Diesel fuel-injection systems: An overview

Diesel engines are characterized by their high levels of economic efficiency. Since the first series-production injection pumps were introduced by Bosch in 1927, injection-system developments have continued unceasingly.

Diesel engines are employed in a wide range of different versions (Figure 1 and Table 1), for example as:

- The drive for mobile electric generators (up to approx. 10 kW/cylinder),
- High-speed engines for passenger cars and light commercial vehicles (up to approx. 50 kW/cylinder),
- Engines for construction, agricultural, and forestry machinery (up to approx. 50 kW/cylinder),
- Engines for heavy trucks, buses, and tractors (up to approx. 80 kW/cylinder),
- Stationary engines, for instance as used in emergency generating sets (up to approx. 160 kW/cylinder),
- Engines for locomotives and ships (up to 1,000 kW/cylinder).

Technical requirements

In line with the severe regulations coming into force to govern exhaust and noise emissions, and the demand for lower fuel consumption, increasingly stringent demands are being made on the diesel engine's injection system.

Basically speaking, depending on the particular diesel combustion process (direct or indirect injection), in order to ensure efficient A/F mixture formation the injection system must inject the fuel into the diesel engine's combustion chamber at a very high pressure (today, this is between 350 and 2,050 bar), and the injected fuel quantity must be metered with extreme accuracy. With the diesel engine, load and speed control must take place using the injected fuel quantity without intake-air throttling.

For diesel injection systems, the mechanical (flyweight) governor is increasingly being superseded by the Electronic Diesel Control (EDC). In the passenger-car and commercial-vehicle sector, the new diesel fuel-injection systems are all EDC-controlled.

1 Bosch diesel fuel-injection systems. Areas of application

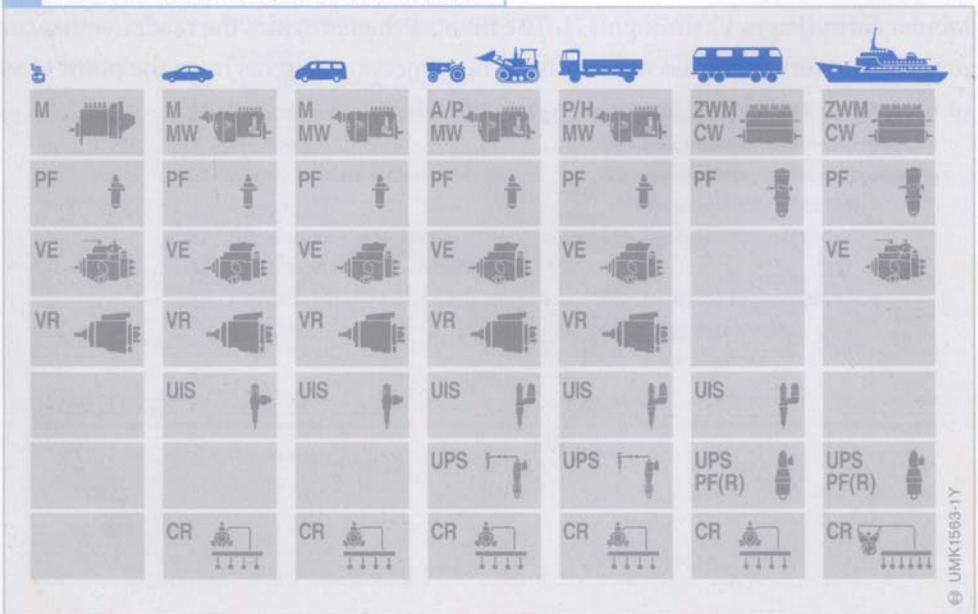


Figure 1
M, MW, A, P, H, ZWM, CW In-line injection pumps in order of increasing size;
PF Single-plunger injection pumps
VE Axial-piston distributor injection pumps
VR Radial-piston distributor injection pumps
UPS Unit Pump System
UIS Unit Injector System
CR Common Rail System

