

# Combustion System Optimization of a Low Compression-Ratio PCCI Diesel Engine for Light-Duty Application

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## ABSTRACT

A new combustion system with a low compression ratio (CR), specifically oriented towards the exploitation of partially Premixed Charge Compression Ignition (PCCI) diesel engines, has been developed and tested. The work is part of a cooperative research program between Politecnico di Torino (PT) and GM Powertrain Europe (GMPT-E) in the frame of Low Temperature Combustion (LTC) diesel combustion-system design and control. The baseline engine is derived from the GM 2.0L 4-cylinder in-line, 4-valve-per-cylinder EU5 engine. It features a CR of 16.5, a single stage VGT turbocharger and a second generation Common Rail (1600 bar). A newly designed combustion bowl was applied. It features a central dome and a large inlet diameter, in order to maximize the air utilization factor at high load and to tolerate advanced injection timings at partial load. Two different piston prototypes were manufactured by changing the internal volume of the new bowl so as to reach CR targets of 15.5 and 15. The baseline and the new in-piston bowls were experimentally analyzed in conjunction with different injector nozzles to assess their best match for PCCI application. To such an end, the ratio of premixed fuel-air was enhanced by advancing injection and increasing fuel-air contact surface. Hence, in addition to baseline injectors with 7 holes and 148 deg spray cone angle, two nozzle configurations featuring 9-hole and reduced spray cone angles (135 deg and 120 deg) were considered in order to assess the benefits of increased

fuel-air contact surface and advanced injection timings, respectively, in charge premixing. The experimental tests were carried out on the highly dynamic test bed of the IC Engines Advanced Laboratory (ICEAL) at Politecnico di Torino. Combustion analysis was also performed by means of an innovative premixed-diffusive multizone diagnostic tool, which has recently been developed at ICEAL. For the different combustion system configurations, engine performance and pollutant emissions were investigated at characteristic engine working points, for both partial and full loads, where wall impingement and air utilization are critical, respectively. In addition, the low CR engine prototypes were tested for NEDC cycle by reproducing the engine operation on a D-class passenger car at the dynamic test bed. Finally, the combustion system which presented the best compromise between partial- and full-load performance was selected.

## INTRODUCTION

Low-emission and high-efficiency diesel engines are indispensable for both environmental preservation and sustainable use of oil. At the same time, further progress in engine performance as well as less expensive and higher durability aftertreatment systems are required by the market. Novel in-cylinder  $\text{NO}_x$  reduction techniques involving various concepts of low-temperature premixed diesel combustion can concur to the achievement of all the mentioned issues that are apparently conflicting.

In this work, a partially Premixed Charge Compression Ignition (PCCI) combustion is achieved in an automotive diesel by coupling a reduction of the engine compression ratio (CR) with suitable timing and quantity of injection pulses. In fact, by lowering CR it is possible to reduce the in-cylinder pressure and temperature levels during the compression stroke. At partial load, a longer ignition delay will result, which leaves time for a high degree of fuel-air mixing and produces a more homogeneous charge and lower temperature combustion, thus moving the local charge thermodynamic conditions to low soot and NO<sub>x</sub> areas in the  $\phi$ -T diagram ([1]). Furthermore, the reduction of in-cylinder peak firing pressure obtained by lowering CR allows higher levels of boosting and thus higher amounts of fuel injection, with the result of higher power densities.

However, a CR reduction can significantly deteriorate the engine cold start behavior, with high HC and white smoke production, in particular if low quality fuel with low cetane number is used. To reduce these drawbacks, the optimization of the combustion chamber shape, glowing, injection and air management systems, together with the adoption of suitable injection strategies, featuring a pilot injection, was shown to be of fundamental importance ([2-10]).

|                           |                                                  |
|---------------------------|--------------------------------------------------|
| Engine type               | 1.9 l – EURO 5                                   |
| Displacement              | 1910 cm <sup>3</sup>                             |
| Bore x stroke             | 82.0 mm x 90.4 mm                                |
| Stroke-to-bore ratio      | 1.10                                             |
| Compression ratio         | 16.5                                             |
| Valves per cylinder       | 4                                                |
| Turbocharger              | Single-stage with VGT                            |
| Fuel injection system     | Common Rail 2 <sup>nd</sup> generation – 1600bar |
| Specific power and torque | 57.6 kW/l – 167 Nm/l                             |

Table 1: Main specifications of the reference engine.

Provided this optimization is performed, low CR diesel combustion can be a key technology to meet the future requirements, as the decreasing trend in CR that started in late 1990s is already demonstrating.

