Energy, Environment, and Sustainability
Series Editor: Avinash Kumar Agarwal

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Design and Development of Heavy Duty Diesel Engines

A Handbook

Springer

Chapter 2
Modern Diesel Combustion

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Abstract The chapter begins with the historical development of diesel combustion and explains engine Combustion Mechanisms followed by Fuel Injection and Supercharging. It explains the important step in the evolution of engine design to reduce NOx by Exhaust Gas Recirculation. Apart from the popular systems there are also Alternative Diesel Combustion Systems to remember. The evolution of the diesel engine is undoubtedly driven by the legislative standards for the Emissions of Internal Combustion Engines. The real concern regarding Global Climate Change imposes the limit to carbon dioxide and hence indirectly the fuel consumption. The particulate affective animal breathing systems as well as global warming is controlled tightly. This calls for accurate measurement of Particle Number. Apart from gaseous emissions, there is also a cap on the noise emissions. Al these requirements are satisfied to a large extent by the use of sophisticated air flow and fuel injection inside the engine. However, the advanced emission norms are satisfied only if there is Exhaust Aftertreatment to abate Nitric oxides and particulates. Hard working large engines have heat recuperation systems to consume the exhaust and coolant heat usefully. For carrying out this work, the losses have to be estimated correctly. To save cost and noise, many times the diesel engines are converted to operation on neat gas. For development of a country's infrastructure the diesel engine is being further developed to compete with other power sources as the engine is advantageous regarding logistics, storage, efficiency and compactness.

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P. A. Lakshminarayanan and A. K. Agarwal (eds.), *Design and Development of Heavy Duty Diesel Engines*, Energy, Environment, and Sustainability,
https://doi.org/10.1007/978-981-15-0970-4_2

2.1 Historical Development of Diesel Combustion

The Diesel Engine was invented by the German Engineer Rudolf Diesel (1858–1913) with a patent application on February 28, 1892 which led to the German patent number 62207.

The diesel engine (compression ignition engine) is an internal combustion engine where the heat of compression is used to initiate the ignition and burn the fuel which has been injected into the combustion chamber. This is in considerable contrast to the spark-ignition engine which employs a spark plug to ignite the air-fuel mixture. The thermal efficiency of the diesel engine is very high due to the use of a high compression ratio, Fig. 2.1.

2.1.1 Piston Lower Side Used for Compression of Charge Air

In the course of the further engine development a variety of split combustion chambers have been investigated until in the 1930s the direct injection engine has been adopted Figs. 2.2 and 2.3 (Knecht 1993).