1 The most important diesel-engine high-pressure fuel-injection systems: Properties and characteristic data

Fuel-injection system	Application	Fuel injection				Engine-related data			
Type	P Passenger cars and light trucks N Comm. vehs. & buses O Off-Highway [1] S Ships/Locomotives	Injected fuel quantity per stroke mm^3	Max. permissible nozzle pressure bar (0.1 MPa)	PI Pilot injection POI Post Injection	m Mechanical e Electronic em Electromechanical MV Solenoid valve	DI Direct injection IDI Indirect injection	No. of engine cylinders	Max. speed min^{-1}	Max. power per engine cylinder kW
In-line injection pumps									
M	P	60	550	–	m, e	IDI	4...6	5000	20
A	O	120	750	–	m	DI/IDI	2...12	2800	27
MW	P, O	150	1100	–	m	DI	4...8	2600	36
P3000	N, O	250	950	–	m, e	DI	4...12	2600	45
P7100	N, O	250	1200	–	m, e	DI	4...12	2500	55
P8000	N, O	250	1300	–	m, e	DI	6...12	2500	55
P8500	N, O	250	1300	–	m, e	DI	4...12	2500	55
H1	N	240	1300	–	e	DI	6...8	2400	55
H1000	N	250	1350	–	e	DI	5...8	2200	70
ZWM	S	900	850	–	m	DI/IDI	6...12	1500	150
CW	S	1500	1000	–	m	DI/IDI	6...10	1600	260
Axial-piston distributor pumps									
VE ... F	P	70	350	–	m	IDI	3...6	4800	25
VE ... F	P	70	1205	–	m	DI	4...6	4400	25
VE ... F	N, O	125	800	–	m	DI	4, 6	3800	30
VP37 (VE-EDC)	P	70	1250	–	em	DI	3...6	4400	25
VP37 (VE-EDC)	O	125	800	–	em	DI	4, 6	3800	30
VP30 (VE-M)	P	70	1400	PI	e, MV	DI	4...6	4500	25
VP30 (VE-M)	O	125	800	PI	e, MV	DI	4, 6	2600	30
Radial-piston distributor pumps									
VP44 (VR)	P	85	1850	PI	e, MV	DI	4, 6	4500	25
VP44 (VR)	N	175	1500	–	e, MV	DI	4, 6	3300	45
Single-plunger injection pumps									
PF(R)...	O	13... 120	450... 1150	–	m, em	DI/IDI	Arbitrary	4000	4... 30
PF(R)... Large diesel engines	P, N, O, S	150... 18000	800... 1500	–	m, em	DI/IDI	Arbitrary	300... 2000	75... 1000
UIS P1	P	60	2050	PI	e, MV	DI	5[2, 2a]	4800	25
UIS 30	N	160	1600	–	e, MV	DI	8[2]	4000	35
UIS 31	N	300	1600	–	e, MV	DI	8[2]	2400	75
UIS 32	N	400	1800	–	e, MV	DI	8[2]	2400	80
UPS 12	N	180	1600	–	e, MV	DI	8[2]	2400	35
UPS 20	N	250	1800	–	e, MV	DI	8[2]	3000	80
UPS (PF[R])	S	3000	1600	–	e, MV	DI	6...20	1500	500
Common Rail accumulator injection system									
CR[3]	P	100	1350	–	PI, POI[4]	DI	3...8	4800[5]	30
CR[6]	P	100	1600	–	PI, POI[7]	DI	3...8	5200	30
CR	N, S	400	1400	–	PI, POI[8]	DI	6...16	2800	200

Table 1

1 Stationary engines, building and construction machines, agricultural and forestry machines

2 With two ECUs, larger numbers of cylinders are possible

2a As from EDC16: 6 cylinders

3 1st generation

4 Pilot injection (PI) up to 90° cks before TDC; post injection (POI) possible

5 Up to 5,500 min^{-1} during overrun

6 2nd generation

7 Pilot injection (PI) possible up to 90° cks before TDC; post injection (POI) up to 210° after TDC

8 Pilot injection (PI) up to 30° cks before TDC; post injection (POI) possible

Injection-pump designs

The diesel engine's injection system has the task of injecting the diesel fuel into the engine's cylinders at very high pressure, in the correct quantities, and at exactly the right instant in time.

