

Light Duty Diesel Engine: Optimization of Performances, Noxious Emission and Radiated Noise

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ABSTRACT

The paper aims at performing an environmental and energetic optimization of a naturally aspirated, light-duty direct injection (DI) diesel engine, equipped with a Common Rail injection system.

Injection modulation into up to three pulses is considered starting from an experimental campaign conducted under non-evaporative conditions in a quiescent optically-accessible cylindrical vessel containing nitrogen at different densities. The engine performances in terms of power and emitted NOx and soot are reproduced by multidimensional modelling of the in-cylinder processes. The radiated noise is evaluated by resorting to a recently developed methodology, based on the decomposition of the CFD 3D computed in-cylinder pressure signal. Once validated, both the CFD and the acoustic procedures are applied to the simulation of the prototype engine and are coupled to an external optimizer with the aim of minimizing fuel consumption, pollutant emissions and radiated noise.

INTRODUCTION

Direct Injection diesel engines generally offer higher thermal efficiency and better reliability compared with gasoline engines. Recent developments of Diesel engines, mainly determined by the introduction of strategies of injection rate modulation, have strongly broadened the range of application of this propulsion system. Diesel engines are worldwide applied within heavy-duty vehicles or marine applications, but nowadays, especially in Europe, they are becoming attractive in light-duty transportation systems and unconventional applications, as in aeronautics [1].

As known, environmental optimization of diesel combustion usually faces with the trade-off between the nitrogen oxides (NOx) and the Particulate Matter (PM) emissions. Each measure devoted to reduce one of these two families of pollutants usually has a negative impact on the other. The effectiveness of double, triple, and rate shaped injection strategies to simultaneously reduce NOx and PM has been

demonstrated [2]. Multiple injection strategy behaves like a retarded single injection on NOx reduction. In addition, the presence of soot producing rich regions is strongly limited with injection modulation. Nevertheless, the future emission regulation still require further improvements.

Nowadays, new combustion concepts, as the Homogeneous Charge Compression Ignition (HCCI), are promising in achieving near zero NOx and PM amounts [3]. This concept, however, presents some drawbacks especially as regards the HC and CO emissions and, at the same time, pose serious problems of noise control. While in a diffusion combustion mode, even at low load, HC and CO emissions are negligible due to high localized temperature peaks, in the lean-premixed combustion mode complete oxidation of HC and CO is difficult to be achieved. The early fuel injection, required to form a lean and uniform (homogenous) mixture, determines a fuel wall impingement too, so increasing the HC and CO emissions. Another shortcoming is the control of combustion phasing, which limits the HCCI combustion mode applicability to very low load operating conditions. Noise emission due to strong pressure gradients is also to be considered as a factor penalizing this combustion mode [4].

For these reasons, more recent studies have been addressed to develop new combustion modes using near-TDC injection technology [5]. In this way combustion occurrence remains controlled by the injection event, but, at the same time, the benefits of the fuel-air premixing are conserved as much as possible, through the enhancement of the mixing process during the ignition delay time. This leads to a lowering of the local temperature peak and equivalence ratio (Premixed Low Temperature Combustion – PLTC), producing a simultaneous reduction of NOx and soot emission.

The enhancement of the ignition delay, allowing a greater time for fuel-air premixing, is thought to be the dominant factor in suppressing NOx and soot formation. Kalghati et al. [6,7] experimentally demonstrated that gasoline fuel, because of its high

ignition delay, is very beneficial for premixed compression ignition, compared to a conventional diesel fuel.

Yun et al. [8] were successful in developing a PLTC mode in a HSDI engine running at 1500 rpm, up to 6 bar IMEP, while maintaining the baseline fuel efficiency. In fact, they prolonged the ignition delay via an advanced SOI and high EGR rate and simultaneously promoted the fuel-air mixing through the employment of a high swirl ratio and injection pressure. At the high load level (6 bar) a three-pulse injection modulation and a higher boost pressure were required. A reduced pressure rise (low radiated noise) was obtained, too.

In the near future, Direct Acting Injectors (DAIs) [2] will further improve the situation, by allowing an almost squared wave shape of the injection mass flow rate, independently on the injection pressure, and will strongly reduce the dwell time between subsequent injection events.

Afore described issues make clear that combustion development and emission production depend on a complex interaction among different parameters, namely injection modulation and phasing, boost pressure, EGR fraction, swirl ratio, fuel properties, and so on. The optimal choice of a so large number of parameters depends on speed and load conditions, and is related to the fulfillment of a number of contrasting objectives, like reduced NO_x, Soot, HC, CO, fuel consumption, noise emissions, with constraints on engine costs, reliability, and so on. This of course requires the integration of experimental activities to new theoretical methods, resorting to 3D CFD modeling and mathematical optimization, too, which may better identify a compromise solution among the conflicting needs.