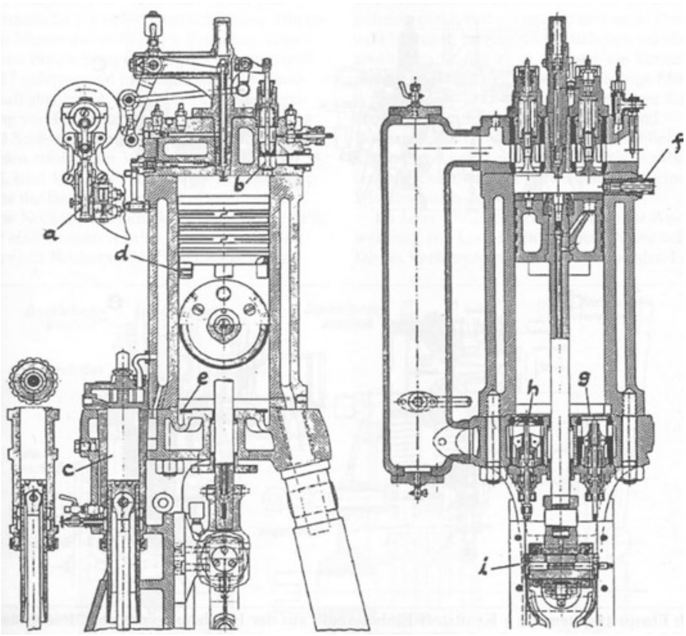
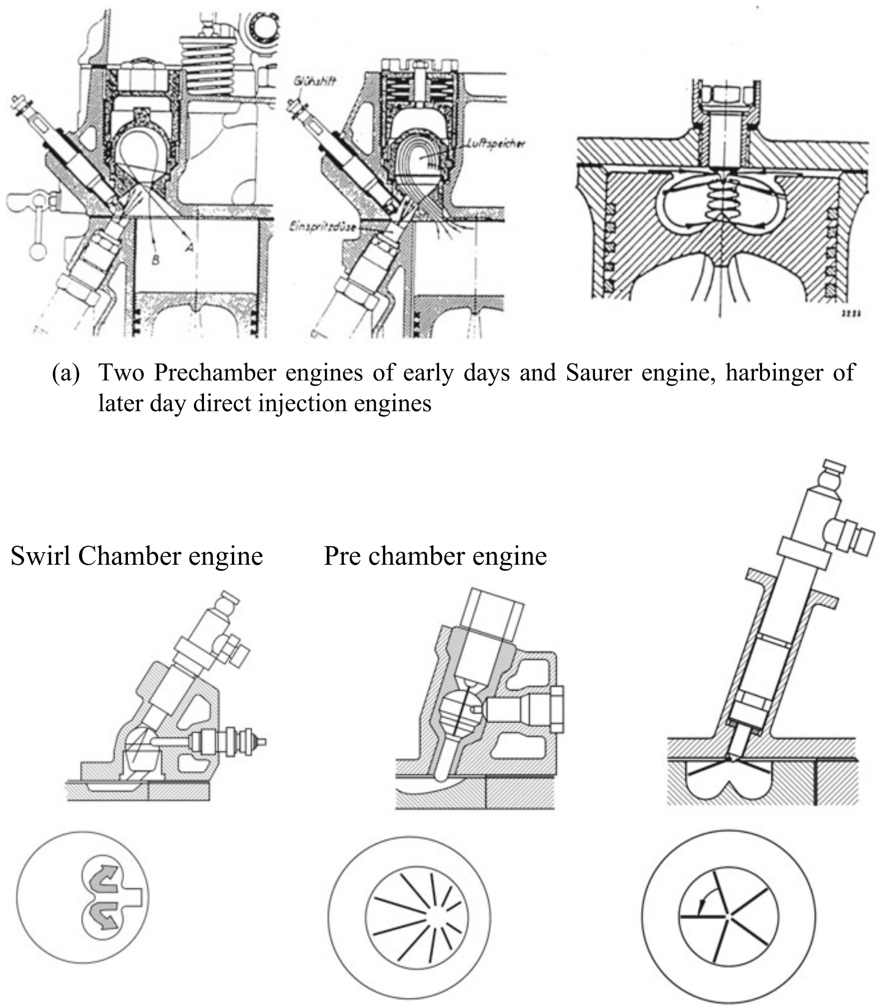


Fig. 2.1 Diesels first engine, 1896–97, Bore = 250 mm, Stroke = 400 mm



(a) Two Prechamber engines of early days and Saurer engine, harbinger of later day direct injection engines

(b) Popular Indirect Injection Engines

(c) Direct Injection engine

Fig. 2.2 Diesel combustion systems

2.2 Engine Combustion Mechanisms

Combustion is defined as the burning of a fuel and oxidant to produce heat and/or work. It is a chemically oxidized exothermic reaction process with a rapid oxidation generating heat. The initial slow oxidation accompanied by relatively little heat is