Depending upon the particular combustion process, the nozzle extends into either the main or the auxilary combustion chamber. It opens at a fuel pressure which is specific to the particular injection system, and closes as soon as the pressure drops again. The major difference between the various injection systems is to be found in the high-pressure generation process.

The very high injection pressures involved necessitate the precision manufacture of all the injection components from high-tensile materials. All components must be exactly matched to each other.

Electronic closed-loop control functions enable the inclusion of numerous auxiliary functions (for instance, active surge damping, Cruise Control, and boost-pressure control).

In-line injection pumps

PE standard in-line injection pumps

The standard PE in-line injection pumps (Figure 1) have a plunger-and-barrel assembly for each engine cylinder. As the name implies, this comprises the pump barrel (1) and the corresponding pump plunger (4). The pump camshaft (7) is integrated in the pump and driven by the engine, and forces the pump plunger in the delivery direction (in this case upwards). The plunger is returned by its spring (5). The individual plunger-and-barrel assemblies (also known as pumping elements) are normally arranged in-line, and plunger lift is invariable.

During the plunger's upward travel, high-pressure generation starts when the inlet port (2) is closed by the plunger's top edge. This instant in time is termed the start of delivery. The plunger continues to move beyond this point and in doing so increases the fuel pressure to such an extent that the nozzle opens and fuel is injected into the engine cylinder.

A helix has been mechanically machined into the plunger, and as soon as it opens the inlet port the fuel pressure collapses, the nozzle needle closes and injection stops.

