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Fuel Injection Systems in Diesel and SI Engines

D.Sc. (Tech) Ossi Kaario

Motivation

- **Why learn about fuel injection systems ?**

- **Fuel injection and fuel injection systems play a fundamental role in defining the engine combustion, fuel consumption, and emissions**
  - **When**
  - **Dosing**
  - **Direction**
  - **Mixing**

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Fuel Injection Systems in Diesel Engines

The goals of fuel injection

- Get the correct amount of fuel to the combustion chamber at the right time and to the right place
- Evaporate the liquid fuel
- Mix the fuel vapor with oxygen to obtain good ignitable mixture

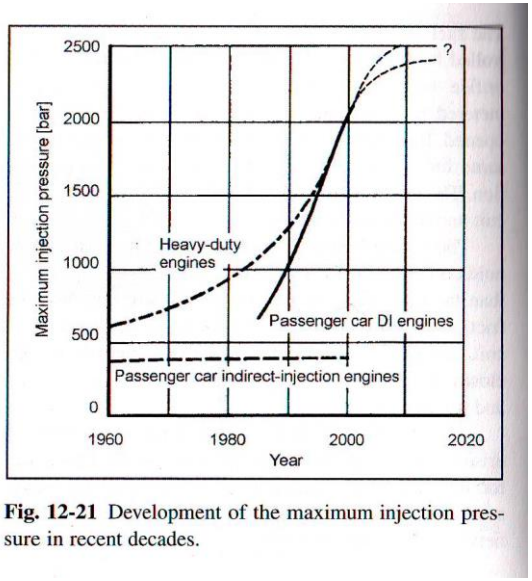
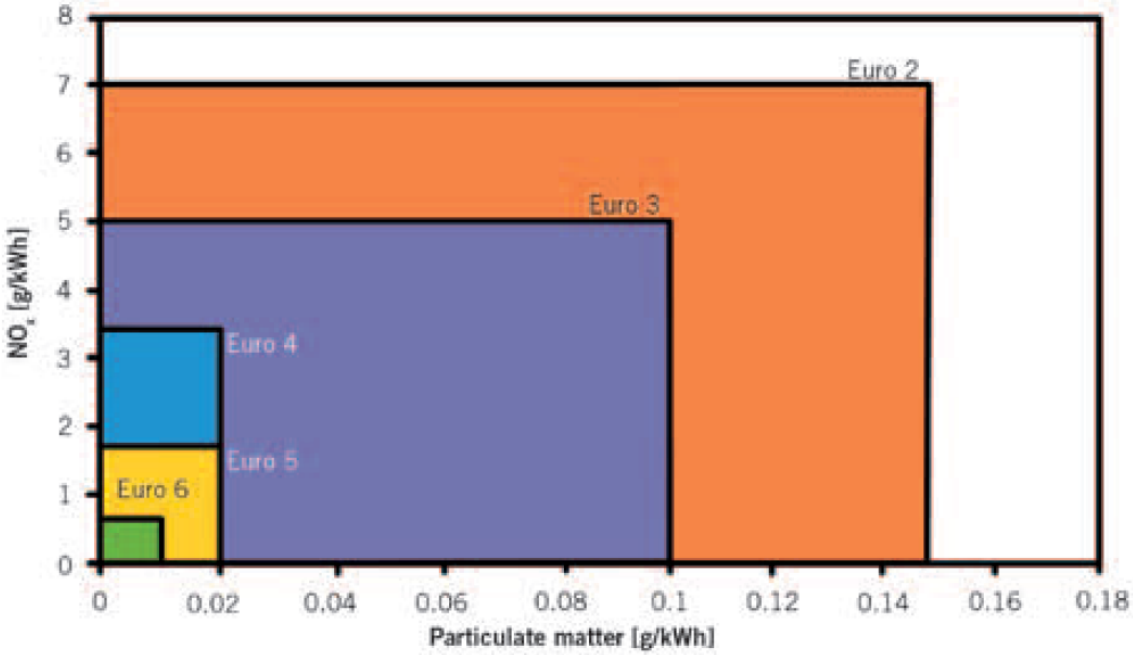


Fig. 12-21 Development of the maximum injection pressure in recent decades.

- In case the fuel injection is well achieved by the above criteria, the combustion process typically yields low fuel consumption, emissions and noice (→ no pressure peaks)

Emission regulations



EU PM- and NOx-emission limits for cars with diesel engine

Euro 6 will come into force 2015

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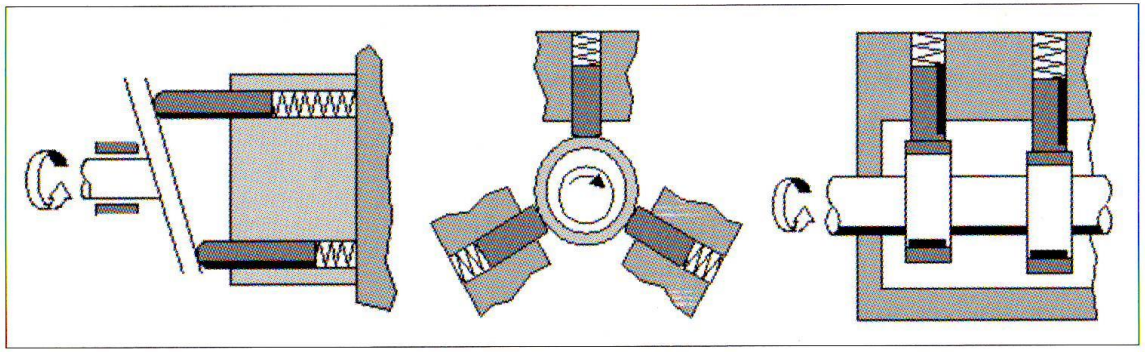
High pressure pump



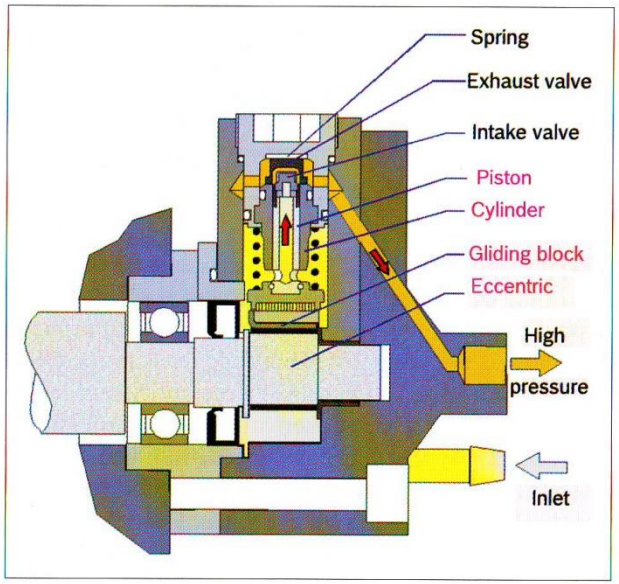
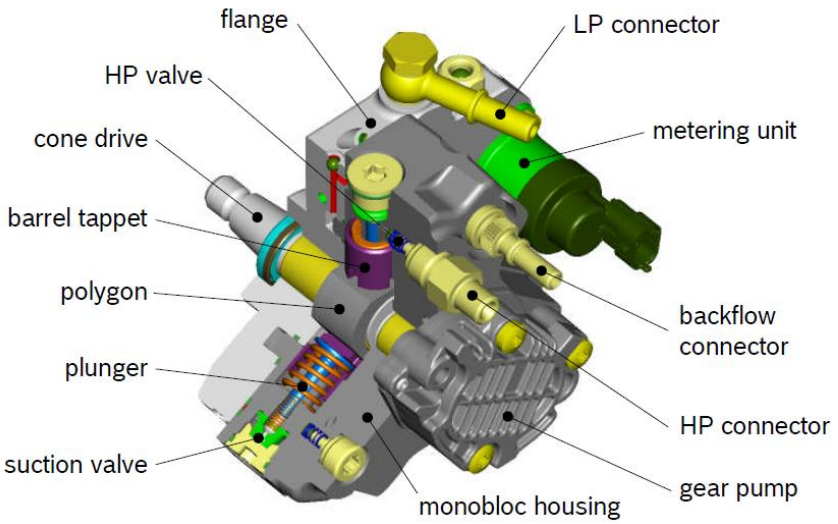


Figure 4.7: Basic designs of high pressure fuel pumps: axial piston pump (left); radial piston pump (center); in-line pump (right)

- **Volume flow ~ rotational speed**
- **Maximum pressure obtained already with relatively low rotational speed**
- **Control applied for the suction side**

Common Rail High Pressure Pump (RB CP3.2)



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Differerent combustion chamber types

Indirect fuel injection

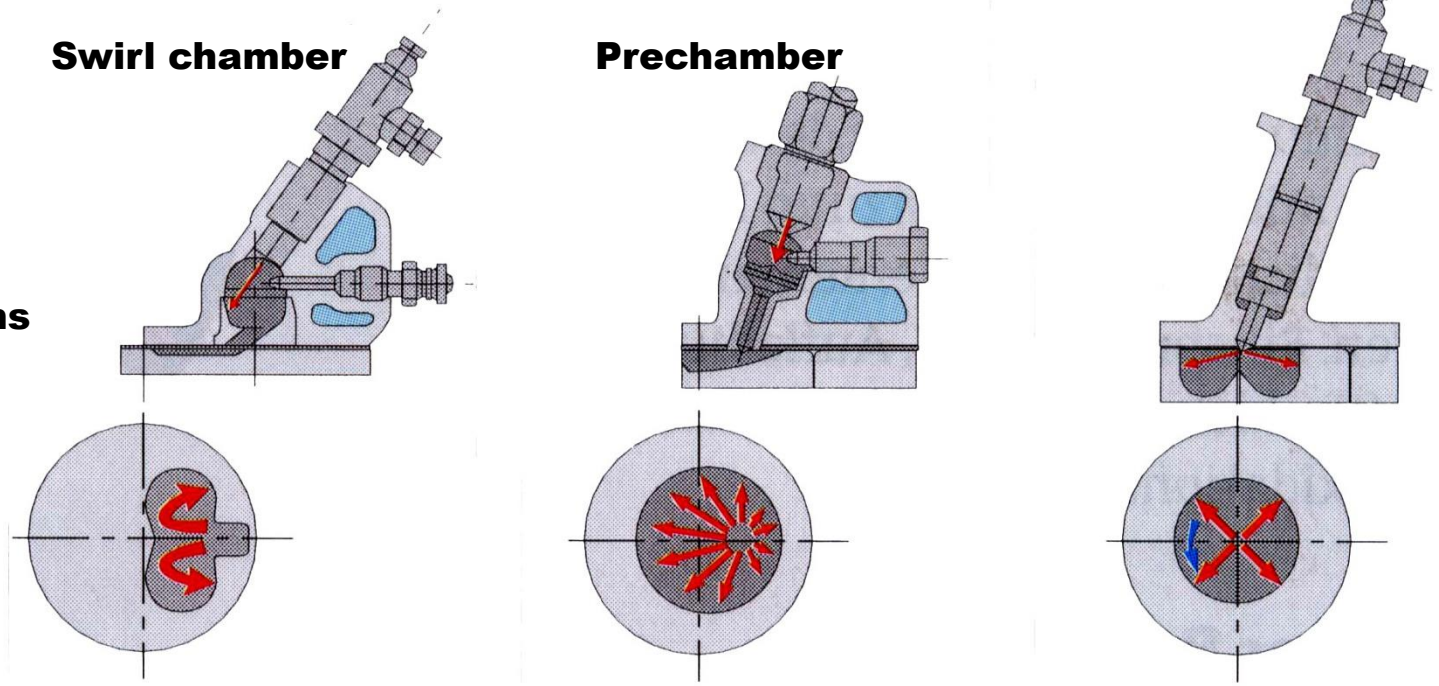
Direct fuel injection

Swirl chamber

Prechamber

Ricardo

-problems in heat transfer



Pictures: MTZ Sonderausgabe 10 Jahre TDI-Motor von Audi

Injection systems in Diesel engines

- Distributor systems
  - Axial piston distributor pump
  - Radial piston pump

- Unit pump systems
  - Pump units assembled in one unit: inline fuel injection pump
  - Separate pump units for every cylinder
  - United injector pump and nozzle, unit injector system and unit pump system

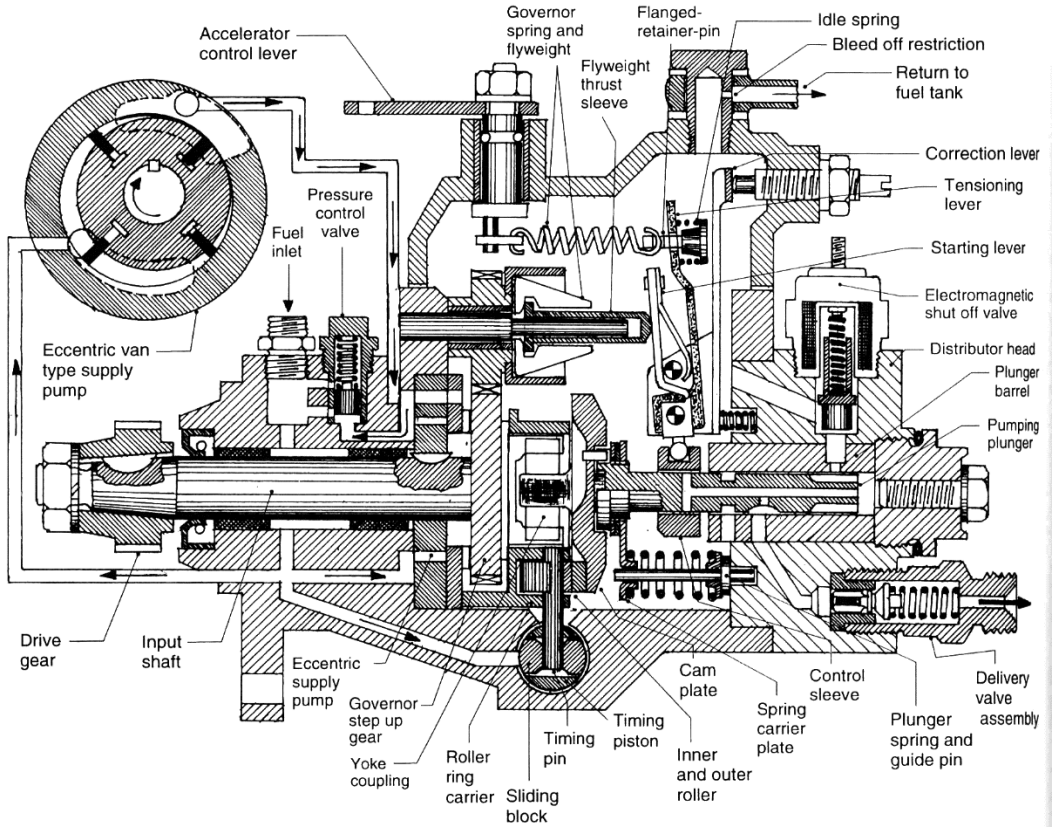
- Common Rail (accumulator) systems

Development

- 1927 Inline pump
- 1930 Diesel fuel filter
- 1962 Distributor pump
- 1986 EDC (Electronic Diesel Control)
- 1994 UIS (unit injector system)
- 1995 UPS (unit pump system)
- 1996 VR-radial piston pump (VP44)
- 1997 CRS (Common Rail System)
- 2001 CRS 2. generation
- 2003 CRS 3. generation (pietzo injector)

Distributor pump

- Only one pump unit for all cylinders
- Nowadays is more and more replaced by CR systems
- Previously used together with pre- and swirl chamber injection in all cars and boats



Inline pump (unit pump)

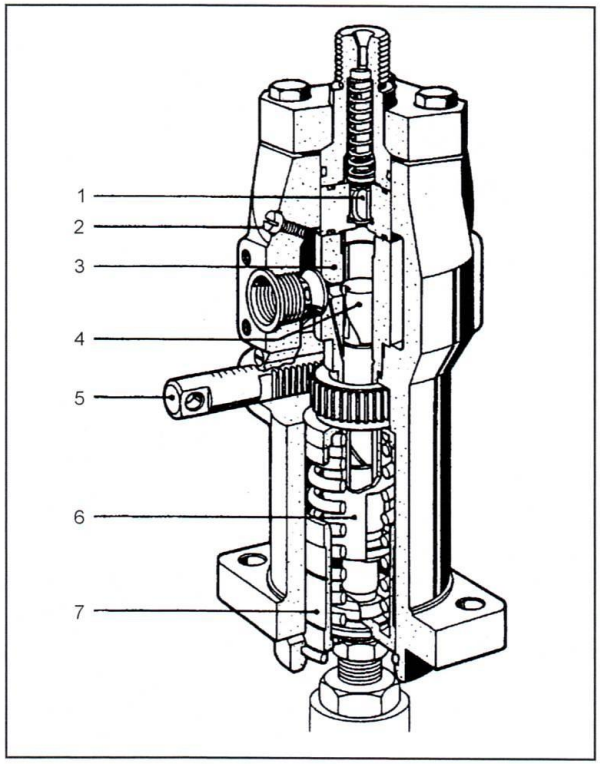


Fig. 12-29 Mechanically controlled single-plunger fuel injection, individual injection pump for large engines[6]: 1, Pressure valve; 2, Vent screw; 3, Pump cylinder; 4, Pump piston; 5, Control rack; 6, Control sleeve; 7, Guide bushing.