COMBUSTION SYSTEM SPECIFICATIONS

The baseline engine is derived from the GM Powertrain 1.9 L in line 4-cylinder 4-valves-per-cylinder EU 5 engine, whose main specifications are reported in Tab. 1. The baseline combustion bowl is the current production one (bowl A in Fig. 1) featuring CR = 16.5.

For the low CR engine, a novel combustion bowl was selected. Figure 1 shows the main differences among the investigated bowl prototypes and the baseline bowl A. In

particular, bowl B is designed according to the shallow-dish concept, increasing the chamber aspect ratio, while bowl C, featuring a central dome shape, is characterized by both a higher K-factor with reference to the baseline bowl for improving the air utilization at full load, and by a lower aspect ratio in order to tolerate advanced injection timings at partial load.

Based on previous findings ([11]), bowl C was selected and two different piston prototypes were manufactured by changing the internal volume of the new bowl, so as to obtain CR targets of 15.5 and 15. The choice of these target values of CR was made on the basis of previous investigations ([11]), looking at mid-term post EU 5 time frame, and also of the results in [6], which assessed the possibility to still have a robust cranking with these CR values. Furthermore, the engine was equipped with high protrusion metallic glow-plugs which offer an increased contact surface for igniting the diesel spray.

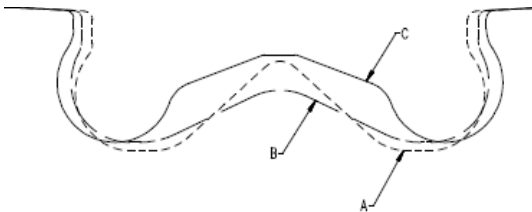


Figure 1: Piston bowl A, B and C cross sections.

|                 |                                 | Inj. 1 | Inj. 2 | Inj.3 | Inj.4 |
|-----------------|---------------------------------|--------|--------|-------|-------|
| Number of holes | [-]                             | 7      | 7      | 7     | 9     |
| Flow rate       | cm <sup>3</sup> /30 s @ 100 bar | 480    | 480    | 480   | 480   |
| Spray angle     | [deg]                           | 148    | 135    | 120   | 148   |

Table 2: Injector nozzle tested configurations.

Four injector nozzle configurations (Tab. 2) were defined in cooperation with the supplier starting from the baseline injector (whose nozzle specifications are reported in the first column), with the main objective of broadening the application of PCCI combustion. To this end, the objective of increasing the premixed fuel-air ratio was investigated through the injection advance and the increase of fuel-air boundary surface. Therefore, Inj. 2 and Inj. 3 featured a reduced spray angle in order to allow advanced timings without any risk of wall wetting, whereas Inj. 4 increased the fuel-air contact surface by means of reduced hole-diameters and additional holes.

With regard to emissions, the PCCI combustion potential for engine-out  $\text{NO}_x$  and PM reductions was assessed and any deterioration of engine-out as well as tailpipe THC and CO emissions was evaluated. PCCI combustion would require different regeneration strategies for the diesel particulate filter (DPF) with respect to conventional combustion, therefore the electronic control unit (ECU) management of DPF regeneration was disabled and the particulate filter was removed from the exhaust line. The correct exhaust backpressure was then set by means of a throttle valve fitted to the exhaust line. A high precious metal loaded diesel oxidation catalyst (DOC) was then installed in order to preliminarily investigate the control of THC and CO during NEDC cycle operation.

## EXPERIMENTAL SETUP

All experimental tests on the reference engine and on the engine equipped with piston and injector prototypes were carried out on a new highly-dynamic test bed (Fig. 2) at ICEAL of PT. The 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. The facility is capable of full four-quadrant operation with high speed and torque dynamics, including simulation of zero torque and gear shifting oscillations in the drivetrain. In particular, a double-shaft APA 100 dynamometer was installed at ICE Laboratory, so that two different engine configurations can be set up at the same time and tested alternatively.