1 In-line fuel-injection pump: Principle of functioning

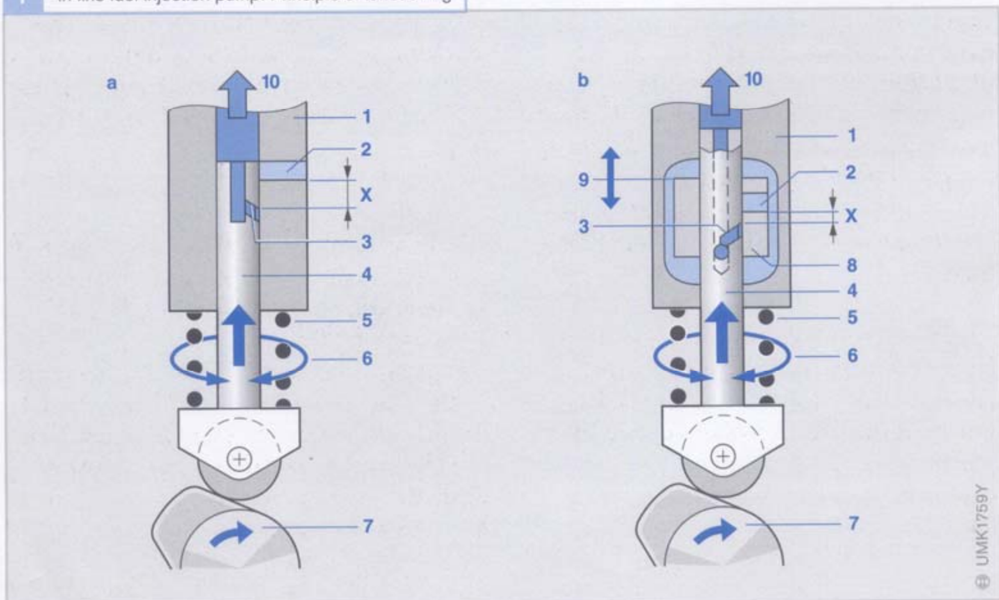


Figure 1
- a PE standard in-line injection pump
- b Control-sleeve in-line injection pump
- 1 Pump barrel
- 2 Inlet port
- 3 Helix
- 4 Pump plunger
- 5 Plunger return spring
- 6 Rotational travel due to action of control rack (injected fuel quantity)
- 7 Camshaft
- 8 Control sleeve
- 9 Adjustment travel due to actuating shaft (start of fuel delivery)
- 10 Flow of fuel to the nozzle
- X Effective stroke

2 Port-and-helix-controlled axial-piston distributor pump: Principle of functioning

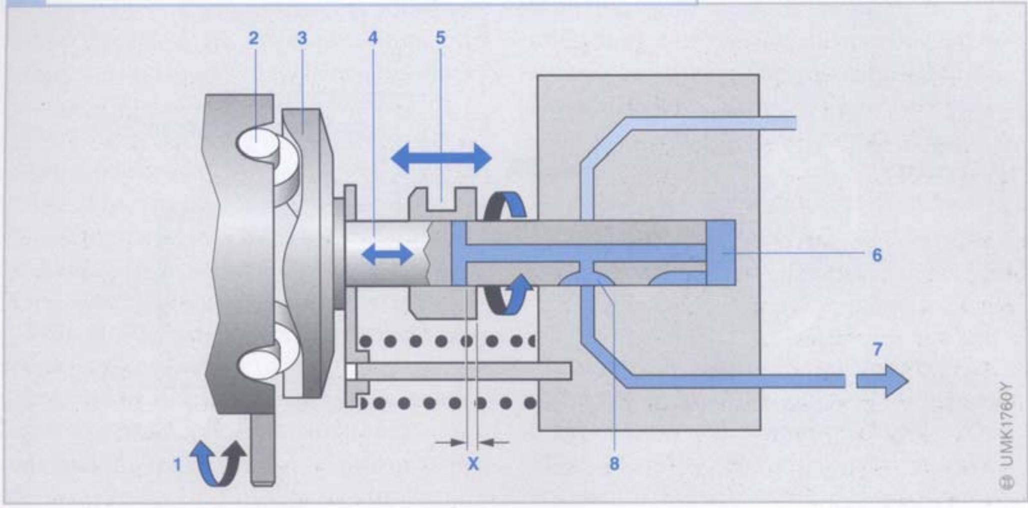


Figure 2
1 Timing-device travel on the roller ring
2 Roller
3 Cam plate
4 Axial piston
5 Control collar
6 High-pressure chamber
7 Fuel outlet to the injection nozzle
8 Metering slot
X Effective stroke

The plunger travel between the closing and opening of the inlet port is termed the effective stroke (X).

The pump is equipped with a control rack (6) which rotates the plunger so that the position of the helix relative to the inlet port is changed. This changes the plunger's effective stroke, and along with it the injected fuel quantity. The control rack is controlled by either a mechanical (flyweight) governor or an electrical actuator mechanism.

Control-sleeve in-line injection pump

The control-sleeve in-line injection pump differs from a conventional in-line injection pump by having a "control sleeve" (Figure 1, Pos. 8) which slides up and down the pump plunger. By way of an actuator shaft (Figure 1, Pos. 9), this varies the plunger lift to (inlet) port closing, and with it the start of injection.

Since the start of injection can be varied independent of engine speed, the control-sleeve version features an additional degree of freedom compared to the standard PE in-line injection pump.

Distributor injection pumps

The distributor pump has only one plunger-and-barrel asembly for all the engine's cylinders (Figures 2 and 3). A vane-type supply pump delivers fuel to the high-pressure chamber (6). High-pressure generation is the responsibility of either an axial piston (Figure 2, Pos. 4) or several radial pistons (Figure 3, Pos. 4). A rotating distributor plunger opens and closes the metering slots (8) and spill ports, and in the process distributes the fuel to the individual engine cylinders via the injection nozzles (7). The duration of injection (injection time) can be varied using a control collar (Figure 2, Pos. 5) or a high-pressure solenoid valve (Figure 3, Pos. 5).