- **Separate pump unit for each cylinder**
- **Tractors and on the other hand power plant / ship engines**
- **In power plants called Unit pumps (although the principles are the same)**

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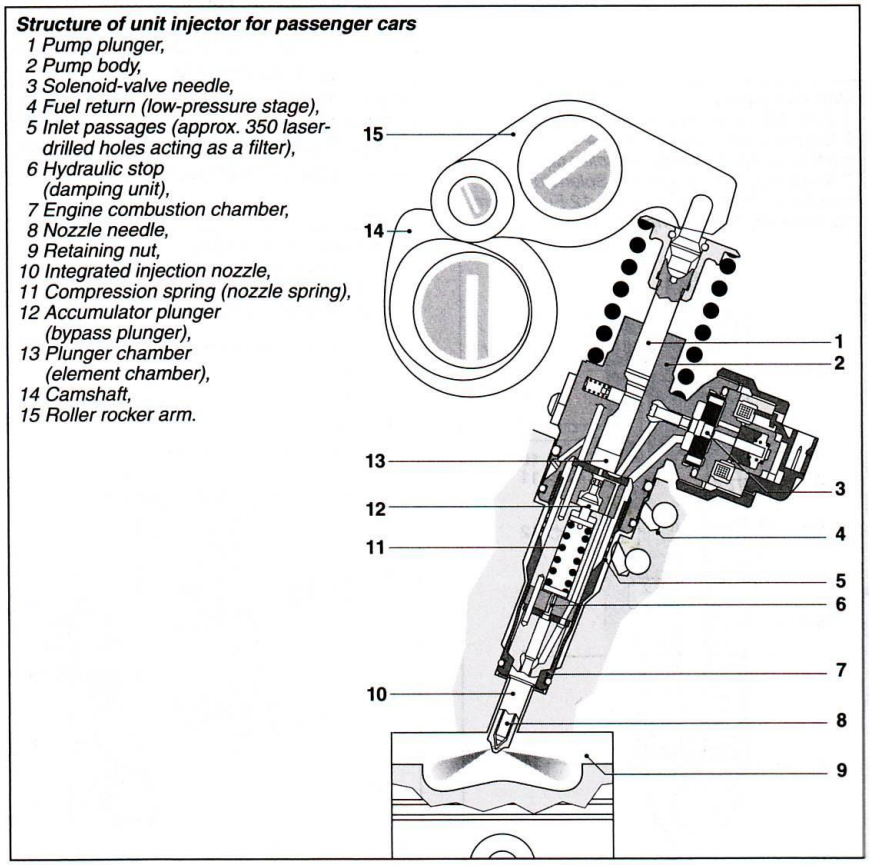
Unit Injector System (UIS)

- **High-pressure pump and nozzle are connected. No high-pressure pipe.**
- **Small volume to be pressurized → highest maximum pressures**
- **Used mainly in cars**



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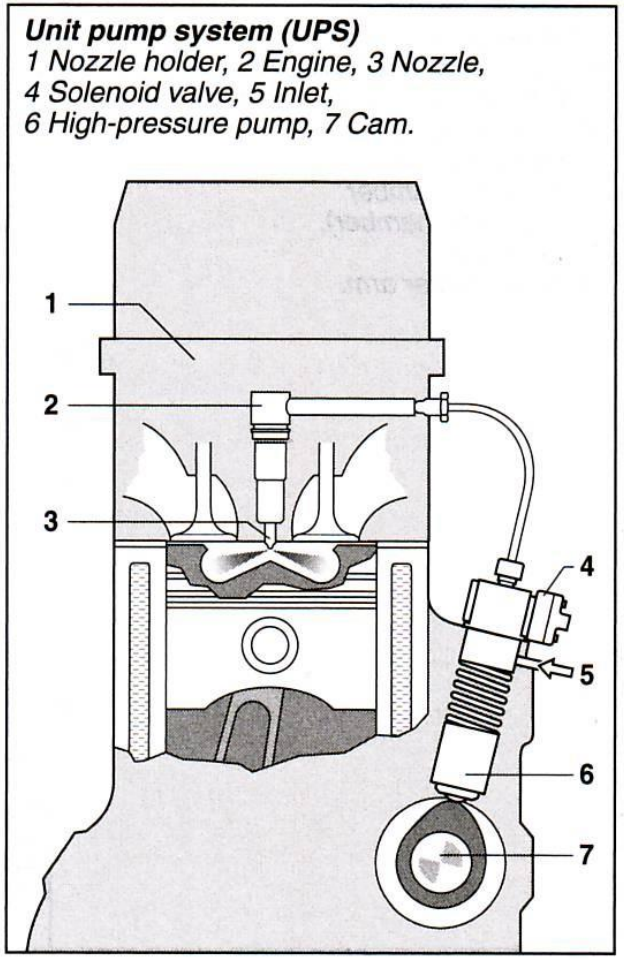
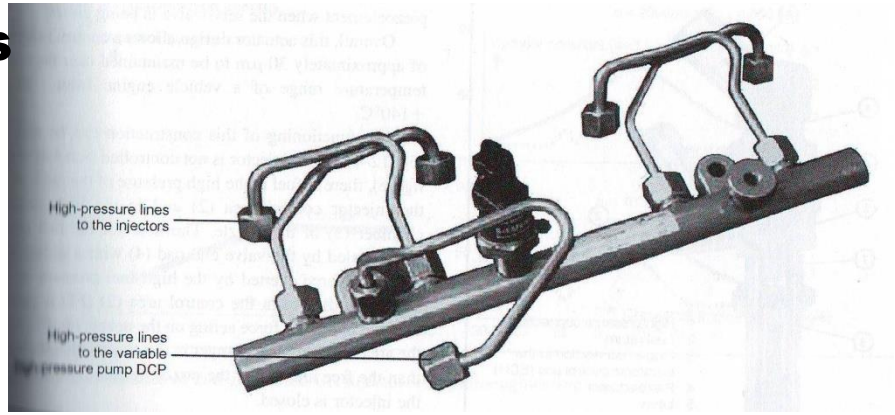
Unit Pump System (UPS)

- **Difference to the UIS system is the high-pressure pipe that allows more flexible location of the pump unit.**



Common Rail System

- Common pressure reservoir into which all the injector nozzles are connected. Pressure pipe is connected to the injector solenoid valve
- Typical injection pressure level 1200...2000 bar
- Pressure level can be freely chosen
- The start and ending of the fuel injection are independent of the cam shaft
- Pre- and post injections
- Used in cars and tractors
- More and more used in power plants and ships



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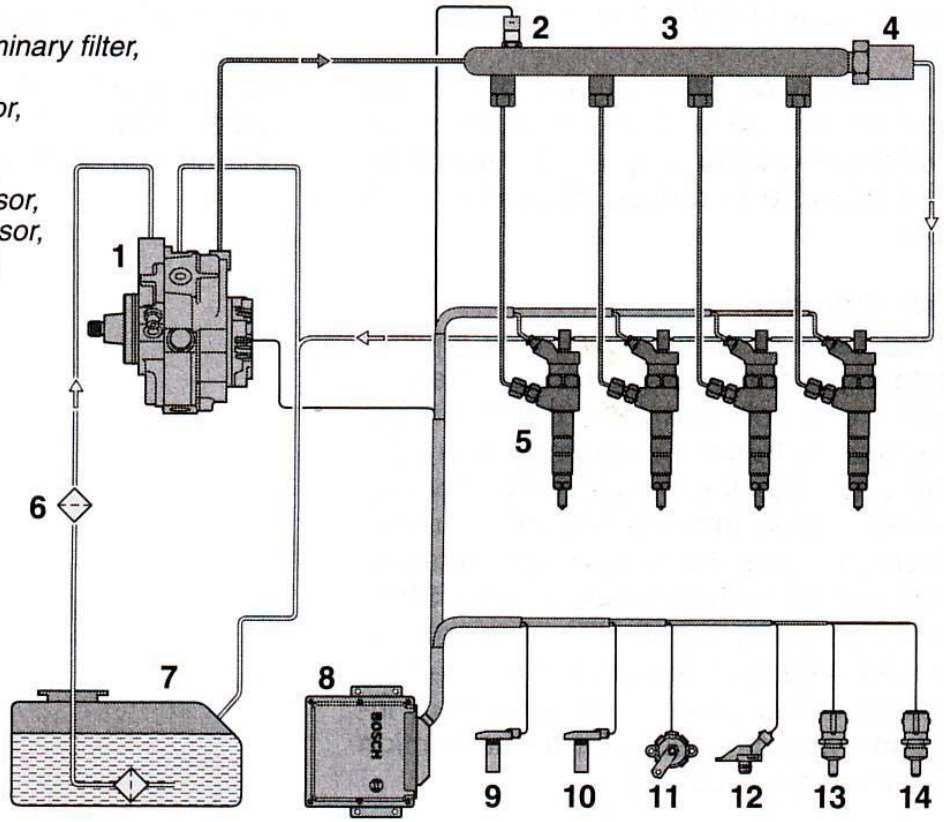
Common Rail System

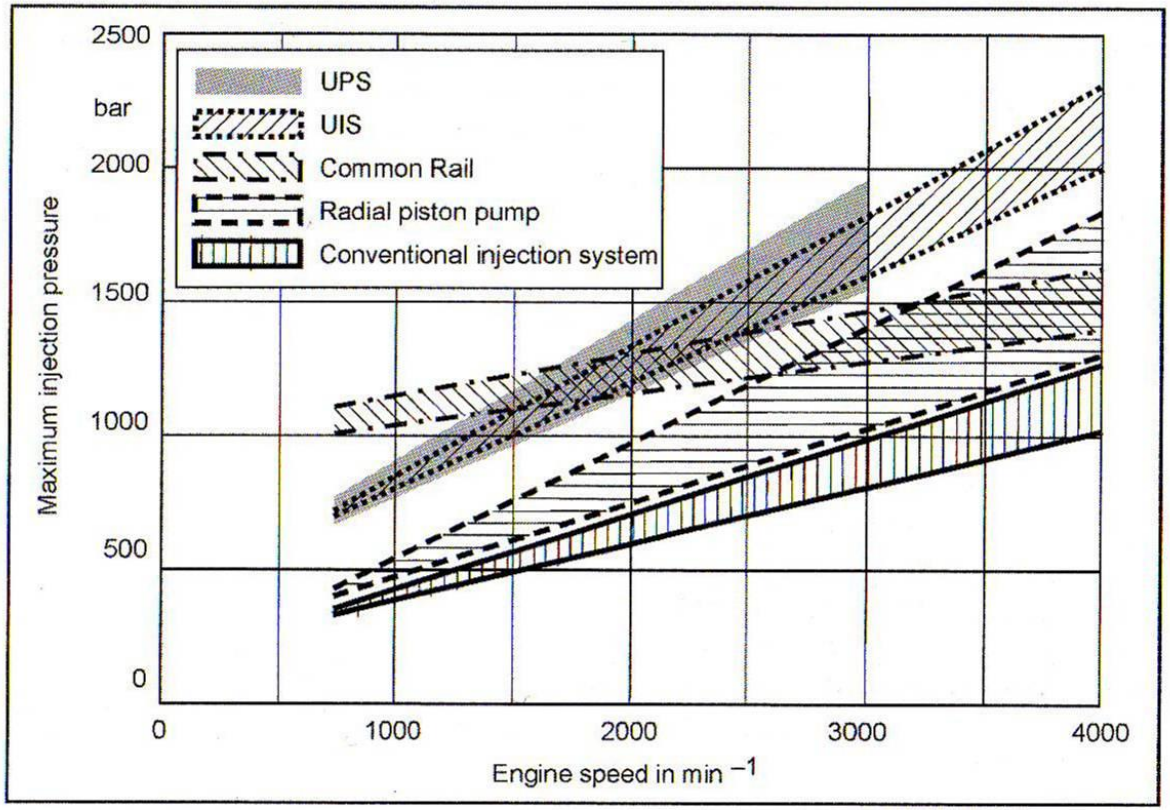
Common-rail system for passenger cars with delivery-controlled high-pressure pump

1 High-pressure pump CP3,
2 Rail-pressure sensor,
3 "Common Rail" fuel rail,
4 Pressure limiter,
5 Injectors,
6 Fuel filter,
7 Fuel tank with preliminary filter,
8 Control unit,
9 Engine-speed sensor,
10 Phase sensor,
11 Pedal-travel sensor,
12 Boost-pressure sensor,
13 Air-temperature sensor,
14 Engine-temperature sensor.



