Abstract PhD Thesis
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An experimental investigation was carried out with the aim to highlight the main benefits achievable by the implementation of an early Premixed Charge Compression Ignition (PCCI) diesel combustion concept, determining at the same time which are the constraints imposed on operating such a highly premixed strategy and which could be viable methods to possibly counteract them.

At first, the potentialities of the early single-injection PCCI concept were evaluated on a 3.0 l, four-cylinder, four-stroke Euro VI production diesel engine (F1C Euro VI) provided by FPT Industrial, equipped with a short-route (high-pressure) cooled exhaust gas recirculation (EGR) circuit, with a high-pressure Common Rail fuel injection system featuring solenoid injectors, and with a variable geometry turbine (VGT). With this engine, specifically designed to run under conventional diesel combustion (CDC) operations, experimental results showed that early PCCI operations (achieved by exploiting high levels of cooled EGR and retaining the control over combustion through highly advanced injection timings) were possible only with a very low maximum reachable brake mean effective pressure (*bmep*), around 2÷3 bar. Simultaneous engine-out soot and NO_x reductions (of up to 99% and 95%, respectively) could be achieved, compared to their CDC levels, but with associated several penalties. In this regard, the increased emission of incomplete combustion products (unburned hydrocarbons, HC, and carbon monoxide), the intense combustion noise (CN), the higher fuel consumption and the worst combustion stability were the most challenging.

To further investigate the early PCCI concept, a modified engine (referred to as F1C PCCI), specifically designed to run under PCCI combustion mode, was derived from the conventional F1C Euro VI engine. Proper hardware modifications were designed by means of 3D CFD combustion simulations based on the preliminary PCCI tests carried out on the conventional F1C Euro VI engine. The final hardware modifications included reduced compression ratio (from 17.5:1 to 14.6:1), modified piston, different fuel injectors with reduced cone angles, a higher volume EGR cooler and a smaller turbo-group. Compared to the standard version, the prototype engine (featuring a single fuel injection calibration) allowed to perform a suitable steady-state calibration in PCCI conditions up to 8.5 bar of *bmep*. Strong reductions of engine-out NO_x and soot emissions were still possible, but tailpipe HC and CO emissions at low load, intense CN and fuel consumption penalties ranging from about 3% to 11% (if compared to the corresponding values obtained with CDC operations with the baseline F1C Euro VI engine) still remained major issues. Nevertheless, it should be considered that the fuel consumption penalty induced by PCCI may be partially mitigated, since its potential to simultaneously reduce soot and NO_x engine-out emissions (getting rid of their well-known trade-off typical of the CDC mode) may lead to minimize the after-treatment requirements and the related costs, i.e. reducing the fuel penalties for active DPF (diesel particulate filter) regeneration and the costs for urea-based additives.

With the aim to address the increase in tailpipe HC and CO emissions, especially for low load and speed operations, a hot (uncooled) EGR strategy was tested at the lowest load engine operating conditions (up to *bmep* = 3 bar). Uncooled EGR, i.e. exhaust gas recirculated into the engine without passing through the EGR cooler (by-passing it), has proven beneficial when the exhaust gas

temperatures were so low that the oxidation catalyst did not exploit its full effectiveness, helping the catalyst to reach its operating temperature in a wider area of the engine map.

Multi-pulse (i.e., double and triple) fuel injection strategies were tested and compared to the baseline single-pulse PCCI combustion operations. Splitting the fuel injection pattern proved to have the potential of reducing engine-out HC and CO emissions, optimizing the spray penetration and reducing the occurrence of over-mixing and wall impingement phenomena, with minor penalties in terms of soot and NO_x. Multi-pulse injection strategies also allowed to effectively dampen excessive CN levels, while slightly improving fuel economy.

Being EGR one of the crucial parameters involved in early PCCI combustion, its rate should be optimized inside a narrow interval to achieve a reasonable compromise in terms of engine-out pollutant emissions, fuel consumption and CN level. Therefore, a "zero-dimensional" (0D) model for the estimation of the EGR flowrate was built and analysed, highlighting how this could be potentially suitable for real-time control applications if implemented on-board the ECU.

Combustion instability may occur due to the high EGR level and its possible uneven distribution among the different cylinders. As combustion phasing is one of the most important parameters affecting diesel combustion, MFB50 (crank angle at which 50% of the injected fuel has burnt) has been exploited as a controlled parameter to implement real-time combustion control techniques. A pressure-based and a model-based combustion controllers, able to control in real-time the MFB50 by properly shifting the start of injection (SOI) of the main fuel injection, have been developed and experimentally tested on the F1C Euro VI engine, in both steady-state and transient conditions, under CDC mode, to prove their robustness. Moreover, steady-state tests have been performed under PCCI operations, highlighting benefits in terms of reduced cylinder-to-cylinder and cycle-to-cycle variability of the combustion process.

A preliminary assessment of the potentialities of single- and multiple-injection PCCI, intended to be calibrated inside a dedicated low-to-medium load and speed portion of the engine map, and combined with a conventional diesel combustion calibration outside of it (simulating a dual-mode operation strategy engine) is evaluated along simulated NEDC and WHTC cycles. The simulation exploits interpolation of steady-state map measurements in terms of exhaust pollutant emissions, fuel and urea consumptions, giving an estimation of the possible benefits/penalties compared to a reference conventional diesel combustion case, even if not intended to be an accurate evaluation of real transient operations carried out in real driving conditions.

Finally, the detrimental effect of the progressive EGR cooler fouling on performance and emissions is presented and discussed. The increased pressure drop across a fouled EGR cooler results in a progressively reducing amount of EGR, thus revealing to be one of the major constraints to the applicability of the PCCI concepts.