The present paper represents a first attempt to answer to the above considerations, and applies a 3D modeling and an optimization procedure [1,9,10,11] to a naturally aspirated light-duty diesel engine (505 cm³ displacement). The engine is equipped with a mechanical Fuel Injection System (FIS) and is originally designed for non-road applications. Starting from the above base engine, a new prototype, equipped with a Common Rail (CR) FIS, is currently under development for being installed on small city-cars. The behavior of the CR injection system is hence experimentally analyzed, in order to define the spray structure (tip penetration and cone angle) realized under non evaporative conditions and for different backpressures. The above data are utilized to properly validate the spray sub-model employed in the 3D calculations. In this way, depending on each specified injection strategy, combustion development and noxious emissions of the prototype engine can be estimated in a medium load operating condition. Each predicted pressure cycle is also processed to estimate the combustion-radiated noise. Noise emission is in fact predicted resorting to a recently developed numerical procedure, validated on acoustic measurements taken on the base engine [11].

The optimization problem is settled in order to identify the control parameters of a three pulses injection profile, for a constant overall mass of injected fuel. These parameters are assumed as independent variables of the multi-objective optimization tool and are selected with the aim of simultaneously minimizing fuel consumption, pollutant emissions and radiated noise. Different injection strategies are identified, depending on the weight of importance assigned to the single objectives. Three solutions realizing different trade-offs among the conflicting needs are presented and discussed.

EXPERIMENTAL ANALYSIS

PERFORMANCE TESTS - The base engine is a naturally aspirated, four strokes, two valves, single-cylinder diesel engine (505 cm³ displacement), equipped with a mechanical FIS. It was installed in a test-bench including an electrical dynamometer, the data acquisition and control units, as well as an emission and acoustic measurement equipment. Performance tests are carried out at full load, in a range of engine speeds going from 1400 to 3000 rpm. At each operating condition, the in-cylinder pressure is detected by means of a piezoelectric pressure transducer [11].

ACOUSTIC TESTS – Radiated noise measurements are also performed on the base engine following the ISO Standards reported in [12]. To this aim, the engine is acoustically isolated from the electrical dynamometer, through properly designed acoustic absorption panels. The engine radiated noise is measured by a free-field microphone located at a distance of 1 m from the engine block, at all the investigated engine speeds. Both the performance and acoustic tests are employed to properly develop and tune a numerical procedure for the estimation of the combustion noise, extensively reported in [11].

INJECTION APPARATUS AND STRATEGIES – A CR injection system to be installed on the prototype engine is separately tested together with a micro-sac injector with five holes, 0.130 and 1.0 mm in diameter and length, respectively. The injection pressure is varied in the range from 28.0 to 140.0 MPa. A Programmable Electronic Control Unit (PECU) controls the apparatus and enables the setting of strategies in terms of injection number and timing. The high pressure pump, supplying the fuel to the CR, is driven by a variable speed electric motor while an heat exchange system on the hydraulic circuit is adopted for fixing the fuel temperature at 21±1 °C. Three different injection strategies are analyzed:

- 1) low load with a triple injection at the pressure of 28.0 MPa;
- 2) medium load with a triple injection at the pressure of 71.0 MPa;
- 3) full load with a single injection at the pressure of 140.0 MPa.

The fuel injection rate for the adopted strategies and the injection system performances are measured by an

AVL Injection Gauge Rate System working on the Bosch tube principle [13].

The stronger controlling factor of the jets development in non evaporative conditions is the density of the gas [14,15] influencing the fuel penetration and the spray cone angle. Some evidences of the influence of the gas nature on the spray shapes are proved in literature [16]. A high molecular weight gas (SF_6 $\rho = 6.2 \text{ kg/m}^3$) is used to reach the required working densities at low pressure values. Pressures of 2.0, 2.6 and 3.3 MPa are set for gas densities of 12.50, 16.15 and 20.62 kg/m^3 , respectively, in an optically accessible cylindrical vessel. The volume is at ambient temperature and injector is positioned on the top with its axis along that of the vessel. A commercial diesel fuel is injected in a single-shot mode operation to prevent droplets fog accumulation in the vessel and windows dirtying. In the spray images acquisition mode, the remote controlled PECU starts both the injection system and a Pulse/Delay Generator. The last one commands the lightening of the jets, through wide quartz windows located on the cylinder wall at different instant from the start of injection (SOI) by three flashes in an orthogonal configuration, and the image acquisition system. The spray images are collected by a CCD camera, 1280x1024 pixels, 8 bit resolution and 0.5 μs exposure time, synchronized with the flashes having the optical axis coincident with the vessel one. A delay generator allows a fine time resolution in shifting the flashes/camera configuration. The images of the jets are processed off-line by a professional digital image processing (IMAGE PRO PLUS). Further details of the experimental set up are reported in [17].