Axial-piston distributor pump

The drive for the cam plate (Figure 2, Pos. 3) comes from the vehicle's engine. The number of cams on the underside of the cam plate corresponds to the number of engine cylinders. These cams ride on the rollers (2) of the roller ring with the result that a rotating-reciprocating movement is imparted to the plunger. For one revolution of the driveshaft, the piston performs as many strokes as there are engine cylinders.

3 Solenoid-valve-controlled radial-piston distributor pump: Principle of functioning

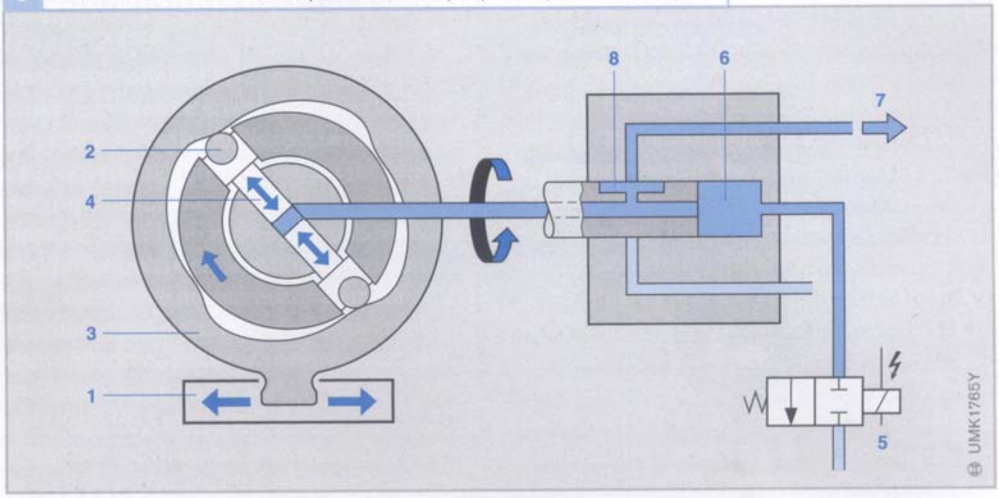


Figure 3
1 Timing device on roller ring
2 Roller
3 Cam ring
4 Radial piston
5 High-pressure solenoid valve
6 High-pressure chamber
7 Fuel outlet to the injection nozzle
8 Metering slot

On the port-and-helix-controlled VE axial-piston distributor pump with mechanical (flyweight) governor, or electronically controlled actuator, the control collar (5) defines the effective stroke and with it the injected fuel quantity.

The timing device adjusts the pump's start of delivery by rotating the roller ring (1).

Radial-piston distributor pumps

Here, instead of the cam plate as used on the axial-piston distributor pump, a radial-piston pump with cam ring (Figure 3, Pos. 3) and two to four radial pistons (4) is responsible for high-pressure generation. Higher pressures can be achieved with the radial-piston pump than with the axial-piston version, although this necessitates the pump having to be much stronger mechanically.

The cam ring is rotated by the timing device (1). On all radial-piston distributor pumps, start of injection and duration of injection (injection time) are solenoid-valve-controlled.

Solenoid-valve-controlled distributor pumps

On the solenoid-valve-controlled distributor pump, an electronically controlled high-pressure solenoid valve (5) is used to meter the injected fuel quantity and to change the start-of-injection point. With the solenoid valve closed, pressure can build up in the high-pressure chamber (6). Once the valve opens, fuel escapes so that there is no fuel-pressure buildup and no fuel is injected. The open and closed-loop control signals are generated in either one or two ECU's (pump ECU and engine ECU, or only in the pump ECU).

