FUEL SUPPLY SYSTEM IN DIESEL ENGINE

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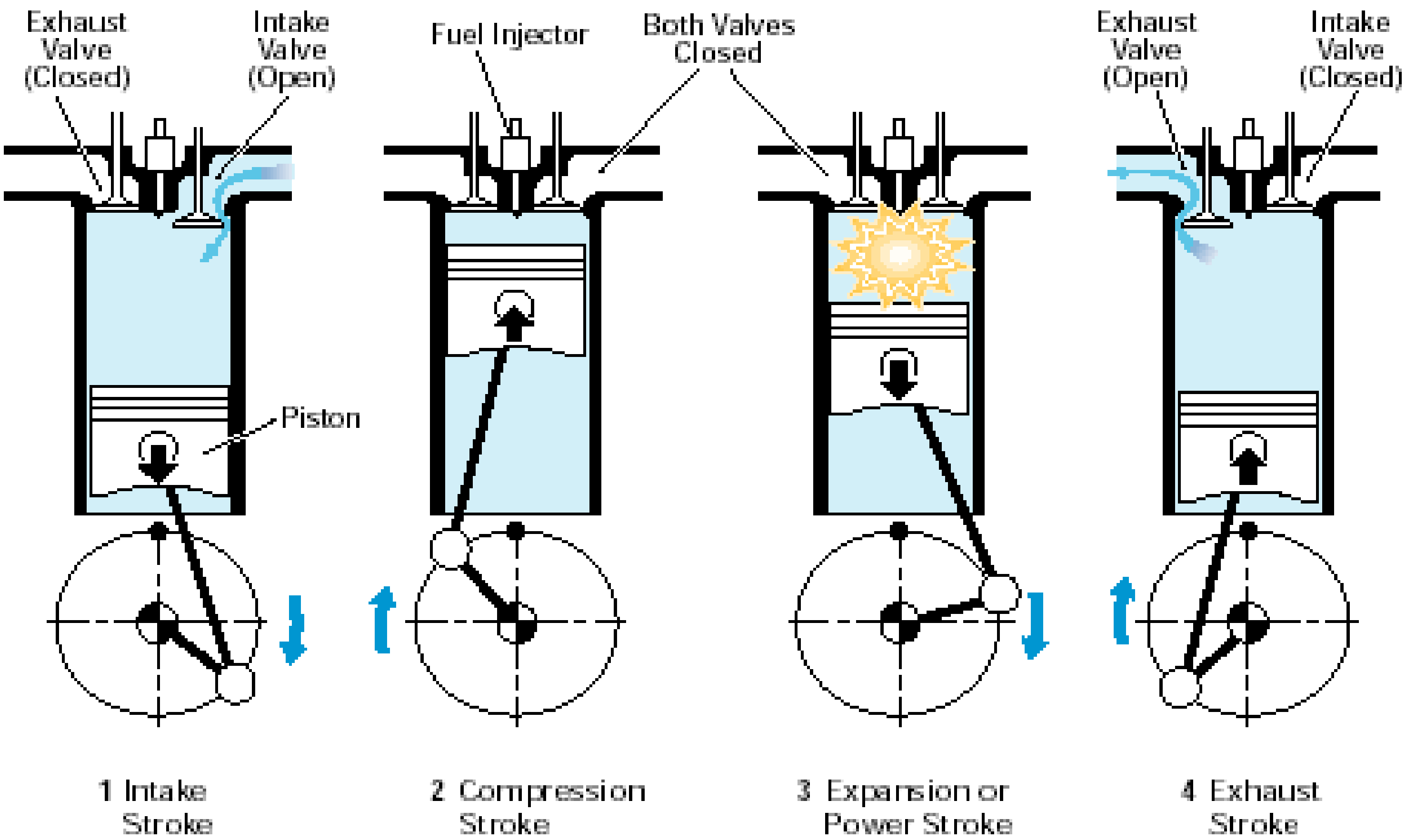
4-STROKE DIESEL ENGINE



Fuel injection begins shortly before the end of the compression stroke.