IMAGE ANALYSIS PROCEDURE – The analysis of the liquid fuel spray images is carried out by image processing procedures. Different steps are adopted: spray image acquisition and background subtraction, image filtering, fuel spray edges determination, liquid spray tip penetration and cone angle measure. Mie-scattering images of fuel spray are taken by the CCD camera using the CamWare control software. An online subtraction of the background is carried out during the acquisition to better distinguish the liquid spray image from the background. A median filter is applied to remove impulse noise from the spray image maintaining the spray edge sharp.

The tip penetration and cone angle of the spray are determined from the spray edges. The penetration is measured by the processed image as the greatest distance from the nozzle to the farthest fuel droplet on the spray edge. The cone angle represents the angle between the tangents to the spray edges in the region up to the axial distance of 10 mm from the nozzle [16,17,18]. Both the liquid spray tip penetration and the spray cone angle are reconstructed on 10 single shot images. Figures 1-3 summarize the experimental activity carried out on the CR-FIS. In figure 1, the injection rates measured in the three analyzed load conditions are compared. Figures 2 and 3 indeed report the spray tip penetration measured at different load conditions and ambient densities. These data will be employed to validate the spray model in the 3D CFD analysis.

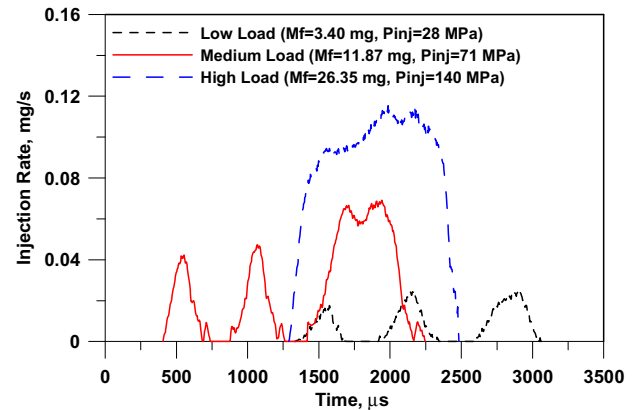


Fig. 1 – Experimental injection rate of the CR-FIS.

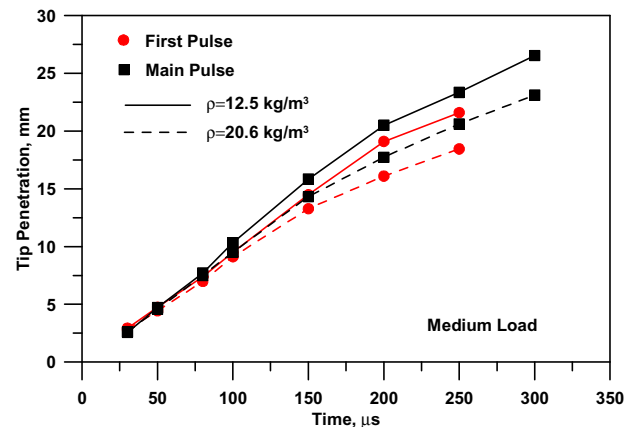


Fig. 2 – Effect of the ambient density on the tip penetration for the medium load operating point.

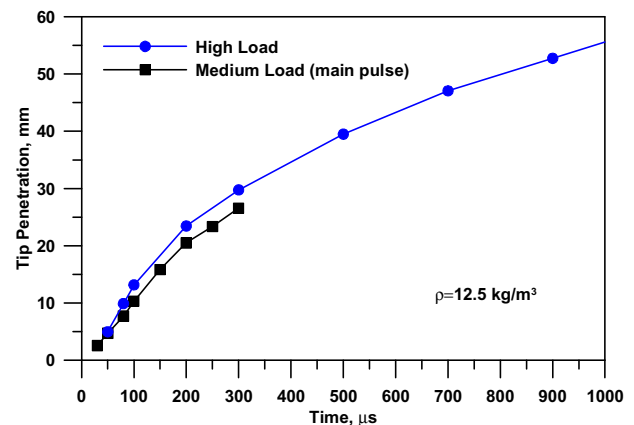


Fig. 3 – Tip penetration at medium and high load conditions

NUMERICAL SIMULATION

1D ANALYSIS – A one-dimensional simulation code [1,11] is employed to initially predict the performance of the base engine. The 1D code solves the mass, momentum and energy equations in the ducts constituting the intake and exhaust system, while the gas inside the cylinder is treated as a zero-dimensional system. Concerning the modeling of the combustion process, a classical Wiebe equation is utilized to compute the heat release rate in the base engine. Proper values of the combustion process duration