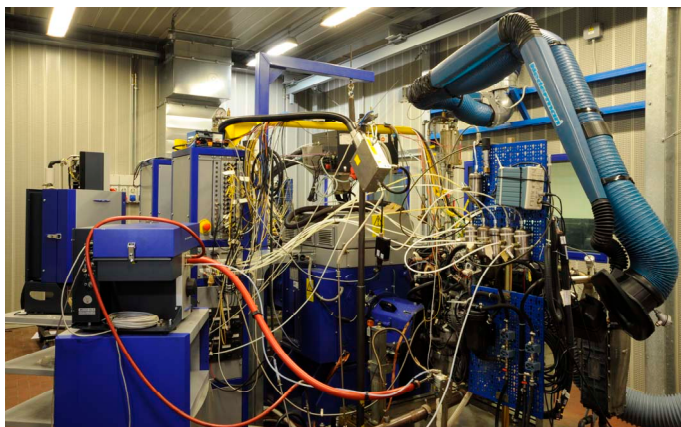


**Figure 2:** AVL high dynamic test bed.

The measuring system 'AVL KMA 4000 Methanol' was used to continuously meter the engine fuel consumption. It is based on the AVL PLU measuring principle of the servo-controlled positive displacement counter and can perform measurements over the range of 0.28-110 kg/h with a reading accuracy of 0.1% for all measurement media (i.e., Diesel fuel, gasoline as well as methanol and ethanol up to 100%).

With reference to the exhaust gas analysis in the present investigation, the test facility is equipped with a 'Pierburg AVL AMA 4000' raw exhaust-gas analyzer, which is basically made up of three analyzer trains. Two of these feature the following modules: 1 heated flame ionization

detector for the THC analysis; 1 heated chemiluminescence detector for the analysis of  $\text{NO}_x - \text{NO}$ ; 3 nondispersive infrared analyzers for measuring low as well as high CO concentrations and  $\text{CO}_2$  levels; 1 paramagnetic oxygen detector. These two trains allow one to measure pollutant levels upstream to and downstream from the aftertreatment system at the same time. The third train is made up of a  $\text{CO}_2$  concentration detector for measuring  $\text{CO}_2$  levels in the inlet manifold so as to evaluate engine EGR ratio.

The dynamic test bed also includes unique facilities for the analysis of diluted engine-out and tailpipe emissions. More specifically, AVL bag mini diluter (BMD) 150 and AVL direct vehicle exhaust (DVE) 150 measuring systems are used as an alternative to CVS sampling systems. DVE accurately meters engine-out flow, whereas BMD precisely dilutes a small heated portion of the exhaust gas with 'zero air' and fills the bags required for emission measurement. A heated constant dilution system is thus obtained, which is suitable for measuring pollutant mass also from SULEV configurations.

For PM emission measurement from diesel engines, 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, which also includes ISAC 400 software for the simulation not only of vehicle (namely, road load, road gradient and moments of inertia of driveline components that are not physically present on the test bed) but also of the driver behaviour (more specifically, use of clutch, accelerator pedal and gear shifting).

The test engine is fully instrumented with piezoresistive pressure transducers and K thermocouples (TCK) for the measurement of pressure and temperature levels at the following locations: upstream and downstream from compressor, at inlet manifold, upstream and downstream from turbine, downstream from aftertreatment system. Additional TCK are also installed for the measurement of temperatures downstream from the intercooler, in the four inlet runners and exhaust runners, as well as upstream and downstream from the EGR cooler. Finally, an air-fuel ratio 'NGK' UEGO sensor is located within the exhaust system. The acquisition of these quantities are directly managed by PUMA OPEN through dedicated firewire front end module (F-FEM), which can manage up to 48 analog input channels with a maximum data capture rate of 5 kHz per channel.

One high-frequency KISTLER 6053CCSP piezoelectric transducer is installed on the engine cylinder head for taking pressure time-histories of gases in the combustion chamber of the cylinder N. 4, whereas a high-frequency KISTLER 4075A10 piezoresistive transducer is used to detect pressure levels in the inlet runner of same cylinder for referencing in-cylinder pressure. An AVL 365C crank-shaft driven encoder generates the time

base for an automatic 14 bit data-acquisition system (based on AVL indimodul 620 system), which is capable of acquiring up to 8 channel data with a maximum frequency of 800 kHz per channel. The acquisition system is managed by AVL indicom software and interfaced with PUMA OPEN 1.3.2, so as to allow both online analysis of the indicated cycle and storage of data for post-processing with specifically developed homemade diagnostic tools.

## COMBUSTION DIAGNOSTICS

Combustion diagnostics is carried out by means of a new multizone model ([12]), which is based on the analysis of measured in-cylinder pressure through the application of the: energy and mass conservation laws to each zone, perfect gas law to each gaseous zone and 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 several diffusive burned gas zones. All of these are internally homogeneous. According to a combustion concept close to the one proposed in ([13]), 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 oxidate 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 ([14-17]). The proposed multizone model is zero dimensional, so that it does not require a geometric characterization of the combustion process. However, it 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 submodels for an accurate calculation of pollutant emissions.