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Experimental analysis of functional requirements to exceed the 100 kW/l in high-speed light-duty diesel engines

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HIGHLIGHTS

- Functional requirements for power density of 100 kW/l in light-duty diesel engines.
- Benefits on power density and efficiency of 3000 bar diesel injection pressure.
- Power density sensitivity versus engine operating parameters has been assessed.

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ABSTRACT

The paper describes the results achieved in an experimental study aimed at identify the operating parameters, in terms of fuel injection characteristics, intake/exhaust conditions and thermomechanical stress of engine and turbocharger, required to exceed the high threshold of 100 kW/l for light-duty high speed diesel engines. In order to increase the power/weight-volume ratio, such target is currently one of the milestones for diesel engine development engineers.

To achieve the specific power target a high-performance prototype 0.5 l single-cylinder engine demonstrator was developed employing some special very robust components and high-quality parts from the state-of-art automotive diesel technology. A prototype advanced piezo injection system, capable of 3000 bar maximum injection pressure, was employed.

Geometrical features of the combustion system and injector nozzle were carefully preconfigured based on the characteristics of the most recent diesel engines developed for premium high-performance cars, as well as on the best knowledge of the authors. The operating parameters in terms of intake – exhaust conditions and injection strategy were properly parametrized in order to find the boundary conditions suitable for the desired specific power target.

The paper discusses the system sensitivity to the boundary conditions of the charging and exhaust systems, and develops a balanced set of targets for the complete system based on thermo-structural, fluid-dynamic and efficiency considerations. The tests confirmed the benefits of the employment of very high fuel injection pressures as a way to face with the trade-off of combining high performance and fuel economy for light-duty high-speed diesel engines.

1. Introduction

While the history of Diesel engines for passenger car application dates back to 1930s, it was not until 1970s that their market share reached a significant level, following the oil shocks. At that time, indirect-injection Diesel cars started to be the natural option for consumers looking primarily to ownership cost. The power density of those engines was quite low for the present standard, in the

Abbreviations: ATDC, After Top Dead Center; bmep, Brake Mean Effective Pressure; DPF, (Engine Close-Coupled) Diesel Particulate Filter; CO_2, Carbon Dioxide; EOI, End Of Injection; FIS, Fuel Injection System; FGT, Fixed Geometry Turbine; fmep, Friction Mean Effective Pressure; HF, Hydraulic flow rate of injector nozzle; HSDI, High Speed Direct Injection; HRR, Heat Release Rate; imep, Indicated Mean Effective Pressure; isfc, Indicated Specific Fuel Consumption; m-air, Air Mass Flow Rate; MBF, Mass Burned Fraction; MCE, Multi-Cylinder Engine; NO_x, Nitrogen Oxides (NO, NO_2); $O_{2,exh}$, Oxygen concentration in the exhaust gases; p_{back}, (Absolute) Back Pressure (exhaust manifold); p_{boost}, (Absolute) Boost Pressure (intake manifold); pcp, Peak Compression Pressure; pfp, Peak Firing Pressure; pmep, Pumping Mean Effective Pressure; p_{rail}, Common Rail Fuel Pressure; SCE, Single-Cylinder Engine; RDE, Real Driving Emissions; SOI, Start of Injection; T_{exh}, Exhaust Gas Temperature; VGT, Variable Geometry Turbine; ϕ, Equivalence Ratio; λ, Relative Air-to-Fuel Ratio; η_{mech}, Mechanical Efficiency; η_g, Global Efficiency.

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range 20–30 kW/l, with the highest values reached by first turbocharged engines then appearing on the market. The situation improved gradually in the mid-1980s, with electronically-controlled diesels hitting the market, and progress continued during the 1990 s thanks to the introduction of direct-injection for passenger cars. Specific power exceeded for the first time 40 kW/l in 1997 with the introduction, now in the history books, of common rail technology. Since then, the pace of performance increase has even accelerated, as can be seen in detail in Fig. 1.

The recent years, in which Diesels have exceeded 50% market share in Europe (with up to 70% in the premium and CUV/SUV segments), have recorded a relaxation of specific power for the core market FGT and VGT applications, in the fork between 55 and 60 kW/l [1]. The premium VGT market still shows modest gains, with best-in-class applications approaching 75 kW/l (which means a notable ~100 hp/l). On the other hand, the high-end market is still showing a race towards higher power densities, driven by sophisticated charging architectures based on Bi-Turbo, Tri-Turbo, Quadri-Turbo as well as combinations of turbine-driven and electrically-driven compressors [2].

The push toward even higher power density for automotive diesels is driven also by the strong demand for CO_2 emission reduction through the application of the engine downsizing concept, actually, today declined in engine right-size concept, in order to balance CO_2 and pollutant emission (mainly NOx) over the upcoming homologation procedure called Real Driving Emission (RDE) cycle [3,4].