Single-plunger injection pumps

PF single-plunger pumps

PF single-plunger pumps are used principally for small engines, diesel locomotives, marine engines, and construction machinery. Single-plunger pumps are also suitable for operation with viscous heavy oils.

Although these pumps have no camshaft of their own (the F in their designation stands for external drive) their basic operating concept corresponds to that of the PE in-line pumps. The cams for actuating the individual PF single-plunger injection pumps are on the engine camshaft. When used with large engines, the mechanical-hydraulic governor, or the electronic controller, is attached directly to the engine block. The fuel-quantity adjustment as defined by the governor (or controller) is transferred by a rack integrated in the engine. The cams for actuating the individual PF single-plunger pumps are on the engine camshaft, and this means that injection timing cannot be implemented by rotating the camshaft. When used with large engines, the mechanical-hydraulic governor, or the electronic controller, is attached directly to the engine block. The fuel-quantity adjustment as defined by the governor (or controller) is transferred by a rack integrated in the engine. Due to the direct connection to the engine's camshaft, this cannot be turned to implement injection timing. Instead, injection timing takes place by adjusting an intermediate element, whereby an advance angle of several angular degrees can be obtained. Adjustment is also possible using solenoid valves.

Unit-Injector System (UIS)

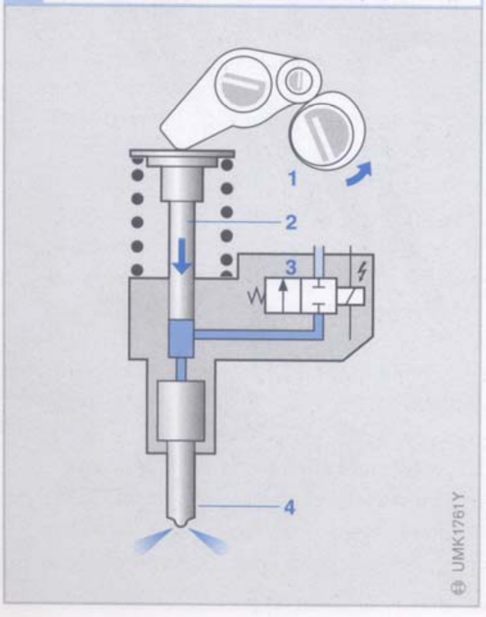
In the Unit Injector System (UIS), injection pump and injection nozzle form a single unit (Fig. 4). One of these units is installed in the engine's cylinder head for each engine cylinder, and driven directly by tappet or indirectly from the engine camshaft through a valve lifter. Compared with the in-line and distributor injection pumps, considerably higher injection pressures (up to 2050 bar) have become possible due to the omission of high-pressure lines. The fuel-injection parameters are calculated by the ECU, and injection is controlled by opening and closing the high-pressure solenoid valve.

Unit-Pump System (UPS)

The modular Unit Pump System (UPS) uses the same operating concept as the UIS. In contrast to the UIS, pump and nozzle holder (2) are joined by a short high-pressure delivery line (3) precisely matched to the respective components. Separation of high-pressure-generation stage and nozzle holder simplifies installation at the engine. The UPS system features an injection unit for each cylinder comprised of pump, delivery line, and nozzle holder. The pump is driven from the engine's camshaft (6).

On the UPS too, injection duration and start of injection are controlled electronically by a high-speed high-pressure solenoid valve (4).