Pressure levels

- **UPS = Unit Pump System**
- **UIS = Unit Injector System (or Pump Nozzle Unit)**



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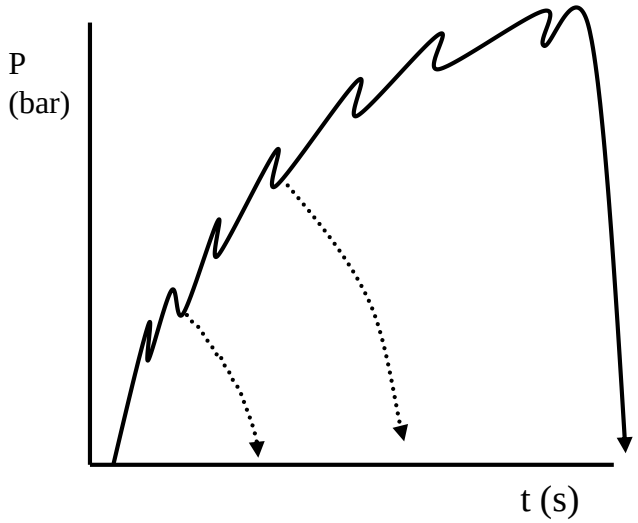
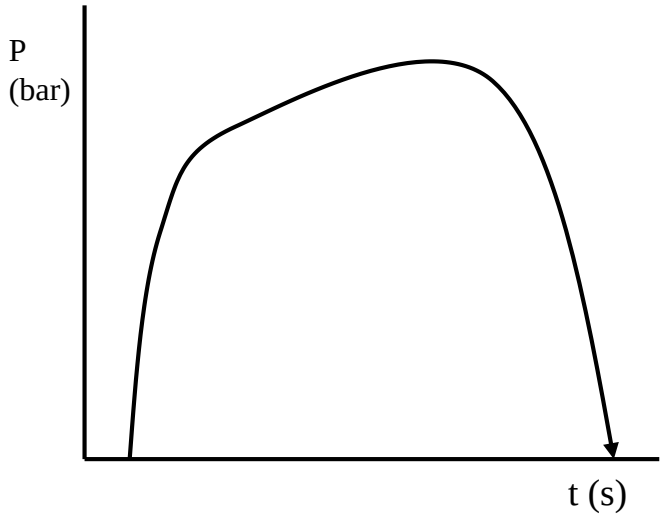
Comparing injection pressures



Traditional injection pressure (inline- or distributor pumps)



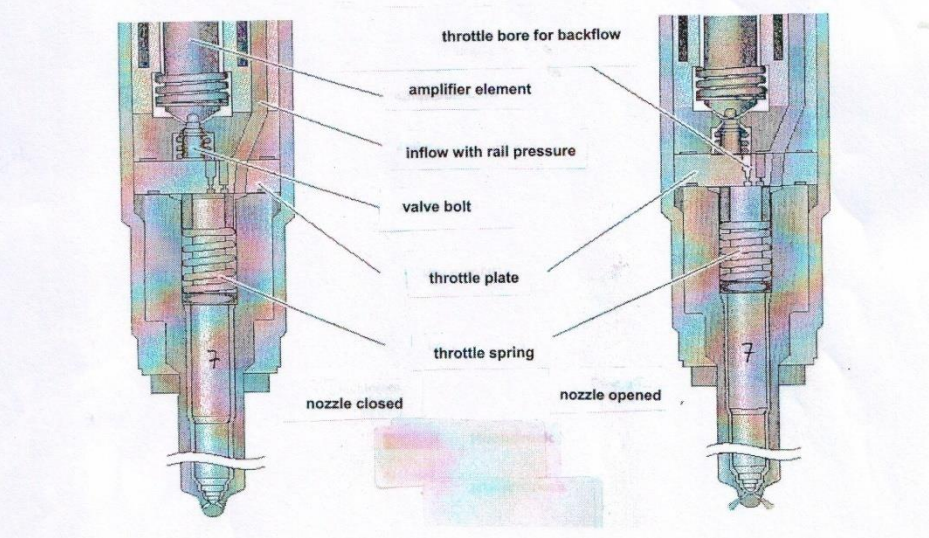
Common Rail injection

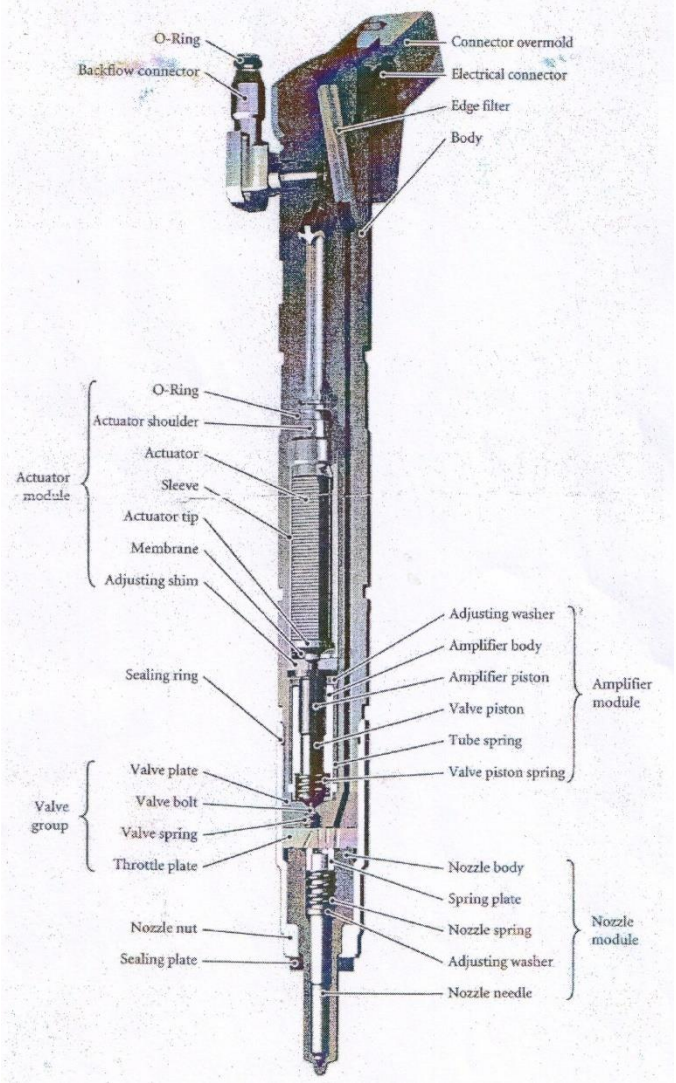
Injectors and Nozzles

- **The goal of the injector and nozzle is to inject the pressurized fuel so that fast droplet breakup and evaporation are achieved, and hence efficient combustion is achieved**
- **Terminology:**
  - **Injector = takes in high-pressure fuel. May be solenoid controlled. Nozzle is attached to the injector. Delivers fuel to the nozzle**
  - **Nozzle = is attached to injector. Distributes fuel into the combustion chamber. Has typically many holes for fuel exit**
  - **In Finnish:**
    - **Injector = suutinrunko, injektori**
    - **Nozzle = suutin, suutinkärki**

Working principle

- **Same pressure both on the top and bottom areas of the needle: needle does not move**
- **Injection starts: pressure decreases on top of the needle**
- **Needle raises because there is a pressure shoulder in the needle into which an upwards directed force is acting**





Working principle

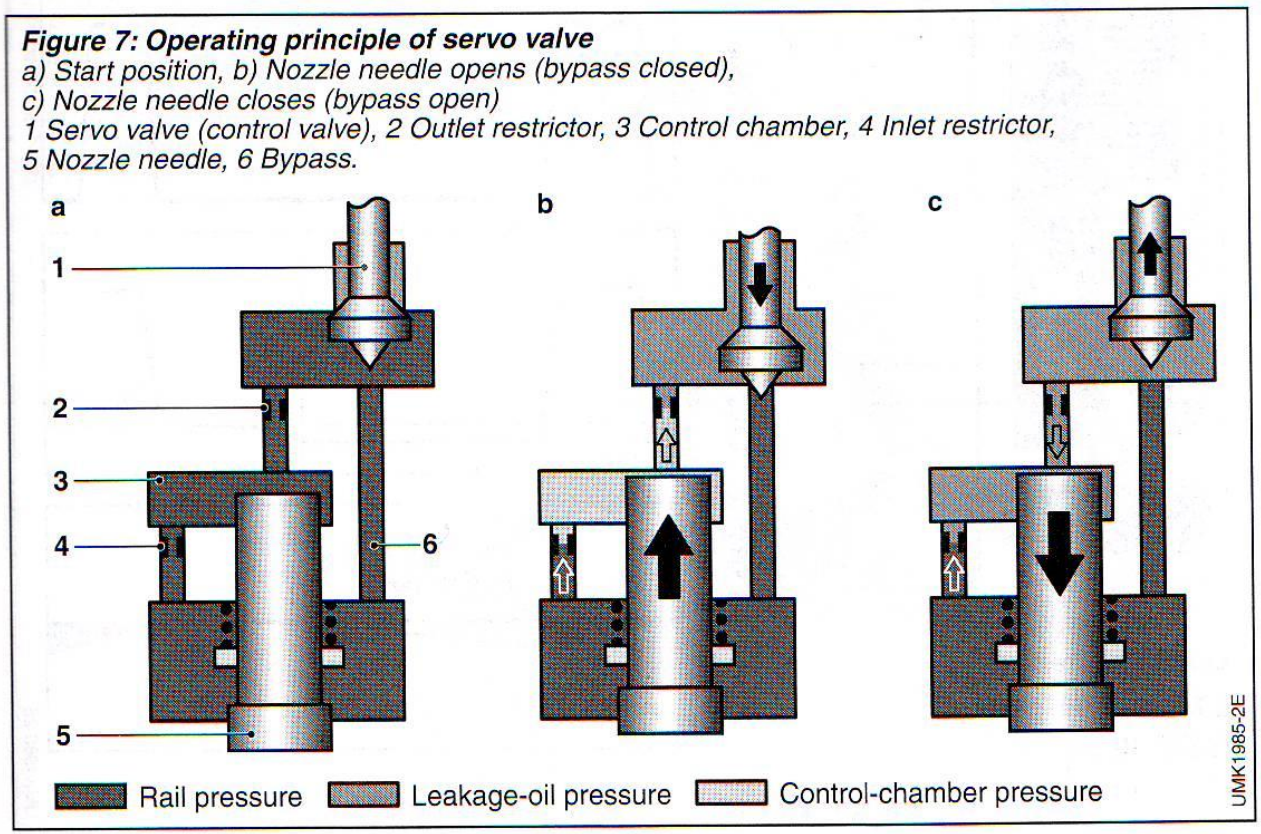
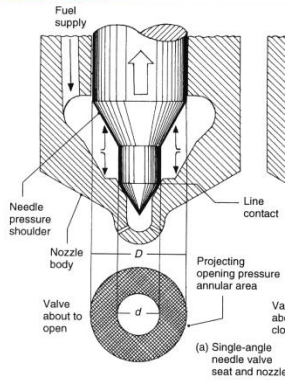


Figure 7: Operating principle of servo valve
a) Start position, b) Nozzle needle opens (bypass closed),
c) Nozzle needle closes (bypass open)
1 Servo valve (control valve), 2 Outlet restrictor, 3 Control chamber, 4 Inlet restrictor,
5 Nozzle needle, 6 Bypass.



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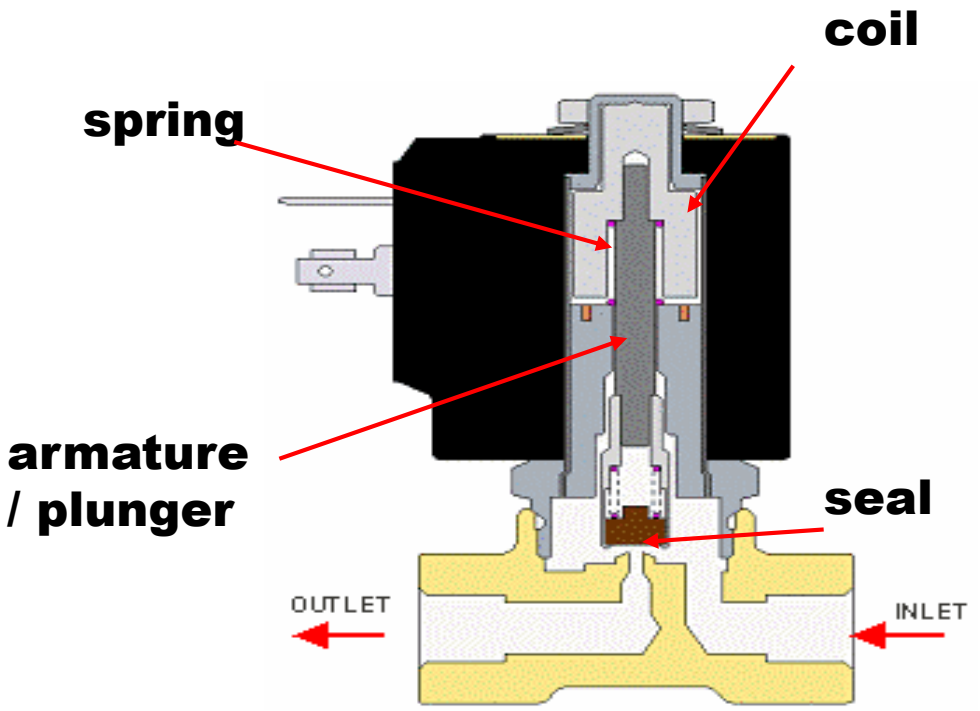
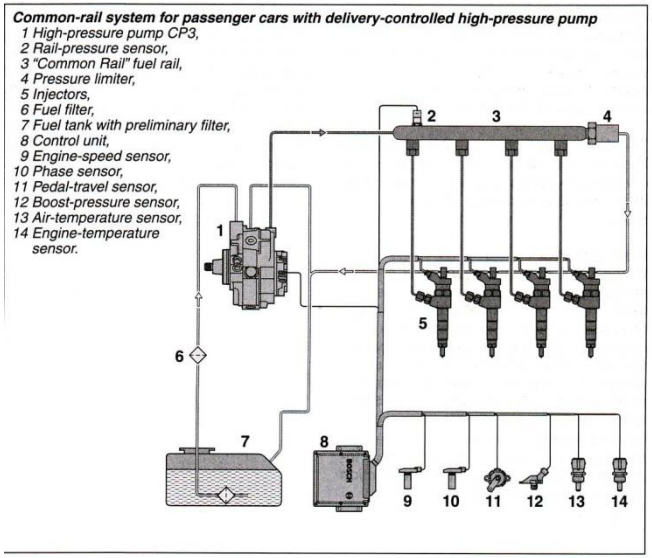
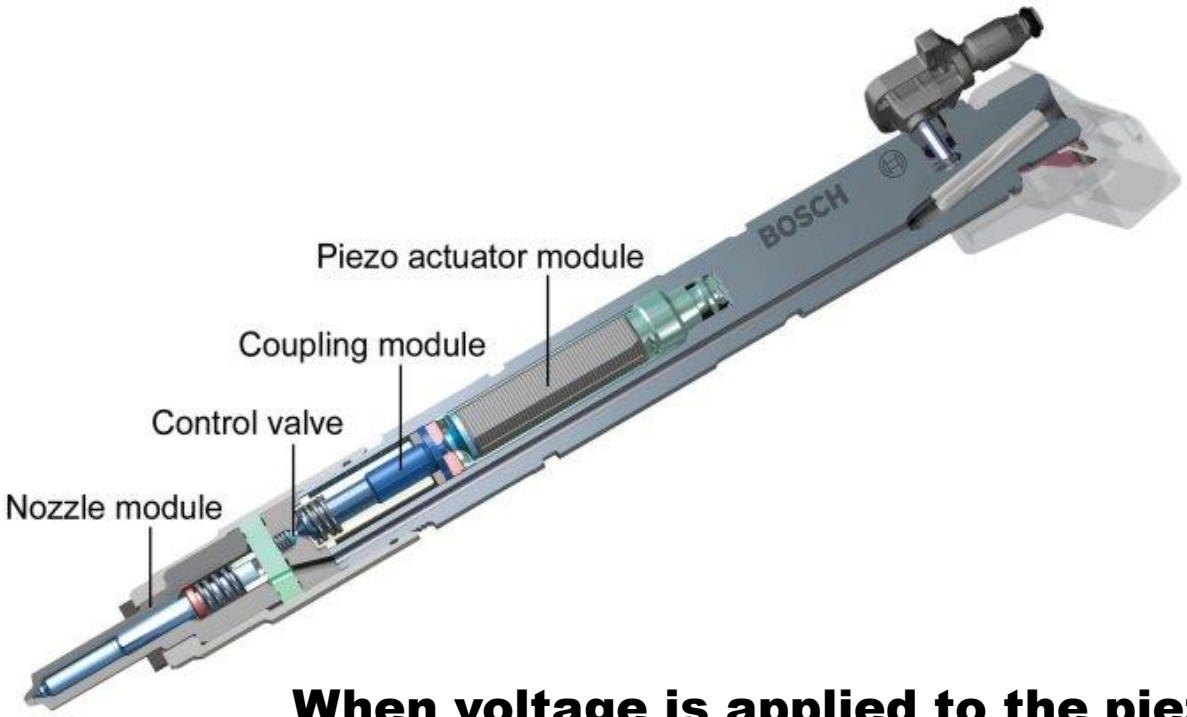
Solenoid valve