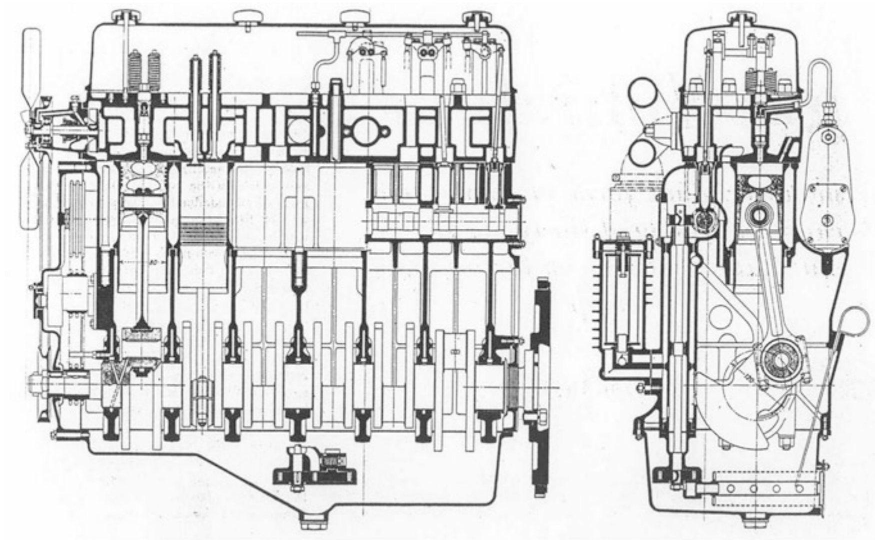


Fig. 2.3 High speed Saurer PD diesel engine with direct injection, 1936. Bore = 80 mm, stroke = 120 mm, cylinder capacity = 3,617 dm^3. 54 kW at 3000 rpm (Heldt 1936)

termed as ignition. Combustion occurs either in flame or non-flame mode whereby the flames are categorized as premixed flames or diffusion (non-premixed) flames. The requirements of combustion are two fluids (fuel and oxidizer) and both fluids must be in a gaseous phase and mixed within the flammability limits. Ignition occurs at a temperature equal or greater than the ignition temperature.

It is the major energy release mechanism on the Earth and key to mankind's existence.

Combustion comprises thermal, hydrodynamic and chemical processes. It begins with the mixing of fuel and oxygen in air. The fuel may be gaseous, liquid or solid and the mixture is ignited by means of a heat source. When ignited, fuel and oxidant chemically react and the consequent heat release is a process that sustains itself. The combustion produces heat, light, chemical species, pollutants, mechanical work as well as plasma.

Sometimes, a low-grade fuel, e.g., coal, biomass or coke can be burned partially (gasification) for producing higher-grade fuel, e.g., methane. Furnaces, combustors, boilers, reactors and engines are designed to utilize combustion heat, chemical species and work.

In modern diesel engines efforts are undertaken to optimise the compression ratio, the piston bowl geometry, the port induced intake air motion, the fuel injector nozzle configuration (number of orifices, size of orifices, the injection angle relative to the piston bowl, the nozzle protrusion), the number and quantity of fuel injection events and especially the supercharging system, in order to realise the engine-out emissions and the power.

2.3 Fuel Injection

An important area of diesel combustion represents the fuel injection. Initially this was mainly accompanied by air assisted injection of the fuel, Fig. 2.4. Later followed the so-called ‘solid injection’ or ‘air-less injection’.

As mentioned, considerable efforts have been directed towards improved Diesel fuel injection systems with higher fuel injection pressures, permitting to influence the rate and time of injection and with regard to injector-to-injector and shot-to-shot accuracy of the injection system.

The mainly used injection systems are:

- in-line pump
- Distributor pump
- Unit pump
- Unit injectors
- Common rail injection.

The duties of the Diesel fuel system are the injection of fuel into the combustion chamber with an optimal rate of injection (*dQ/dt*), a good fuel atomisation and ensuring optimal injection timing. A flexible control of these parameters in the whole operating area by the control system is very essential.