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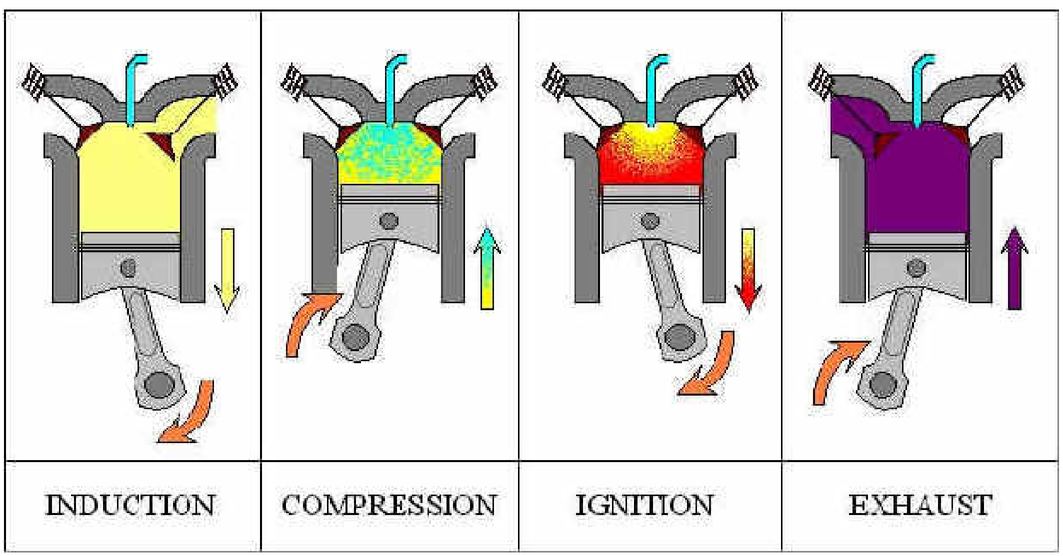
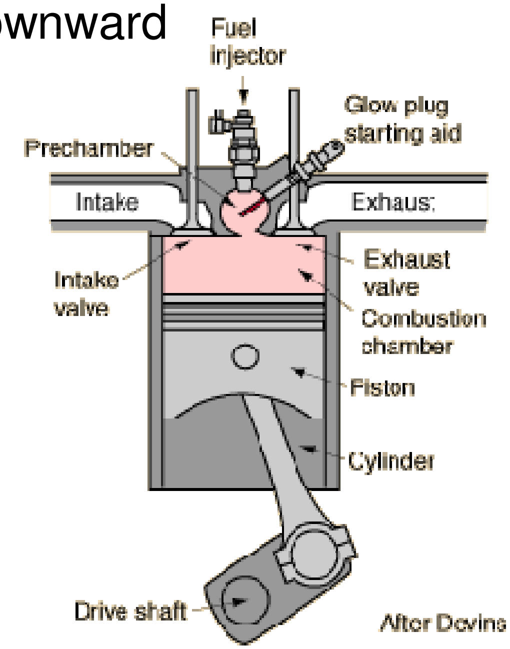
The Diesel Engine

- Developed by Rudolph Diesel in 1892
  - Focused on high efficiency replacement for steam engine
  - Increased efficiency from 12% to 26%
- Demonstrated the engine at the World's Fair in Paris in 1898
  - Running on peanut oil
- How does it works?
  - Air is drawn into cylinder and compressed by rising piston
  - As the air is compressed, the temperature rises
  - As the piston rises to the top of it's stoke, the fuel is injected at very high pressure into combustion chamber (mixing with the hot air
  - The mixture ignites and forces the piston downward





[Diesel Fuel systems.flv]

FUEL INJECTION SYSTEM IN DIESEL ENGINES

- The task of fuel-injection system is to meter the appropriate quantity of fuel for the given engine speed and load to each cylinder, each cycle, and inject that fuel at the appropriate time in the cycle at the desired rate with the spray configuration required for the particular combustion chamber employed.
- It is important that injection begin and end cleanly, and avoid any secondary injections.
- To accomplish this task, fuel Is usually drawn from the fuel tank by a supply pump, and forced through a filter to the injection pump. The injection pump sends fuel under pressure to the nozzle pipes which carry fuel to the injector nozzles located in each cylinder head. Excess fuel goes back to the fuel tank.