- **Used typically together with CR injection**





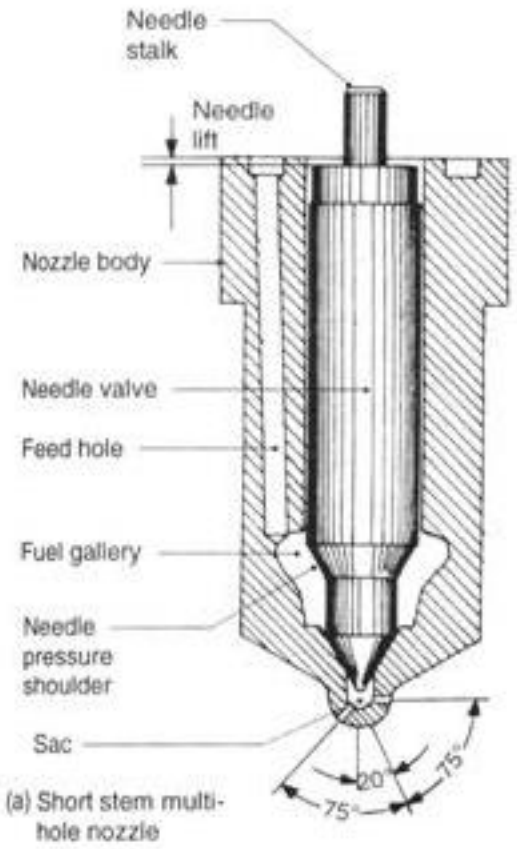
Piezo Injector valve

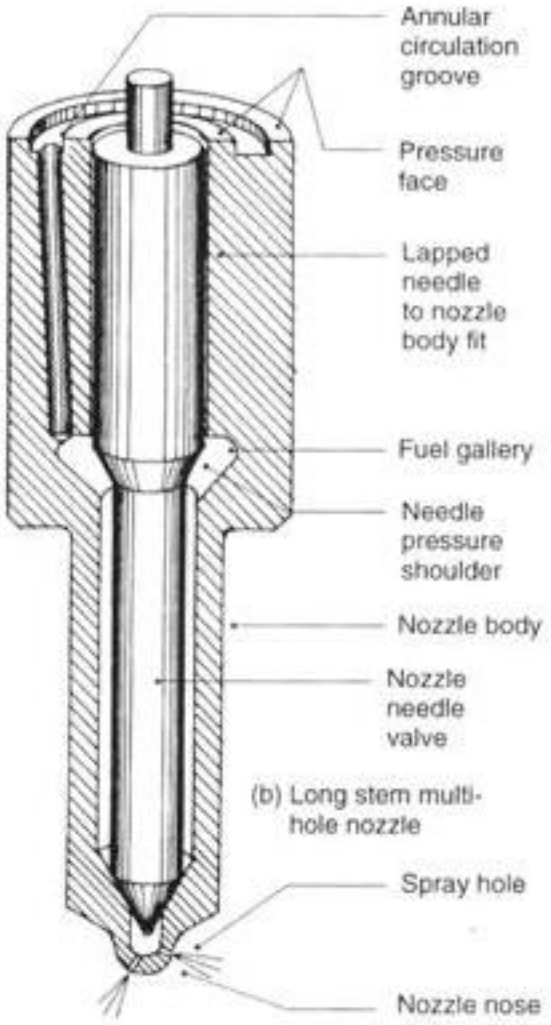


When voltage is applied to the piezo stack (actuator module), its size increases (~60μm). Piezo injectors are very fast (<100 micro-s), light, and consume low amount of energy.

Nozzles

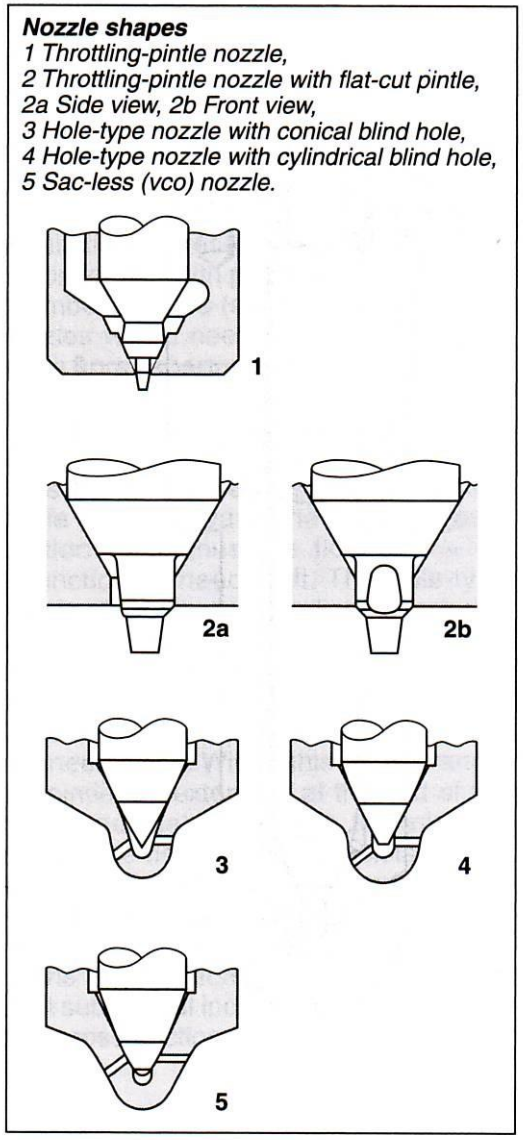
- **Nozzle delivers fuel to the combustion chamber and participates to the breakup of fuel into droplets**
- **Has great role in successfull combustion process**





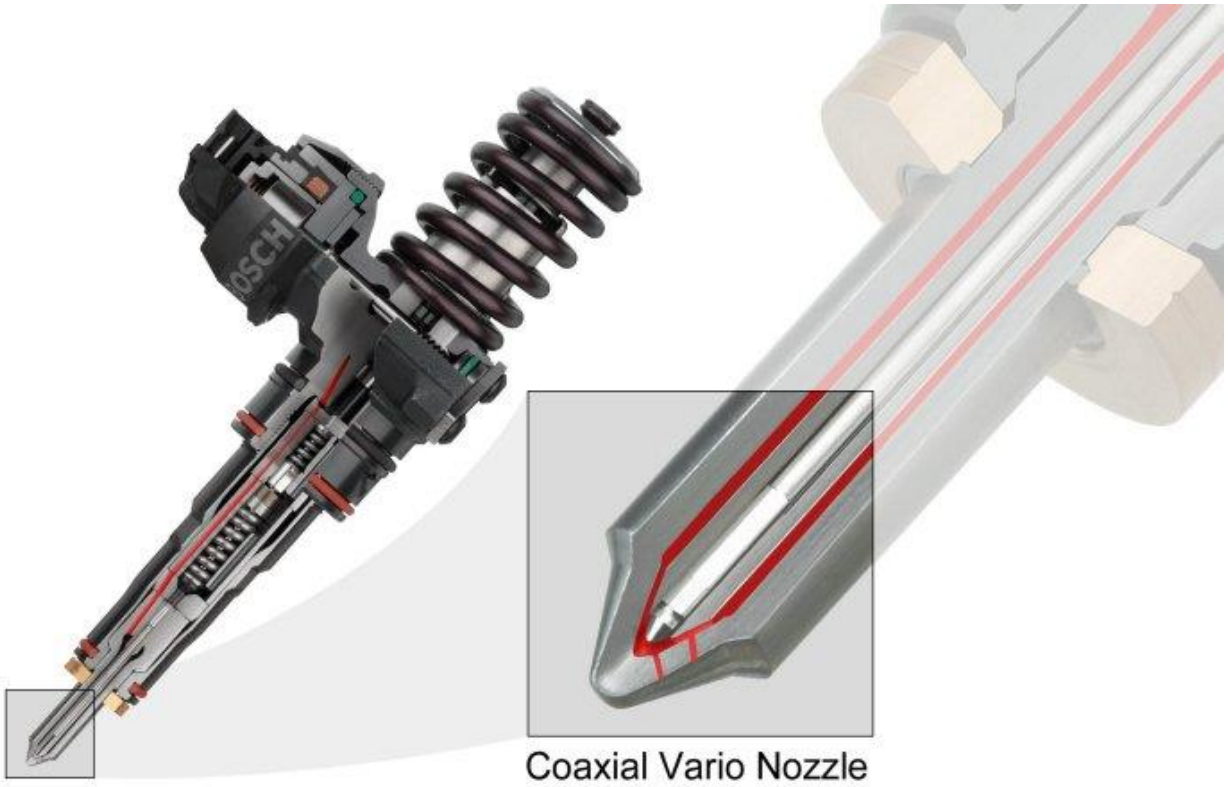
Nozzles

- **Pintle nozzles are mainly used in direct injection SI engines**



Duel nozzle diesel & water

Bosch



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Injection profiles

- **Influences engine fuel consumption, power, emissions, and noice**

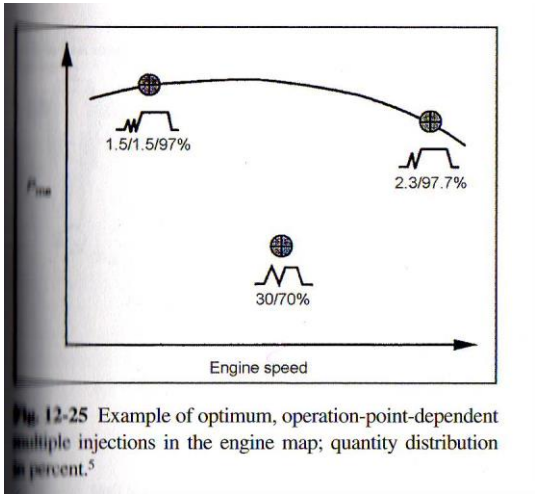
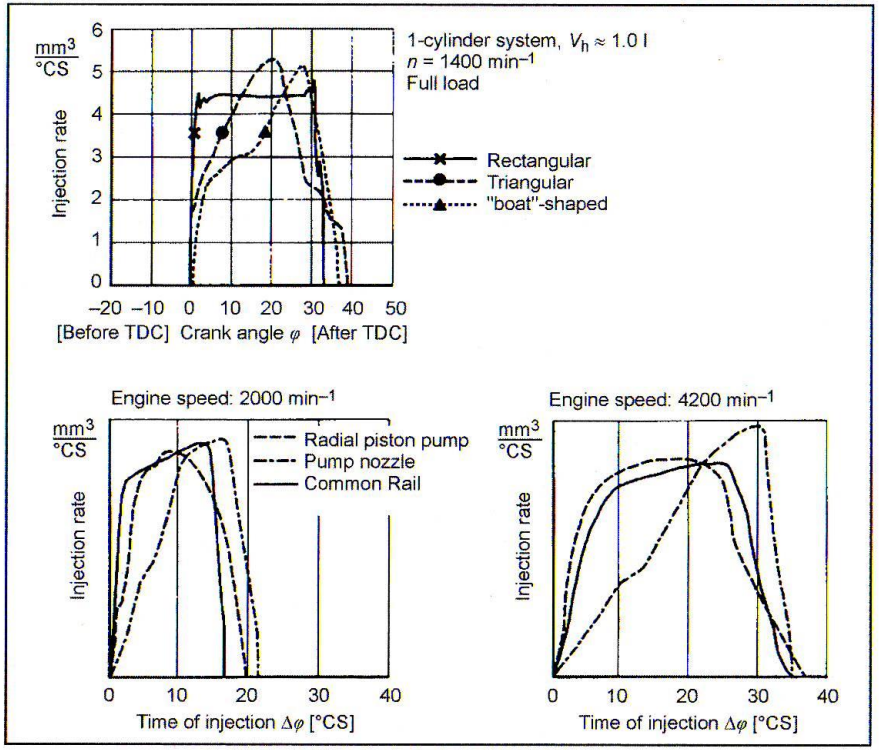
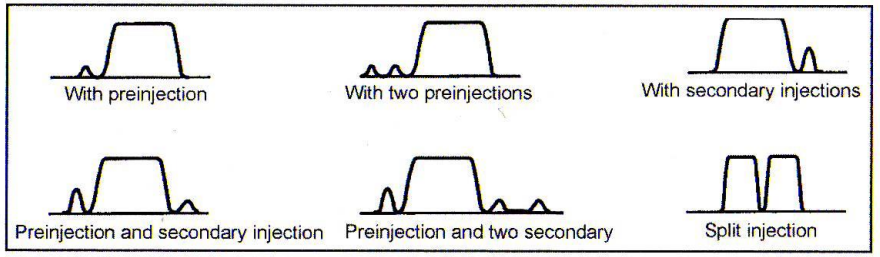


Fig. 12-25 Example of optimum, operation-point-dependent multiple injections in the engine map; quantity distribution in percent.[5]





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Calculating the theoretical fuel exit velocity form a nozzle

- **Theoretical fuel exit velocity from nozzle**

$$p_1 + \frac{1}{2}\rho\, u_1^{\,2} = p_2 + \frac{1}{2}\rho\, u_2^{2} \quad \Rightarrow \quad U_{Exit} = \sqrt{\frac{2\,\Delta P}{\rho_f}}$$

- **Velocity in practice**

$$U_{Exit} = C_v \sqrt{\frac{2\,\Delta P}{\rho_f}}$$

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Discharge coefficient Cd

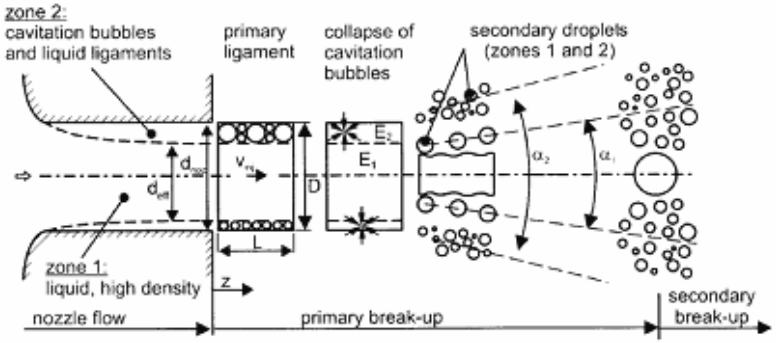
- **Discharge coefficient**

$$C_d = C_v \cdot C_a$$

C_d **used when calculating mass flow** $\dot{m} = C_d \, A \rho_f \sqrt{\frac{2\,\Delta P}{\rho_f}}$

C_v **'velocity coefficient', used when calculating real injection velocity**

C_a **'area contraction coefficient', used when calculating effective nozzle hole diameter**



Pumping power

- **The power needed to pressurize fuel**
- **Isentropic pumping power**

$$P_s = \dot{V}\left(P_2 - P_1\right)$$

- **Practical pumping power**

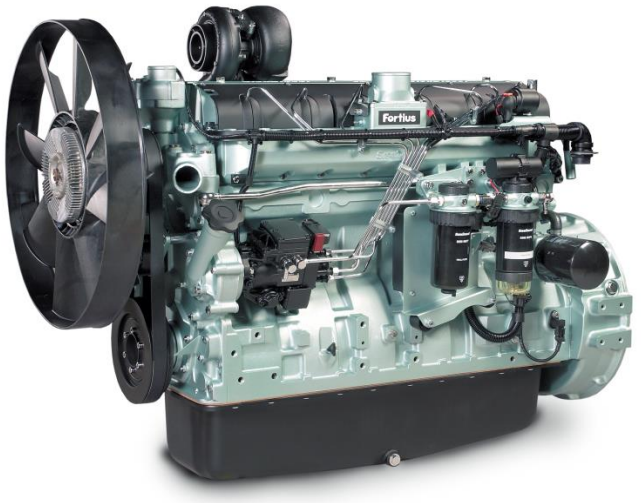
$$P_{tod} = \frac{P_s}{\eta_s}$$

η_s = **isentropic efficiency**

Comparing car and tractor diesel engines

- **BMW 123d**

- **Sisudiesel 66 ETA**



Engine comparison

	BMW 123d	Sisudiesel 66 ETA
⇨ Teho	150 kW / 4000 r/min	150 kW / 2200 r/min
⇨ Vääntömomentti	400 Nm / 2000 - 2250 r/min	850 Nm / 1200 - 1500 r/min
Sylinteriluku	4	6
Iskun pituus	90,0 mm	120 mm
Sylinterin halkaisija	84,0 mm	108 mm
⇨ Iskutilavuus	1998 cm^3	6600 cm^3
Ominaisteho	75.2 kW/l	22.7
Minimi ominaiskulutus	204 g/kWh	198 g/kWh
Puristussuhde	16,0	16,5
⇨ Massa	161 kg	510 kg
Mitat (pit. × lev. × kork.)	717 × 842 × 688 mm	1185 × 645 × 997 mm