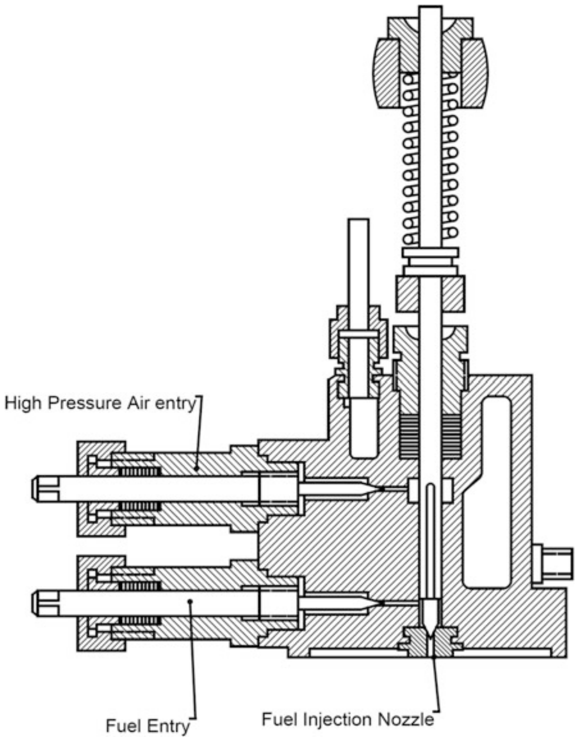


Fig. 2.4 Injection valve with pressure air assistance in diesel engine 1895

The general requirements on fuel injection systems of heavy-duty diesel engines in view of low fuel consumption and low emissions are:

- Accurate fuel metering injector-by-injector and shot-by-shot; smaller production tolerances.
- Increased injection pressures also in the engine's low speed range.
- Flexible injection rate control in the whole engine operating range including the adoption of multiple injection events.
- Reduction in nozzle hole diameters e.g. from approximately 0.18–0.10 mm
- Increased number of nozzle holes in conjunction with a low port-induced in-cylinder air motion
- Flexible control system
- Diagnostic system.

In view of EURO VI legislation for heavy duty road vehicles, manufacturers push to even higher injection pressures up to 3000–4000 bar (Delphi, Scania).

The major limitations on injection pressure are related to the strength of the nozzle tip (the high pressure in the nozzle tip can cause fatigue). The metal between the holes may suffer crack propagation from crack initiation sites within the holes. Another aspect that could lead to failures is the strength of the injection pipes, the cam stresses and the ability to accept the pump drive torque.

Currently all modern diesel engines which need to comply with stringent emission legislation are equipped with the common rail injection.

2.3.1 Unit Injector

In this system the injection pump and the fuel injector form one unit. The unit injector is driven by the engine's camshaft either directly via a push rod or indirectly via a rocker-arm assembly. Due to the fact that no high-pressure tubes are required, higher injection pressures can be realised, Fig. 2.5. Cam-operated unit injectors do not allow an engine speed-independent choice of the injection pressure: the maximum pressure is available at rated speed, but the pressure is reduced at low speeds due to the design of the cam. Novel systems with forced control of the needle permit a flexible adjustment of the injection pressure at needle opening.

Two important limitations of electronically controlled unit injectors are their inability to adequately decouple injection pressure from engine speed and their inability to allow sufficient multiple injection events.