The engineering community has been wondering if and where a practical limit for power density of mass-produced diesel engine does exist. Although some preliminary indication on the limits for very high power density were provided in 2009 and 2010 by the past experiences of Thirouard et al. and Lamping et al., the recent achievement of 100 kW/l brings that question back again [5–7]. Therefore, starting from the experiences carried out by Thirouard and Pacaud [7], the present paper analyzes such a question reviewing the limiting factors to diesel power density and the innovations now available which may overcome them.

Among such advances, also with respect to the previous experiences, three main technology key enablers for the power density target were considered: an air charging system capable of boost levels in excess of 4 barA (absolute pressure), an advanced low compression ratio combustion system design and a fuel injection system (FIS) capable of 3000 bar of injection pressure. By the way, the latest is one of the most parameters that permits to improve the global emissions [8,9]. The new fuel injection system design permits to achieve 3000 bar of fuel injection pressure (p_{rail}), the high rail pressure combined with an increase of the hydraulic flow permits to reduce the smoke emissions levels [10,11].

To carry out an experimental analysis on the capability to exceed a power density of 100 kW/l for the combustion systems architecture under development, a special prototype single-cylinder research engine has been setup, by means of the integration of several technologies considered as an enabler for the project target.

In the following, material and methods employed for the study are described, together with a comprehensive analysis of the functional requirements to exceed the power density target. The combustion process analysis for a diesel engine operating with 3000 bar of injection pressure and over 100 kW/l is also presented.

2. Material and methods

2.1. Laboratory engine system

The development targets for the project required a careful integration of technologies defining the combustion system, such as the cylinder head, the piston, the injector *etc.* This work has been carried out assembling and integrating several components, representing the state of the art of the light-duty diesel engines and Fuel

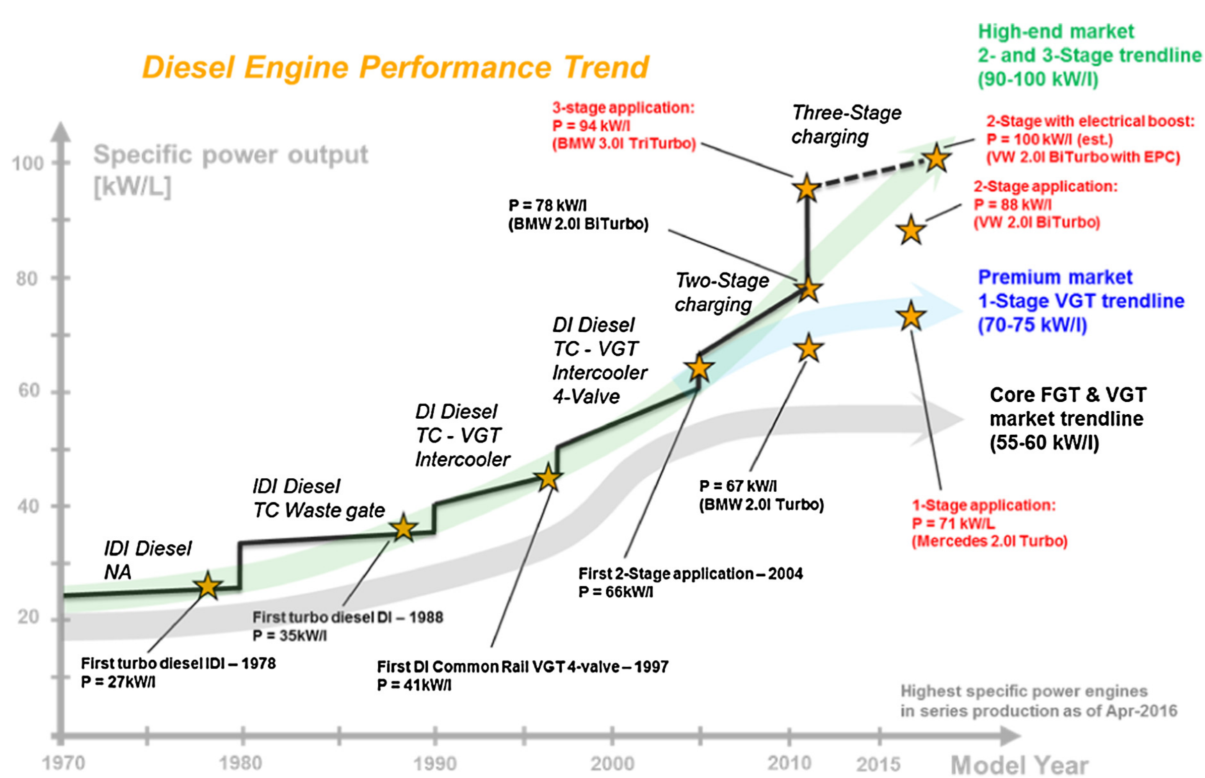

Fig. 1. Diesel engine specific power evolution.