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Fuel Injection Systems in Gasoline Engines

Kul-14.4700 Transport Biofuels, Combustion, and Emission Control

2014

Ossi Kaario

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Carburetor

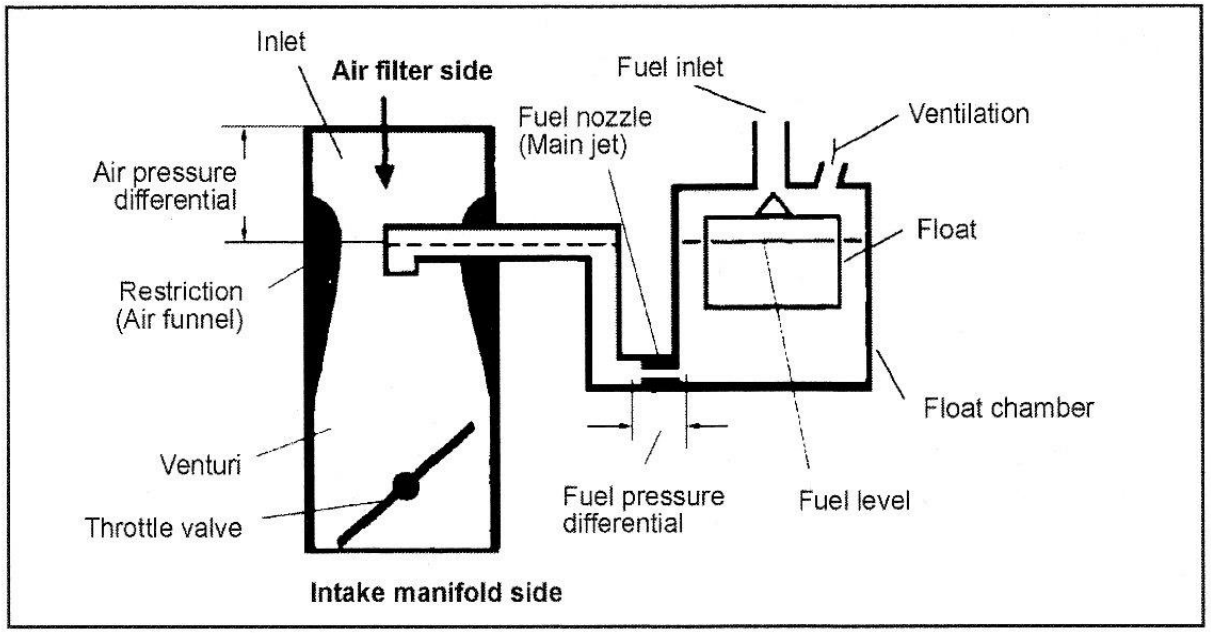

Fig. 12-1 Functional principle of the carburetor.

Bernoulli $$p_1 + \frac{1}{2}\rho\, u_1^{\,2} = p_2 + \frac{1}{2}\rho\, u_2^{2}$$

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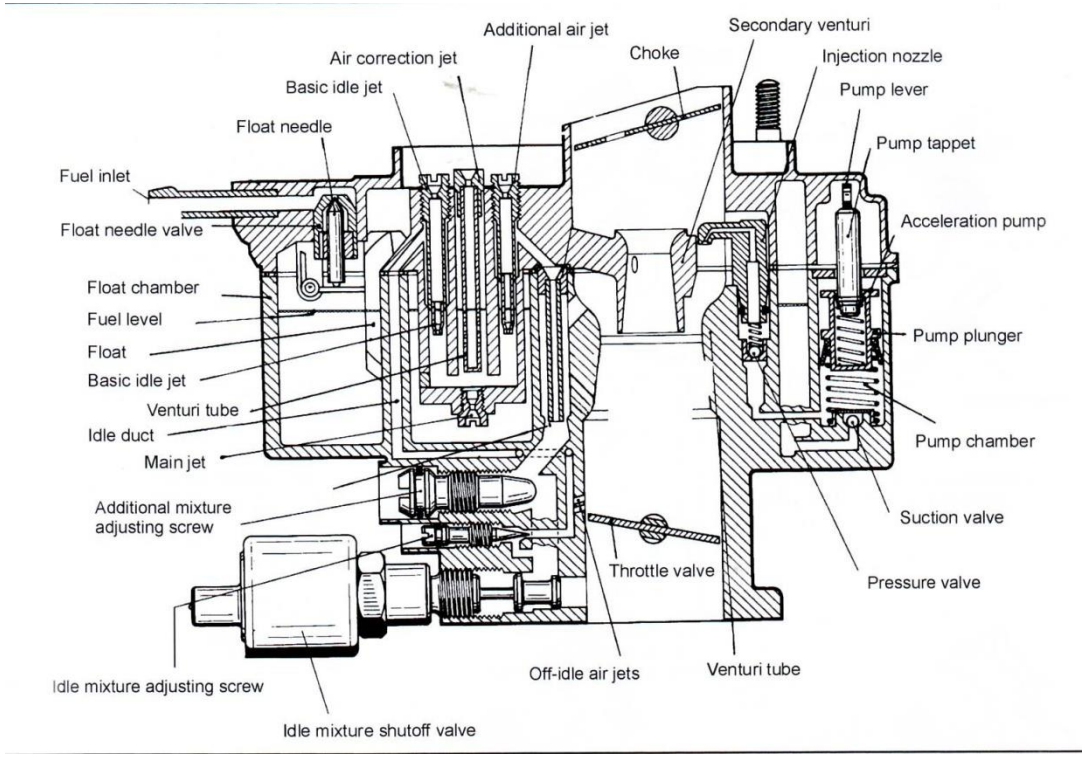
Carburetor

- Old but well working technology
- Problems with e.g. cold starting (fuel vapor condensation to cold surfaces) and accurate fuel delivery
- Utilized in e.g. chain saws or lawn movers
- Secondary venturi



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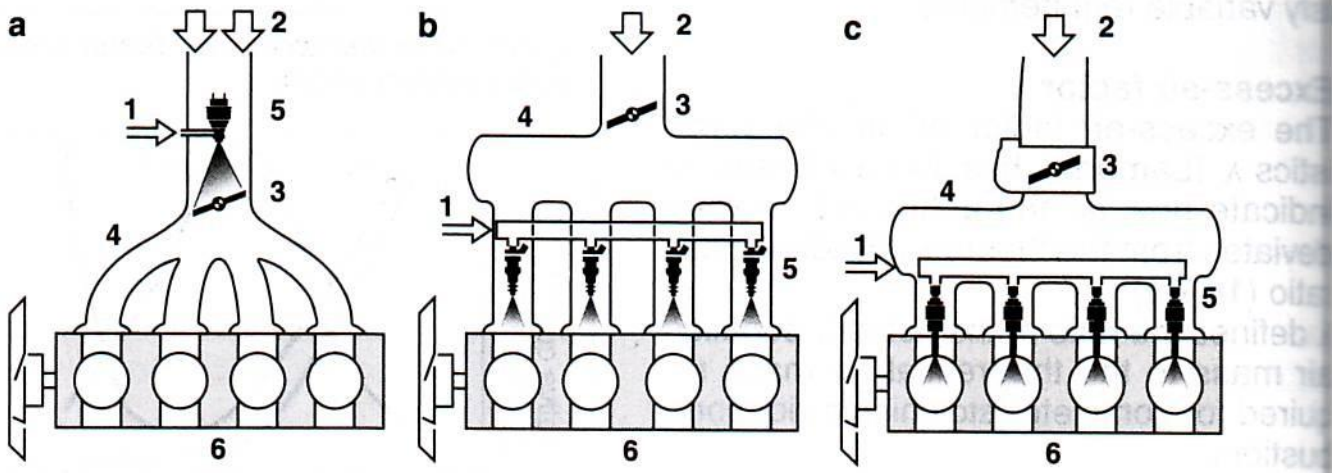
Fuel injection

Schematic representation of fuel-injection systems
a Single-point injection, b Multipoint fuel injection, c Gasoline direct injection.
1 Fuel, 2 Air, 3 Throttle valve, 4 Intake manifold, 5 Fuel injector, 6 Engine,
7 Throttle device (ETC), 8 High-pressure fuel injector.



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Multi-point injection

- **Injection pressure 3...5bar**
- **Controls:**

Starting enrichment

Acceleration control

Full throttle controll

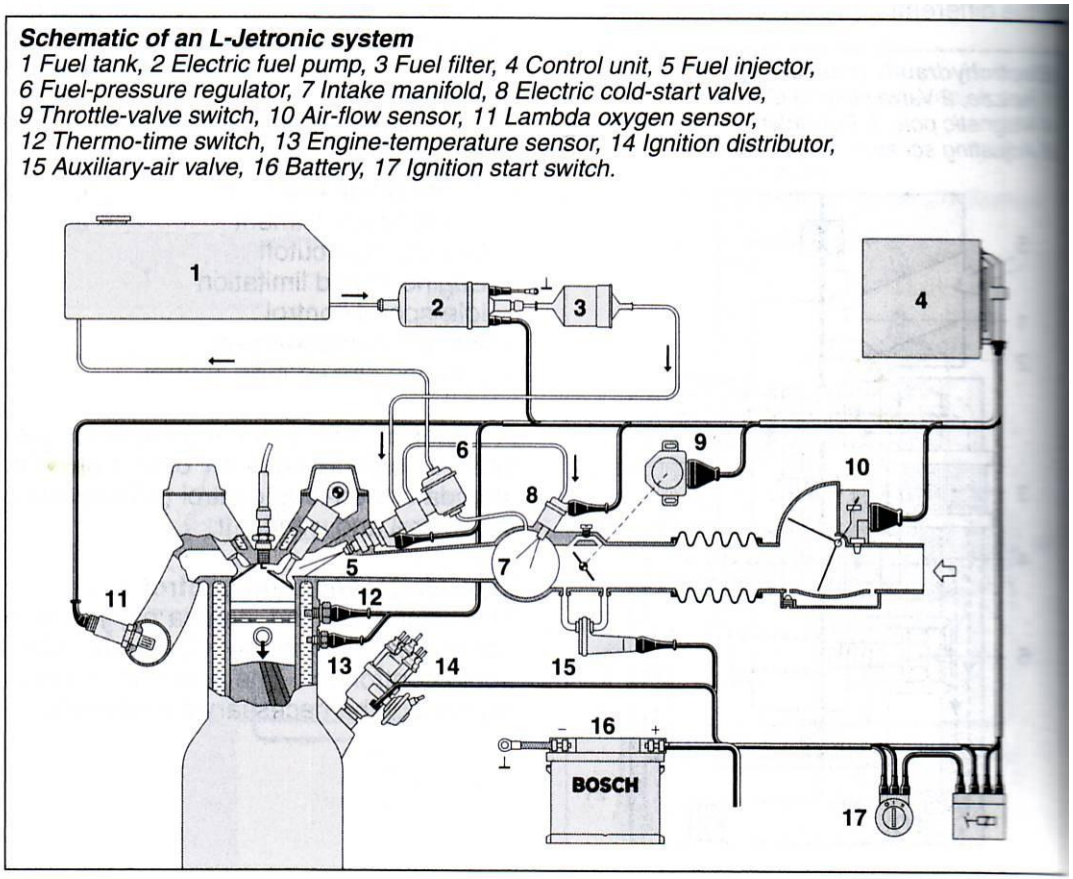
Fuel cut-off

Limit to rotational speed

Idle control

Altitude control

Lambda control



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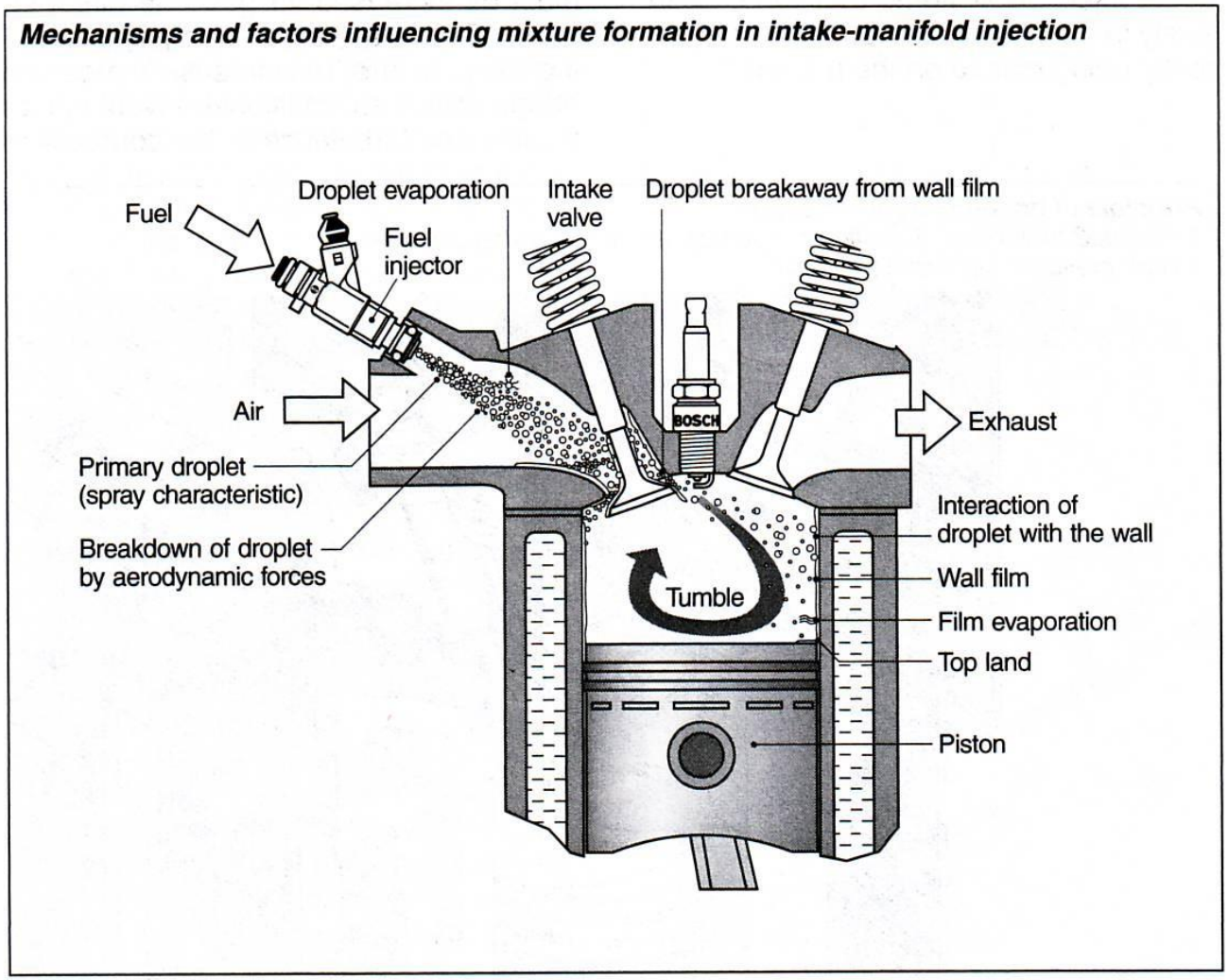
Multi-point injection