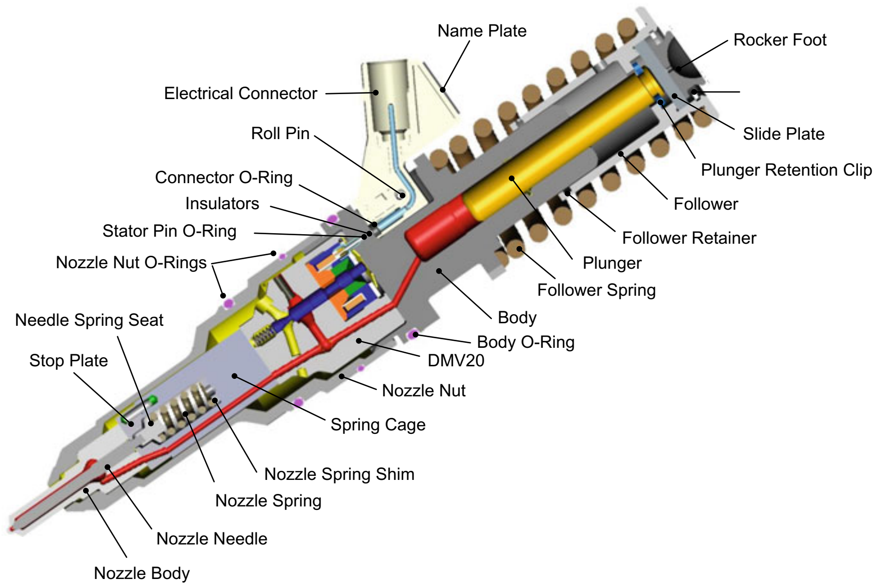


Fig. 2.5 Electronic unit injector (Bosch)

2.3.2 Common Rail Injection System

The common rail injection system was in principle invented in the early years of the 20th century (Knecht 2004). This system permits a choice of injection pressure independently of the engine speed. The injection begin and end can be relative freely **chosen**. Injection pressure is generated by a high-pressure pump and is available in a rail for all cylinders. Electrically operated injectors are used in place of pressure-controlled fuel injectors.

In a common rail injection system, the in-line pump and the distributor pumps are being replaced by more flexible fuel injection systems which offer a higher-pressure capability.

Mainly used in HD diesel engines were *unit injectors* and since 1999 more and more *common rail* systems are employed. The common rail system is widely used in passenger car diesel engines, in light duty vehicles (LDV) and now also in Heavy Duty engines. Particularly this injection system permits multiple injections, Fig. 2.6 (Imarisio and Rossi Sebastiano 2000; Egger et al. 2000; Krieger 2000; Dingle and Lai 2005):

- Very advanced pilot injection in order to achieve a partially homogeneous combustion or to improve cold operation
- A pilot injection with a transition to a boot injection for combustion noise- and smoke-reduction
- A main injection or a split main injection for stable rich operation

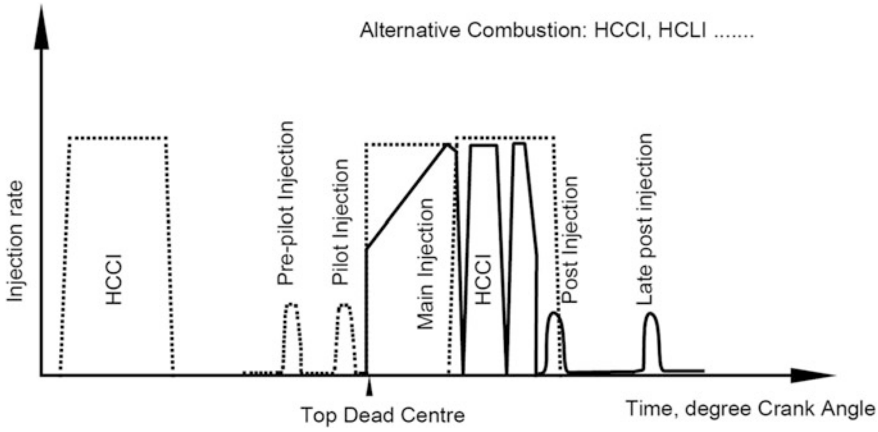


Fig. 2.6 Multiple fuel injection

- A post injection which leads to additional kinetic energy for a particulate matter (PM)-reduction
- Late post injection as a help for particulate trap regeneration or to increase NOx-conversion in SCR-systems or in NOx absorber catalysts for hydrocarbon addition.

In common rail injectors the conventional magnetic valves are being replaced by piezo-electric actuators which are faster than current solenoids and are also lighter, Fig. 2.7. The amplifier piston common rail system is suited for high injection pressure despite a relative low rail pressure and permits flexible rate shaping, Fig. 2.8. Ultimately a closed loop Lambda-control can help to reduce emissions.