4 High-pressure components of the Unit Injector System (UIS): Principle of functioning



5 High-pressure components of the Unit Pump System (UPS): Principle of functioning

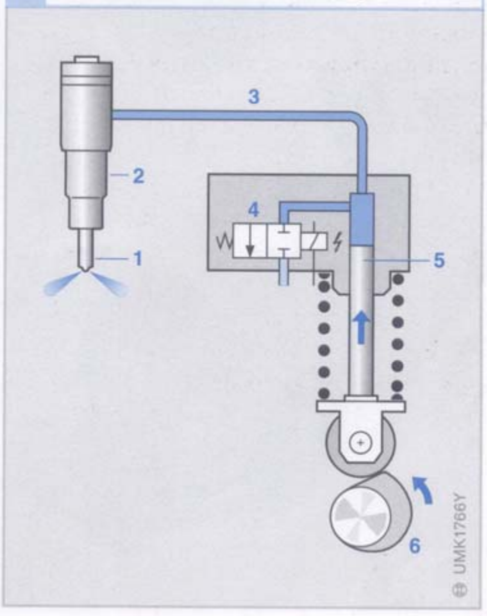


Figure 4
1 Actuating cam
2 Pump plunger
3 High-pressure solenoid valve
4 Injection nozzle

Figure 5
1 Injection nozzle
2 Nozzle holder
3 High-pressure line
4 High-pressure solenoid valve
5 Pump plunger
6 Actuating cam

Accumulator injection system

Common-Rail System CRS

In this system the processes of pressure generation and fuel injection are decoupled from each other (Figure 6). Injection pressure is generated and controlled by a high-pressure pump (1), and is for the most part independent of engine speed and injected fuel quantity. It is permanently available in the "rail" (fuel accumulator, 2) for injection.

The CRS thus provides maximum flexibility in the injection-process design.

Each engine cylinder is provided with an injector (4) which forms the injection unit. Opening and closing the high-pressure solenoid valve (3) controls the injection process. The instant of injection and the injected fuel quantity are calculated in the ECU.

6 High-pressure components of the Common Rail System (CRS): Principle of functioning

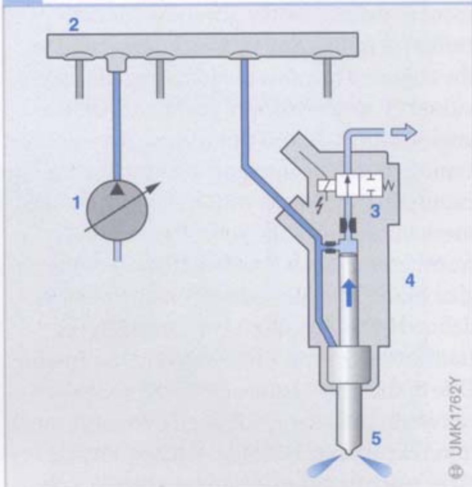


Figure 6
1 High-pressure pump
2 Rail (high-pressure fuel accumulator)
3 High-pressure solenoid valve
4 Injector
5 Injection nozzle