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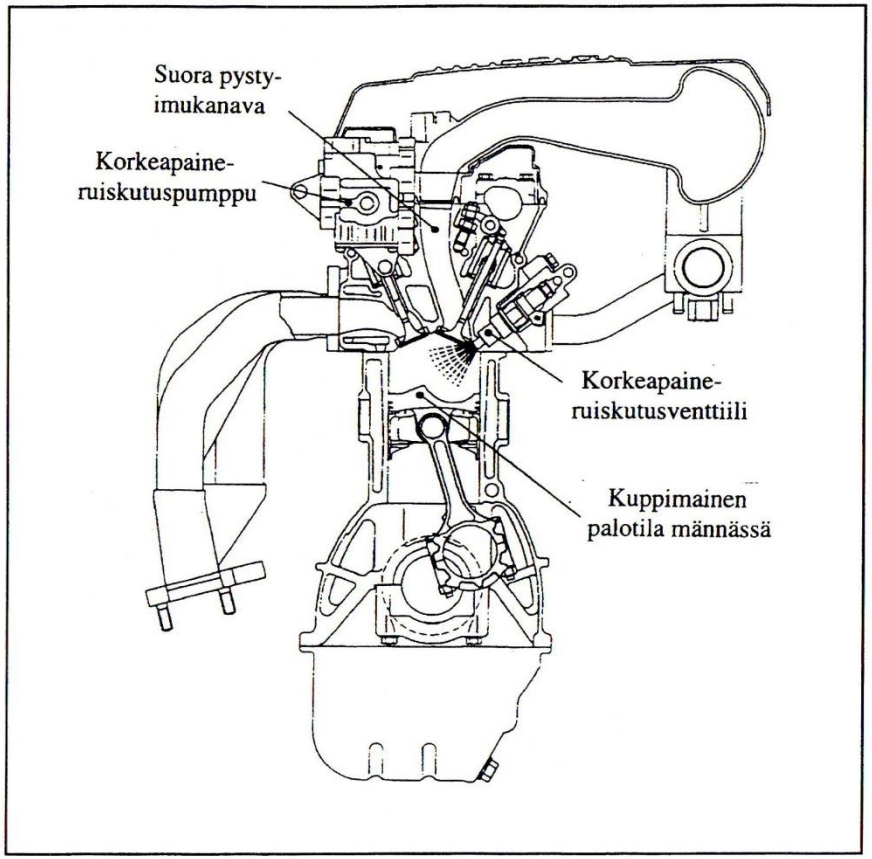
Gasoline direct injection

- **Reduced fuel consumption close to 20%**
- **Part load stratified charge → Full load homogeneous charge**
- **Control demanding**
- **Not as sensitive to knocking behavior compared to intake manifold injection systems**



Kuva 2.4. Nelisylinterisen Mitsubishi 4G93-suoraruiskutusbensiinimoottorin poikkileikkaus. Sylinterin halkaisija D = 81 mm, iskunpituus S = 89 mm, puristussuhde e = 12, palotila osittain sylinterin kannessa, osittain männässä, lähes pystysuora imukanava, kaksi yläpuolista nokka-akselia /2.4/.

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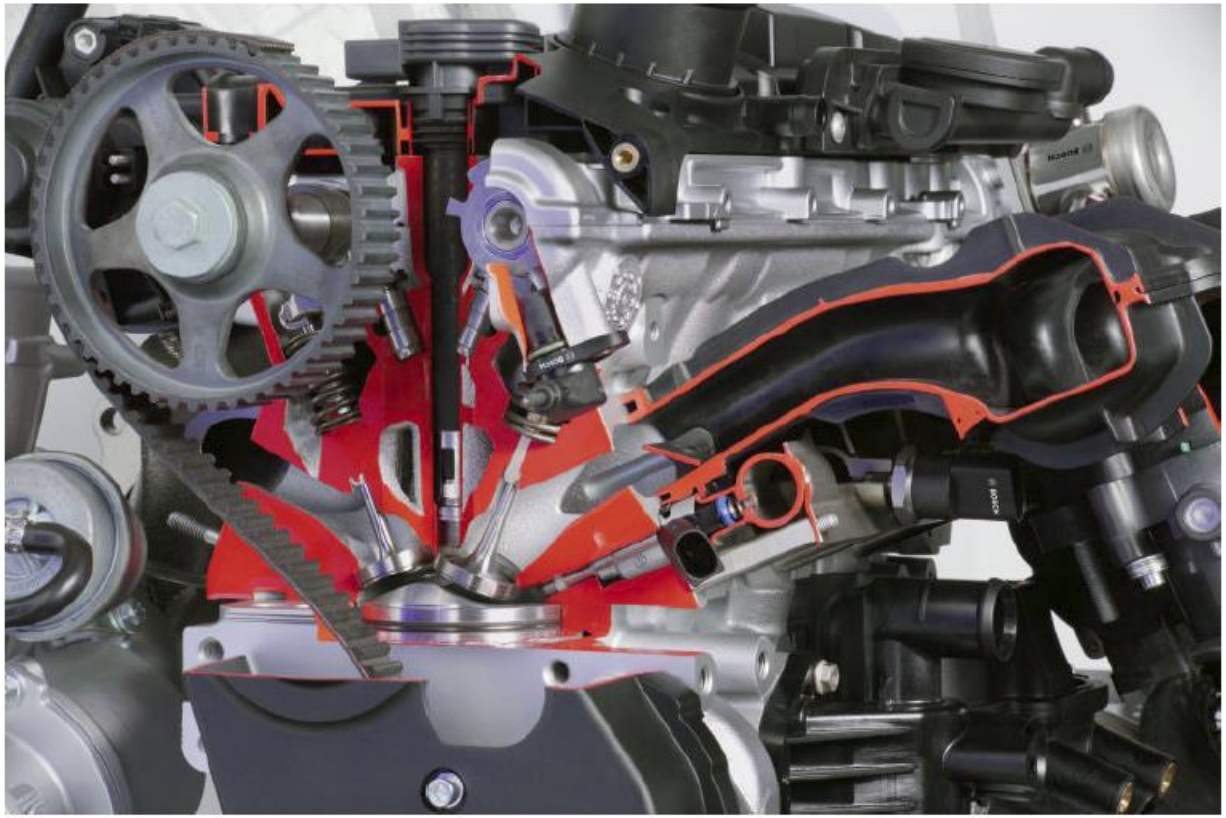
Gasoline direct injection



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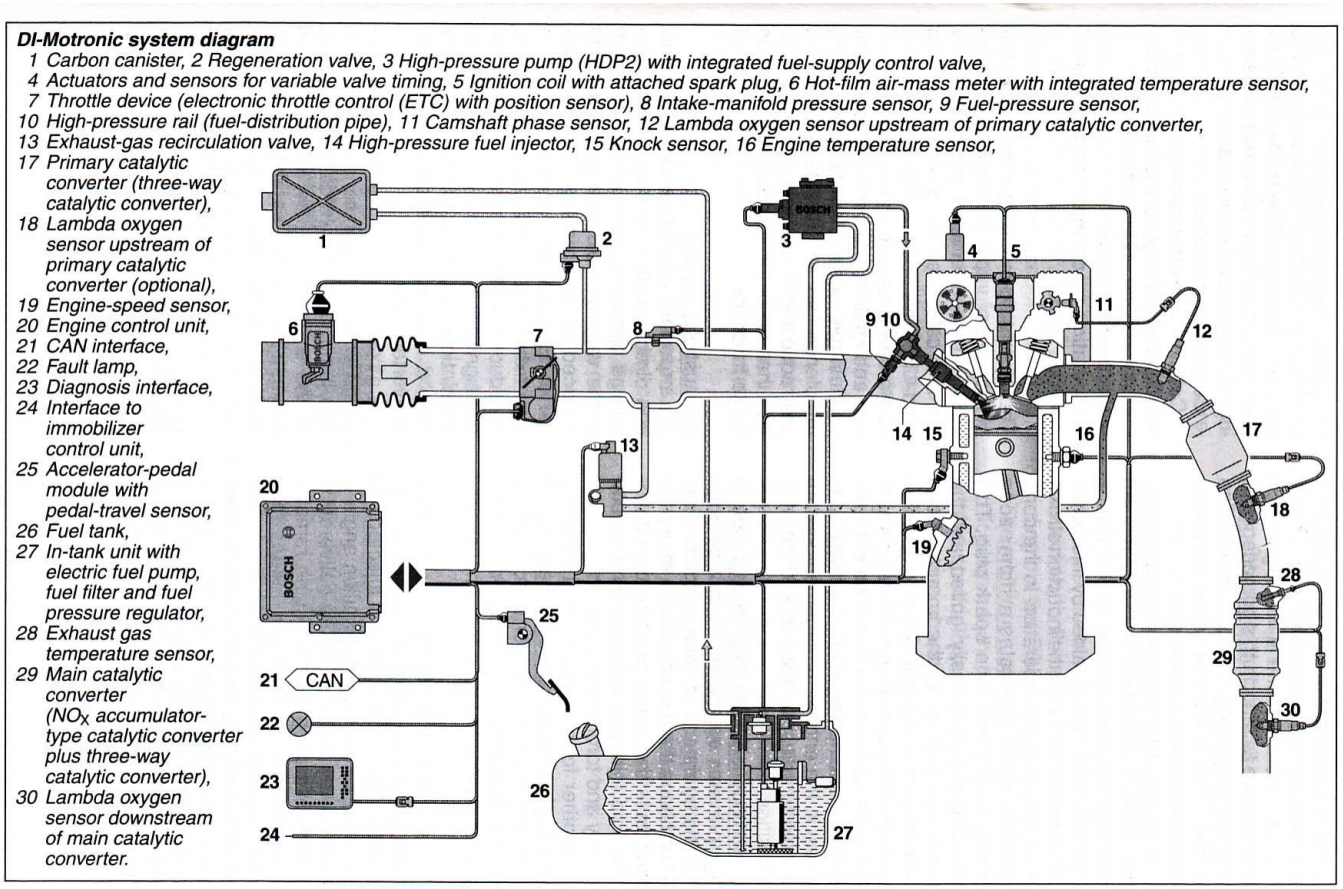
Gasoline direct injection, Bosch



- **Injection pressures 50...200 bar**

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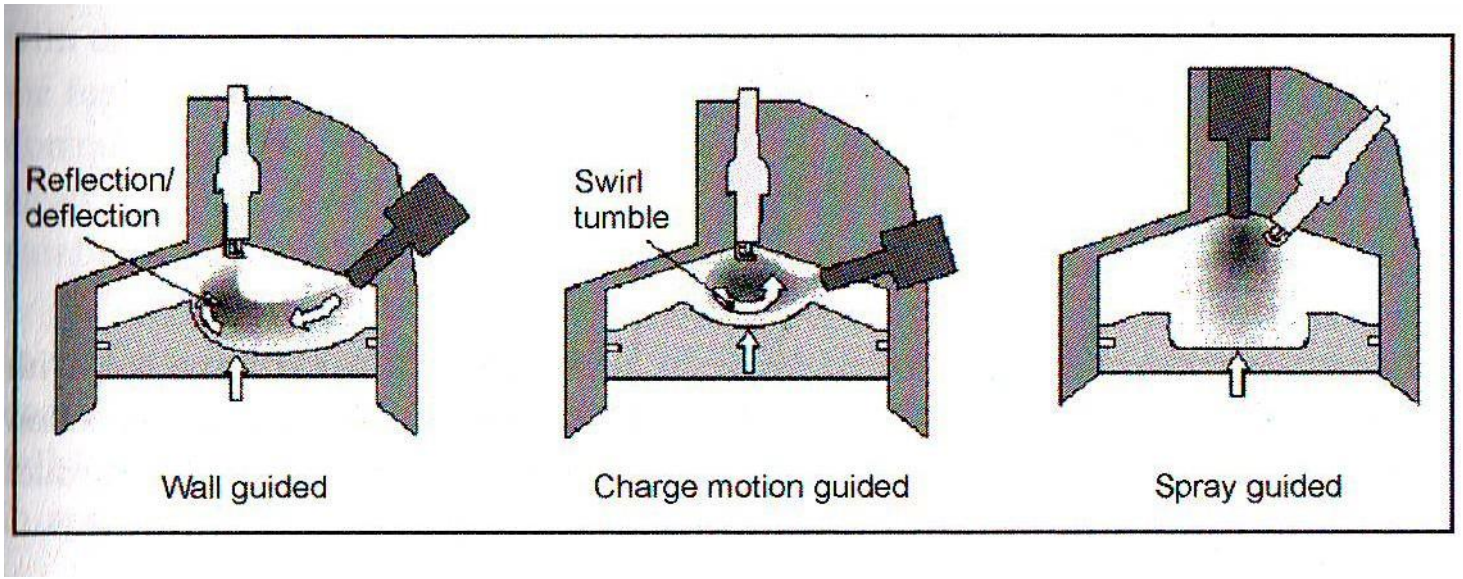
Gasoline direct injection



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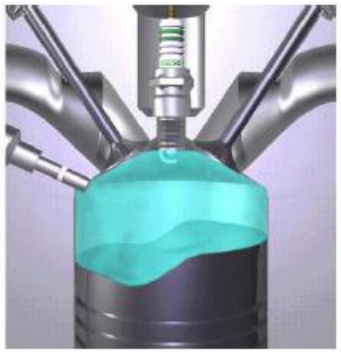
Toimintatilat:



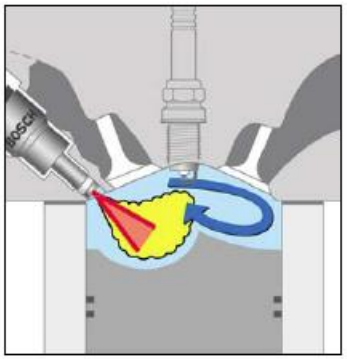
Kerrossyöttö

- $\lambda = 1 \ldots 3$
- Kerroksittainen seos

Homogeeninen

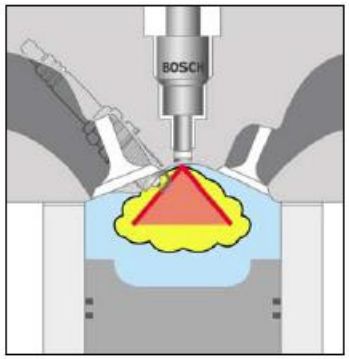
- $\lambda = 1$
- Tasalaatuinen seos

Täytöstavat:



Seinämäohjattu

Täytöstä ohjataan sylinteritilan muotoilun avulla



Suihkutusohjattu

Täytöstä ohjataan polttoainesuihkun avulla

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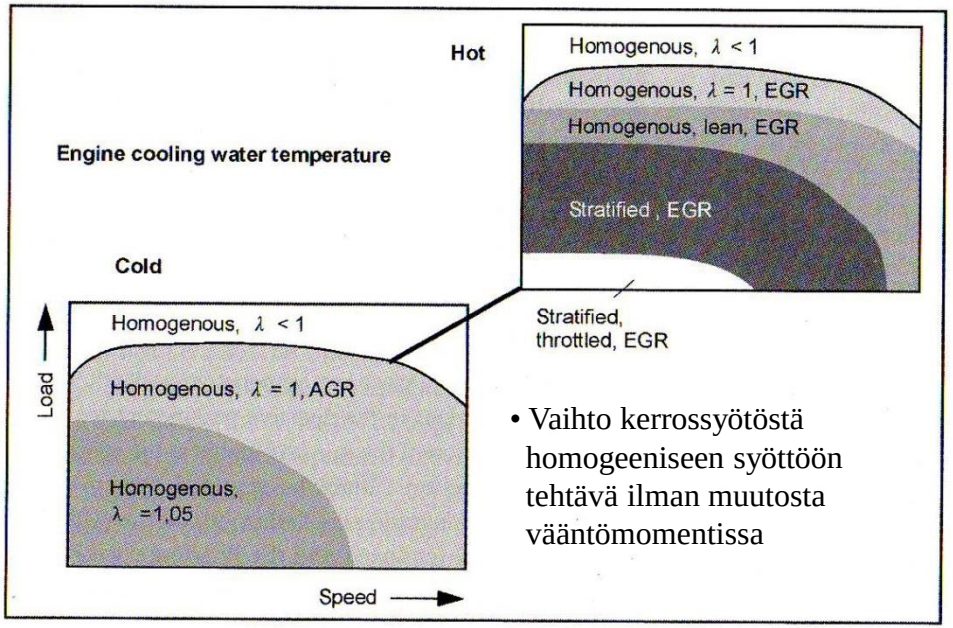
Direct fuel injection, mixture formation

- **High load homogeneous charge, total Lambda close to 1**
- **Partial load stratified charge, high total Lambda**
- **Combustion chamber has two charge areas:**
  - **Close to spark goal is Lambda=1**
  - **Elsewhere ”insulation” layer between ignitable mixture and cylinder wall (air + egr)**



- Vaihto kerrossyötöstä homogeeniseen syöttöön tehtävä ilman muutosta vääntömomentissa

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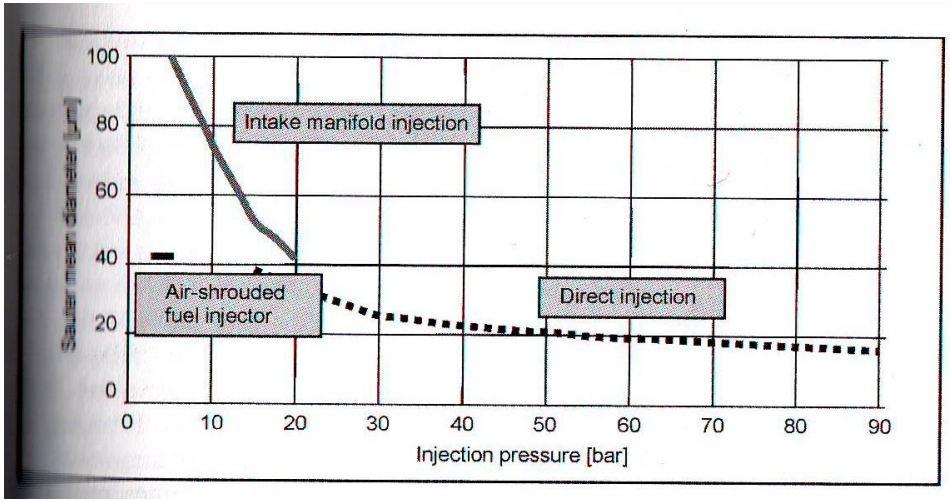

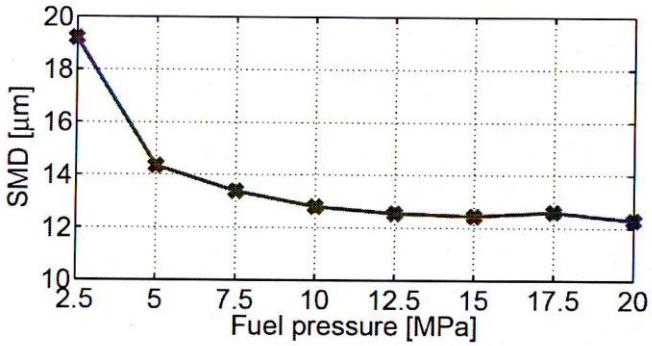

Figure 13. Influence of fuel pressure on the Sauter mean diameter (D32)of droplets in the spray core. Measurements taken in a heated spray chamber under evaporating conditions (1 MPa/600 K) [78].

M. Skogsberg, Phd thesis, 2007, Chalmers

Why does much lower fuel injection pressure suffice in SI engines compared to diesel engines ?

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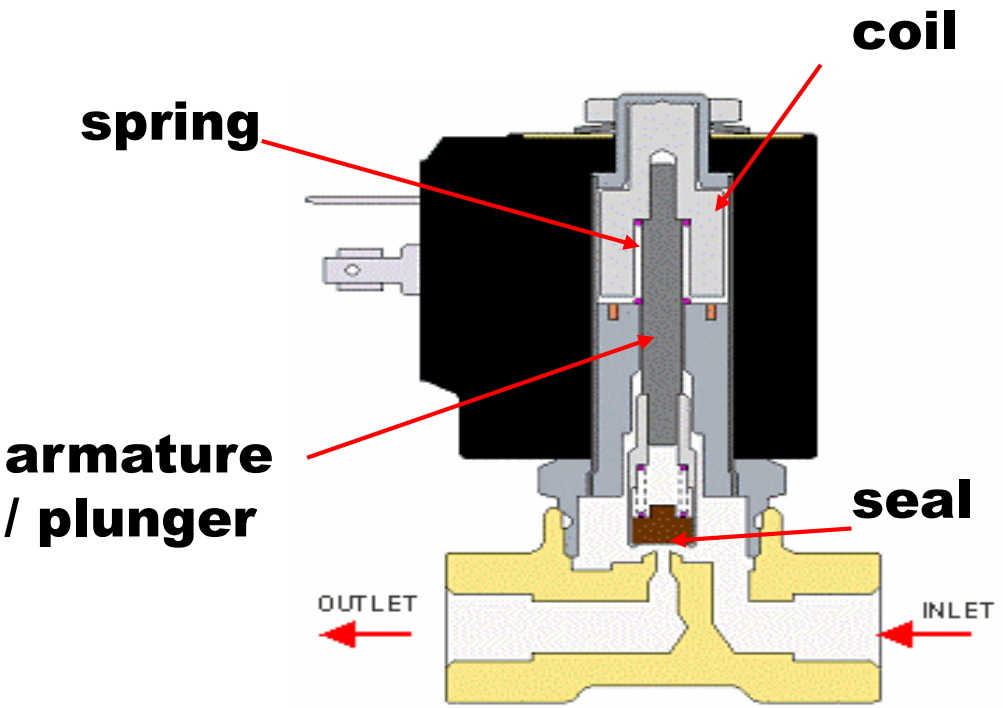
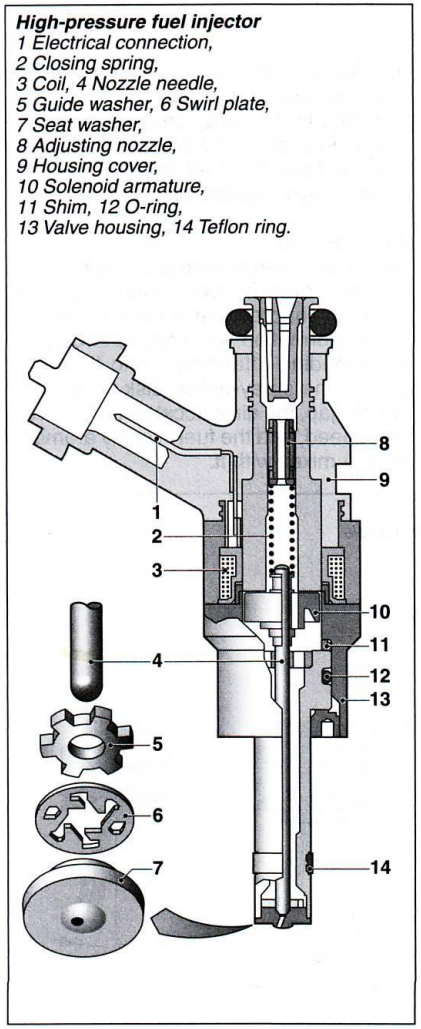
Solenoid valves

- **Control: electric current in the coil produces a magnetic field which raises the plunger**
- **Direct or indirect acting**





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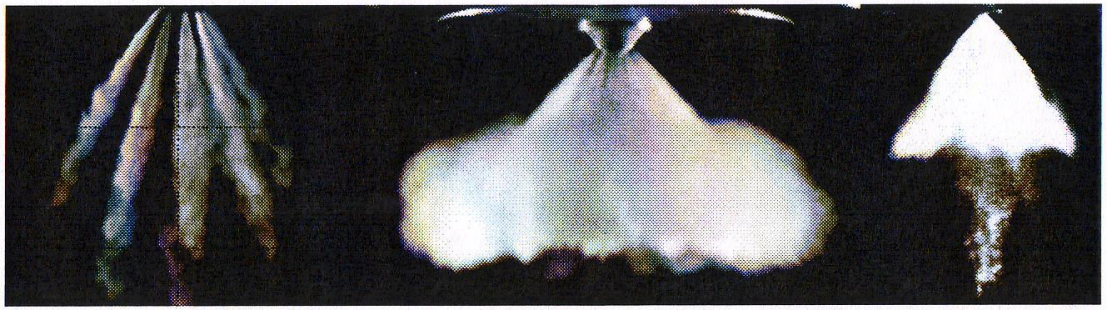

Figure 15. Examples of sprays from three types of injectors: left, multi-hole; center, outwards opening A-nozzle; right, an inwards opening swirl type nozzle. Note that the images are not taken using the same geometrical scale.

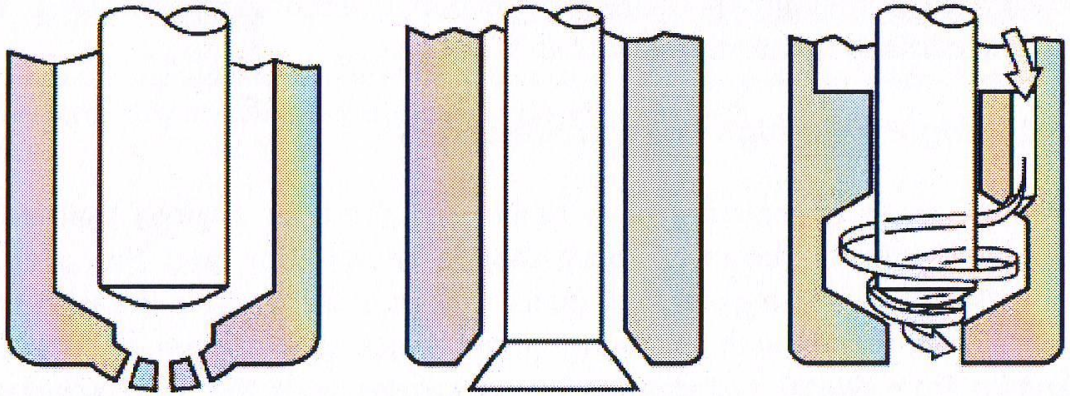

Figure 16. Cross-sections of three types of injector; left, multi-hole; center, A-nozzle; right, inwards opening swirl type nozzle. Reprinted with permission from SAE Paper No. 980498 [30], © 1998 SAE International.

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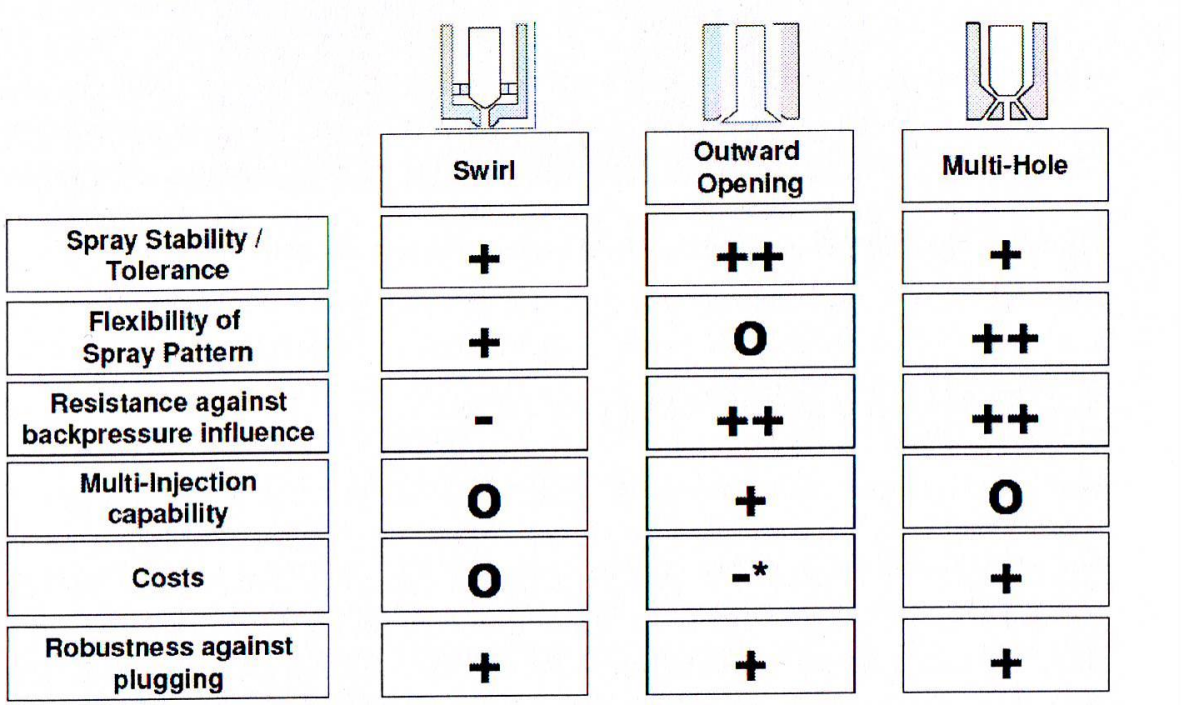

	Swirl	Outward Opening	Multi-Hole
Spray Stability / Tolerance	+	++	+
Flexibility of Spray Pattern	+	o	++
Resistance against backpressure influence	-	++	++
Multi-Injection capability	o	+	o
Costs	o	-*	+
Robustness against plugging	+	+	+

*) in combination with piezo-electric actuation

Figure 18. Atomization concepts for DISC fuel injectors. Reprinted with permission from SAE Paper No. 2007-01-1404 [7], © 2007 SAE International.