Regarding fuel injection equipment, the following areas are currently in development:

- *injection rate shaping* aiming to choose within the whole operating area of an engine from a square to a ramp and to a boot injection
- multiple injection
- *Increase of fuel injection pressures which helps to improve the mixture formation due to* the higher turbulent kinetic energy and smaller fuel droplets and, hence, higher droplet surface which leads to an improved combustion process in the low-medium engine speed range. Around the rated power, however, an increased injection pressure may be needed to ensure acceptable injection duration.
- Currently *advanced combustion-feedback based control strategies* are considered a means to provide low fuel consumption and reduced emissions. Such a control can be realised with permanently in each individual cylinder installed pressure sensors.

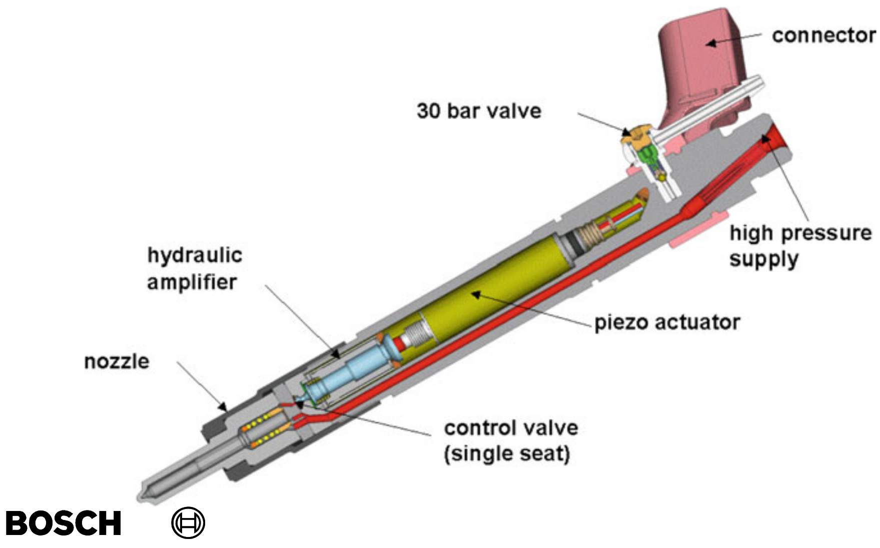


Fig. 2.7 Bosch piezo injector

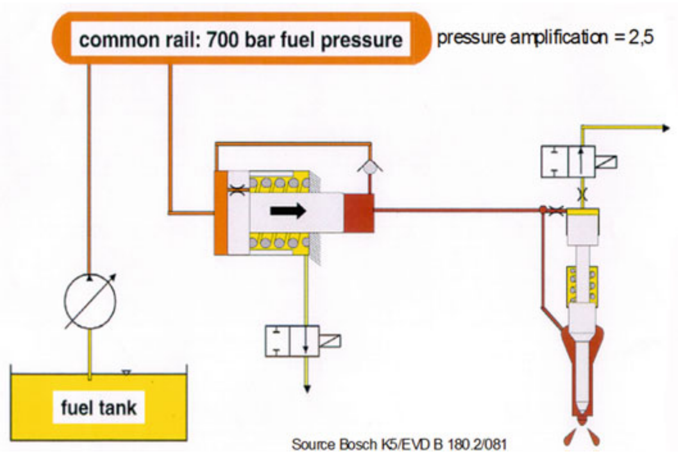


Fig. 2.8 Amplifier piston common rail system (APCRS), Bosch

- The envisaged advantages can be: reduction of dispersion in emission cycles, improved emission stability over lifetime, compensating for tolerances, enable highest power density, improved diagnosis, more stable diesel particulate filter regeneration, improved cold startability, cylinder selective control, enabling alternative combustion concepts and others.