7 Examples of the high-pressure components as used in Bosch diesel injection systems

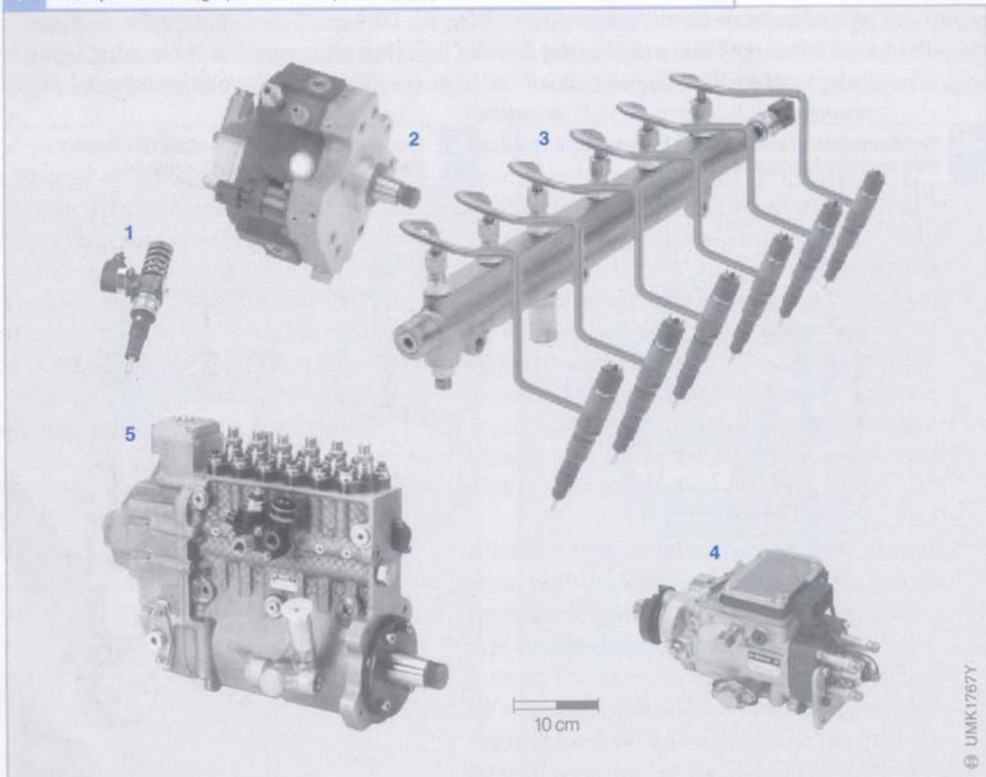


Figure 7
1 P1 Unit Injector (passenger cars)
2 CP2 Common Rail high-pressure pump (commercial vehicles)
3 Rail with injectors (commercial-vehicle CRS)
4 VP30 distributor pump (passenger cars)
5 RP39 control-sleeve in-line pump (commercial vehicles)

A brief history of diesel injection

Bosch started at the end of 1922 with the development of a fuel-injection system for diesel engines. All technical factors were favorable: Bosch had experience with internal-combustion engines, production engineering was highly developed, and above all it was possible to apply the know-how that Bosch had accumulated in the manufacture of lubrication pumps. Notwithstanding these facts, for Bosch there was considerable risk involved in this development work, and numerous challenges had to be surmounted.

The first injection pumps went into series production in 1927. At that time, the precision achieved in their manufacture was absolutely unique. They were small and of lightweight design, and were behind the diesel engine now being able to run at high speeds. These in-line pumps were installed as from 1932 in commercial vehicles, and as from 1936 in passenger cars. From this point onwards, there was not letup in the development of the diesel-engine and its injection equipment.

In 1976, the diesel engine was given a new lease of life when Bosch introduced the distributor injection pump with automatic timing device. And a decade later, after years of intensive development work to bring it to the volume-production stage, Bosch brought the Electronic Diesel Control (EDC) onto the market.

Development engineers are constantly faced with the need for the even more precise injection of minute quantities of diesel fuel, at exactly the right instant in time, and under higher and higher injection pressures. This has led to a number of innovative injection-system developments (see adjacent Figure).

The diesel engine is still at the forefront regarding fuel economy and efficient utilization of fuel.

New injection systems make even better use of this potential. In addition, the internal-combustion engine's power output is continuously increasing, while its noise and emissions figures have continued to drop.

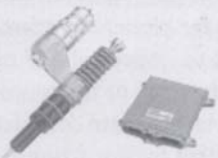
Milestones in diesel injection technology

1927
First series-production in-line pump

1962
First axial-piston distributor pump, the EP-VM

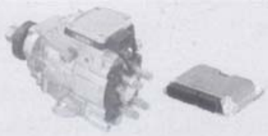
1986
The first electronically controlled axial-piston distributor pump

1994
First Unit Injector System (UIS) for commercial vehicles

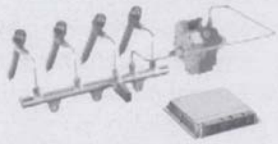


1995
First Unit Pump System (UPS)

1996
First radial-piston distributor pump



1997
First Common Rail accumulator injection system (CRS)



1998
First Unit Injector System (UIS) for passenger cars

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