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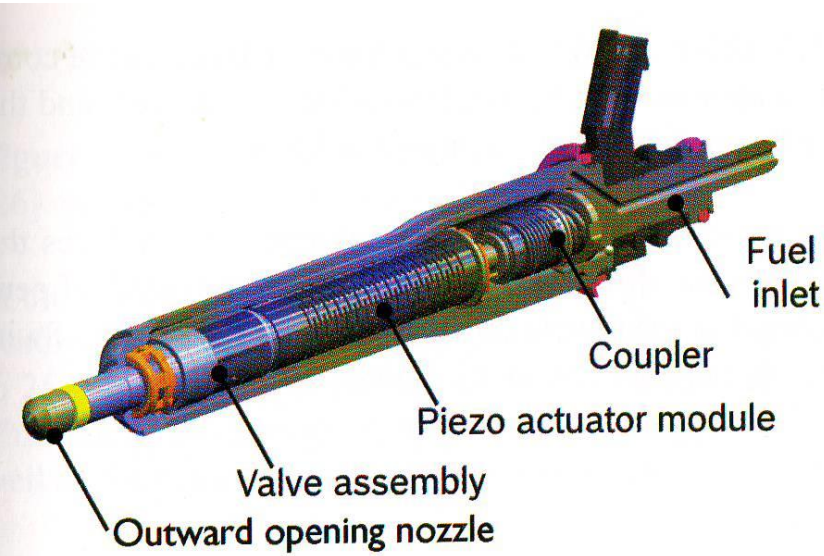
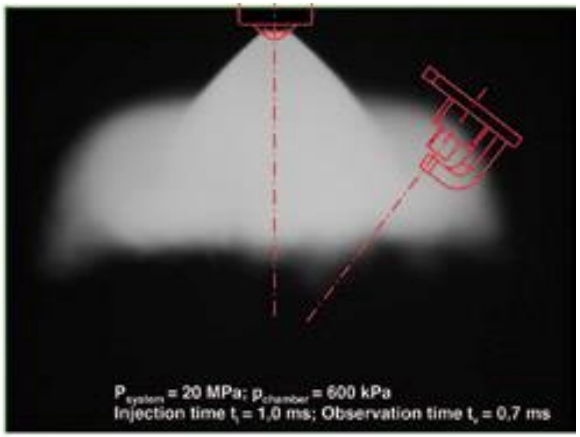
Injector for direct injection



- **Piezo element replaces solenoid valve**
- **Fast**
- **Low energy consumption**



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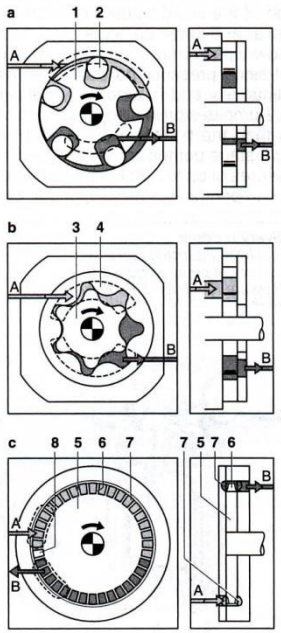
Pressurizing fuel

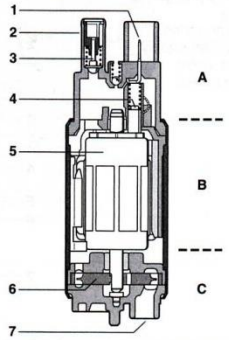
Low pressure systems

Electric fuel pump principles
a) Roller-cell pump,
b) Internal-gear pump,
c) Flow-type pump.

A Suction opening,
B Outlet.
1 Slotted washer (eccentric), 2 Roller,
3 Inner driving wheel, 4 Rotor (eccentric),
5 Impeller ring, 6 Impeller blades,
7 Passage (peripheral).



Electric fuel pump design using a flow-type pump as an example
1 Electrical connection,
2 Hydraulic connection (fuel outlet),
3 Non-return valve,
4 Carbon brushes,
5 Motor armature with permanent magnet,
6 Impeller ring of flow-type pump,
7 Hydraulic connection (fuel inlet).



High pressure systems

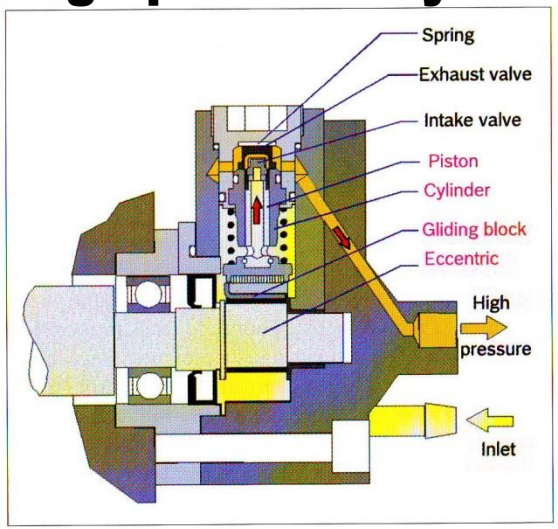
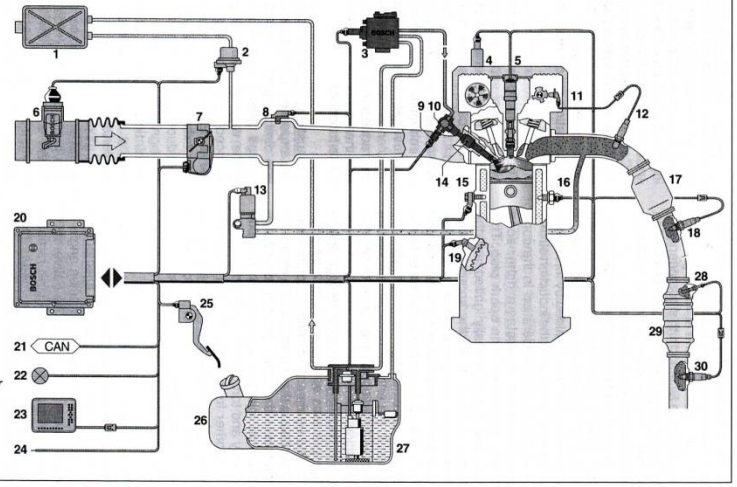


Figure 4.8:
Three-cylinder radial piston pump [18]

DI-Motronic system diagram
1 Carbon canister, 2 Regeneration valve, 3 High-pressure pump (HDP2) with integrated fuel-supply control valve,
4 Actuators and sensors for variable valve timing, 5 Ignition coil with attached spark plug, 6 Hot-film air-mass meter with integrated temperature sensor,
7 Throttle device (electronic throttle control (ETC) with position sensor), 8 Intake-manifold pressure sensor, 9 Fuel-pressure sensor,
10 High-pressure rail (fuel-distribution pipe), 11 Camshaft phase sensor, 12 Lambda oxygen sensor upstream of primary catalytic converter,
13 Exhaust-gas recirculation valve, 14 High-pressure fuel injector, 15 Knock sensor, 16 Engine temperature sensor,
17 Primary catalytic converter (three-way catalytic converter),
18 Lambda oxygen sensor upstream of primary catalytic converter (optional),
19 Engine-speed sensor,
20 Engine control unit,
21 CAN interface,
22 Fault lamp,
23 Diagnosis interface,
24 Interface to immobilizer control unit,
25 Accelerator-pedal module with pedal-travel sensor,
26 Fuel tank,
27 In-tank unit with electric fuel pump, fuel filter and fuel pressure regulator,
28 Exhaust gas temperature sensor,
29 Main catalytic converter (NO_x accumulator-type catalytic converter plus three-way catalytic converter),
30 Lambda oxygen sensor downstream of main catalytic converter.



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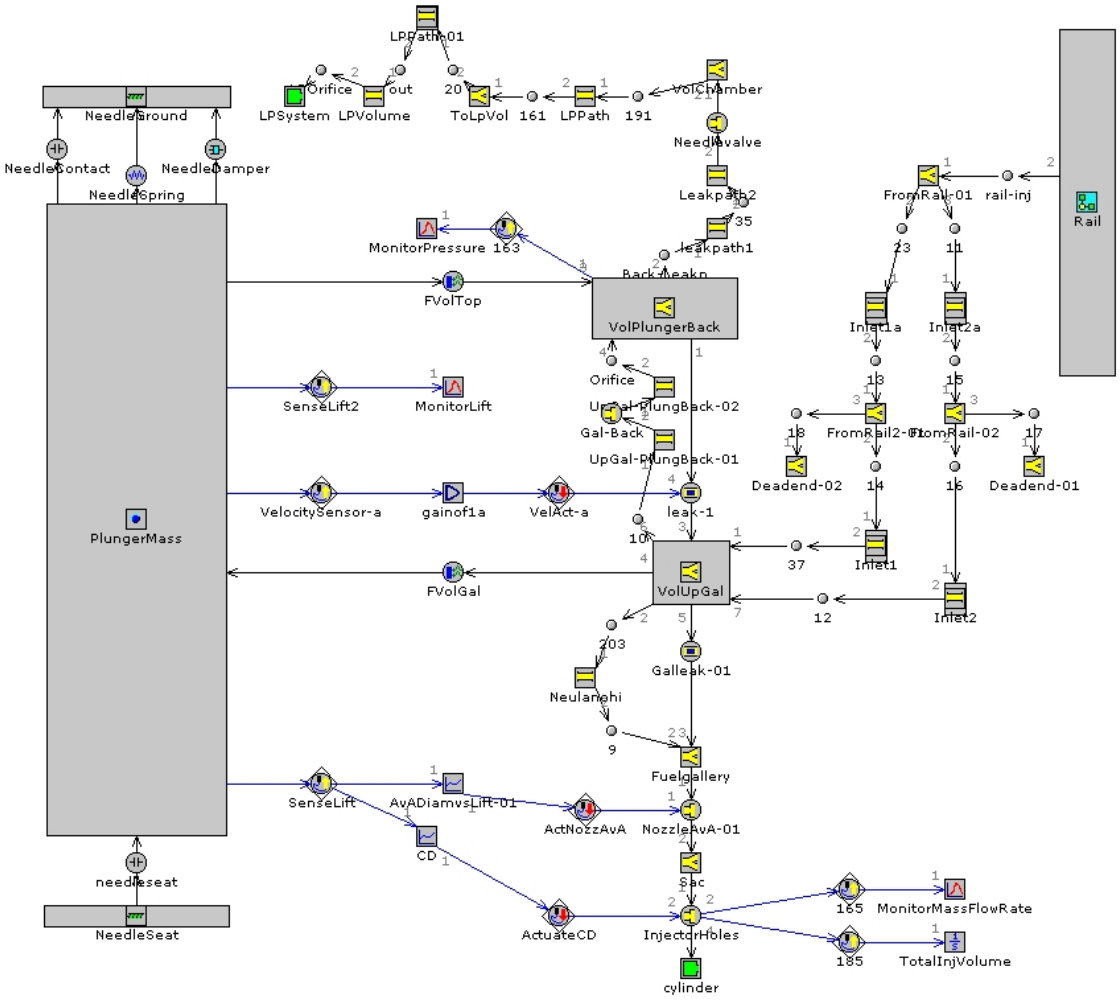
Simulation



GT-Fuel model of EVE injection system

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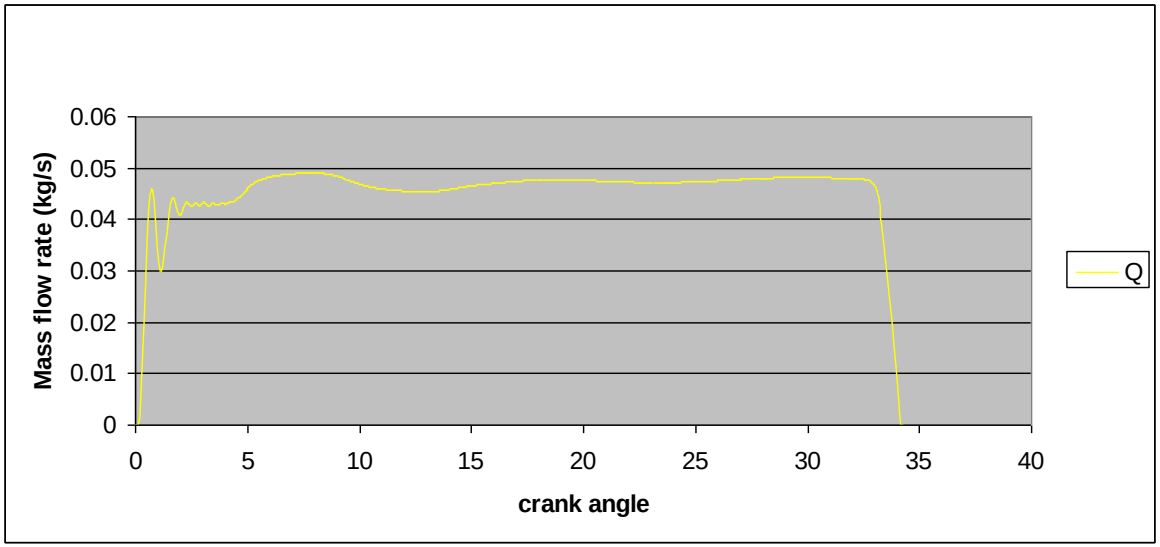
Simulation



Computed mass flow rate in the nozzle hole

Fig. A. Tilli

More about 1-D simulations, course Kul-14.4400

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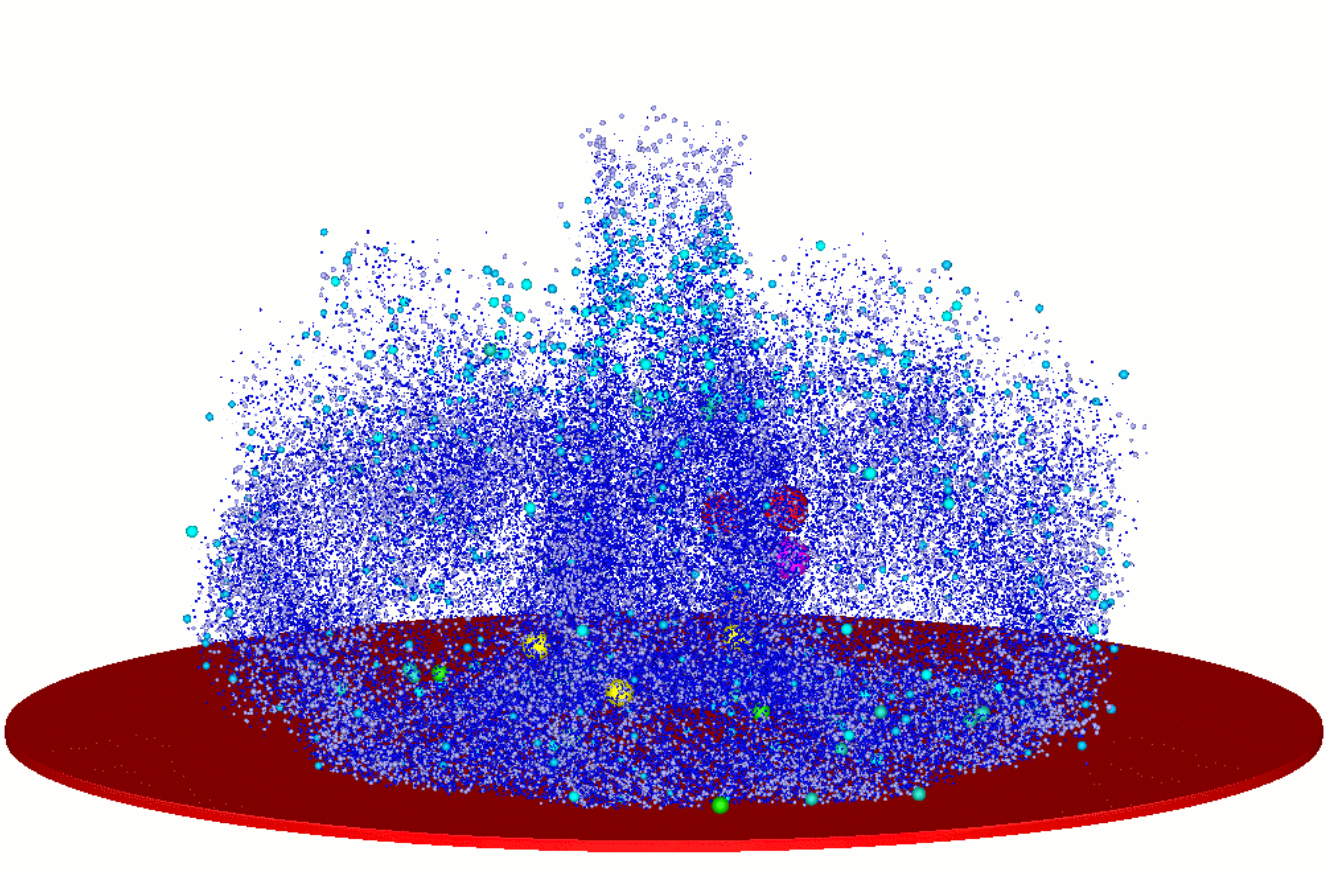
CFD Simulation



HCCI type fuel sprays obtained by CFD Fig. O. Kaario

More about CFD simulations, course Kul-14.5200