemical reaction rates during combustion, due to the decrease of local oxygen concentration and the increase of charge diluents. The reduction of chemical reaction rates is also supported by the results in Figs. 5b,c. More specifically, as EGR rate increases, the pilot burning is delayed due to a progressively longer ignition delay, and the correspondent HRR is lowered (Fig. 5b). At the same time, main injection burning is retarded and the related premixed HRR is slightly increased (Fig. 5c).

Figure 5d highlights that premixed and diffusive burned gas temperatures decrease as EGR rate increases, as a consequence of the increased charge thermal capacity and reduced local oxygen concentration of the combustion charge. Owing to lower diffusive burned gas temperatures, thermal NO formation reduces when EGR increases (Fig. 6a). As regards CO (Fig. 6b) evolutions, the peak values are not strongly influenced by the EGR rate, whereas CO oxidation rate during the expansion stroke reduces as EGR rate increases. This latter effect can also be found for soot oxidation rate (Fig. 6c) after the soot peak. With reference to soot formation, no trend with EGR rate is apparent for the soot increase that occurs from start of combustion (345 deg in Fig. 6c) to soot peak (375 deg in Fig. 6c). This is also confirmed by the ϕ -T diagram of Fig. 6d, where the average equivalence ratio during premixed combustion, which is associated to the soot formation rate, does not depend on EGR rate. This result further supports the previous experimental studies in [12]. As a matter of fact, on the one hand an increase of EGR rate lowers the local oxygen concentration, thus increasing local ϕ values during mixture formation, but on the other hand it increases ignition delay, thus promoting the mixing of a greater volume of charge with fuel, which determines a lowering of ϕ value.

PCCI DIESEL ENGINE: EFFECTS OF DWELL TIME (DT)

Injection strategy effects on combustion process and emission formation were investigated in the PCCI diesel engine presented in [3, 4]. The experimental data were acquired within a collaborative research project among GMPT-E, Politecnico di Torino and FTZ Zwickau, which was aimed at developing a low compression ratio PCCI diesel engine. Part of the activity carried out at Politecnico was focused on the identification of the most suitable conditions for realizing PCCI combustion concept by coupling a reduction of the engine compression ratio (CR) with suitable timing and quantity of injection pulses ([3]). A newly designed combustion bowl featuring a central-dome was designed. It was characterized by both a high K-factor (84.8%), for improving the air utilization at full load, and a low aspect ratio (29.3%), so as to tolerate advanced injection timings at partial load. Reduced CR prototypes (CR = 15.5 and CR = 15) were realized to achieve high specific power densities