FUEL INJECTION SYSTEM IN DIESEL ENGINE

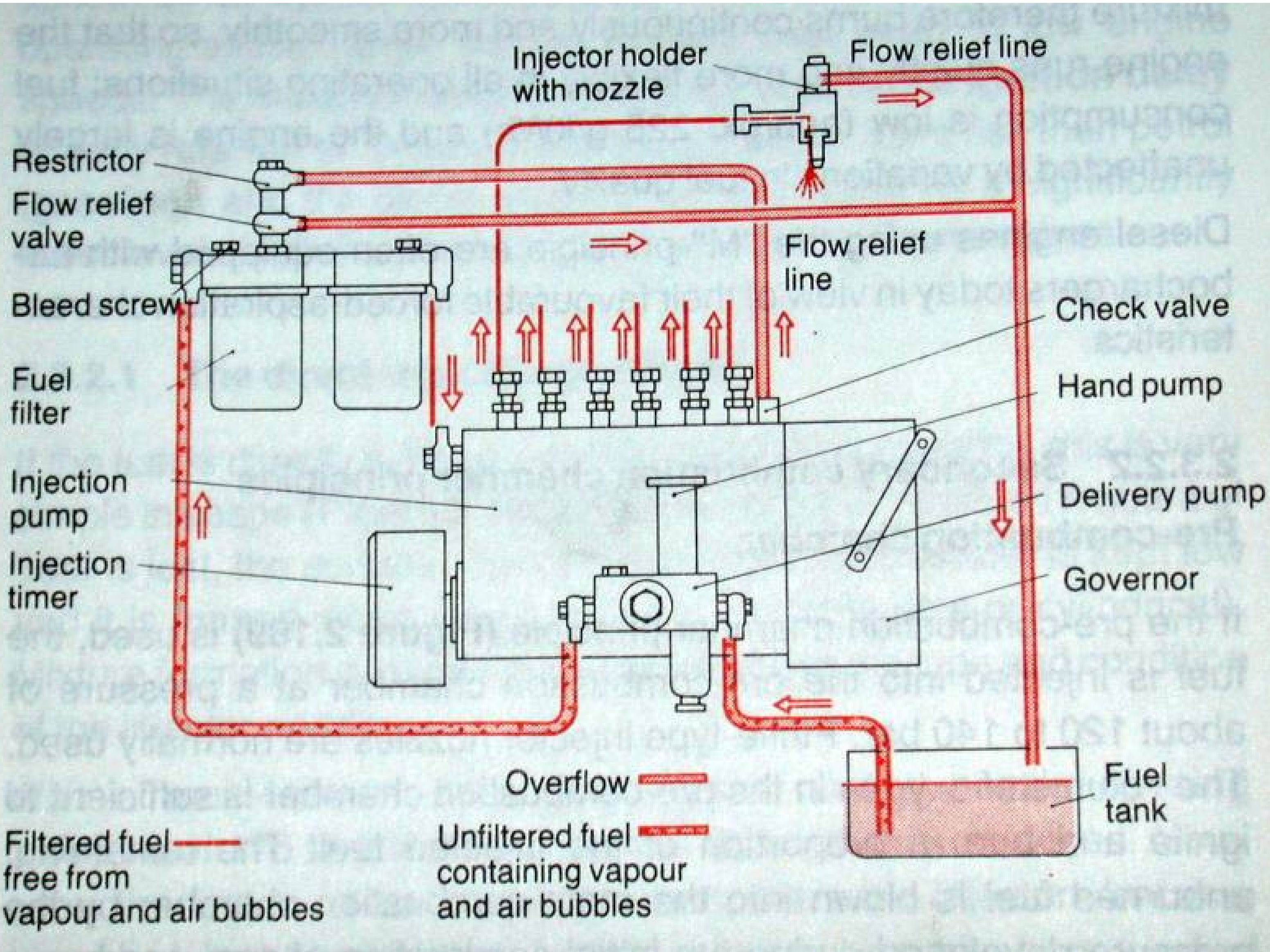
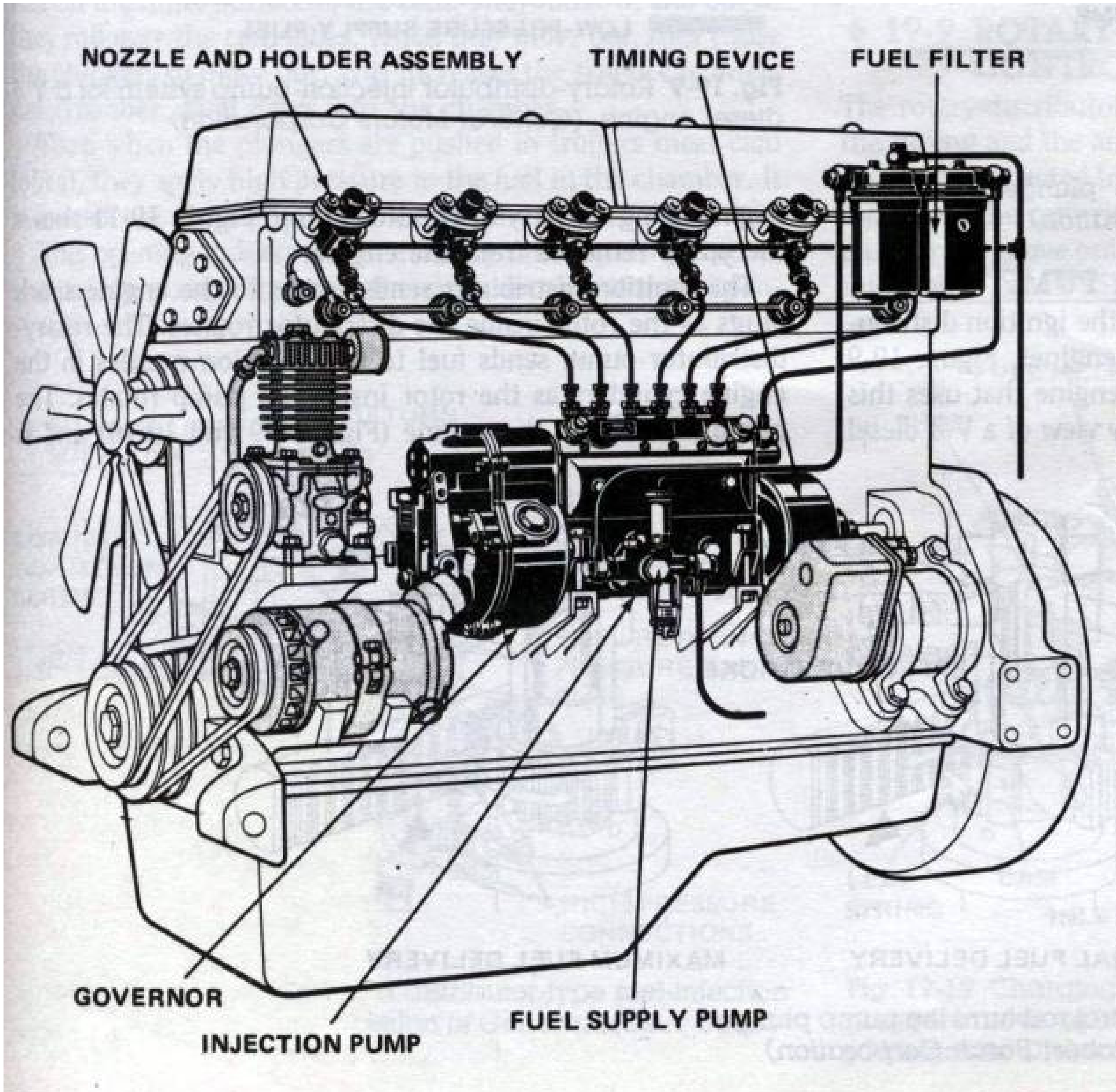


Figure 2.191: Fuel circuit (for suction-side scavenging of injection pump)

FUNCTIONAL ELEMENTS

- **Pumping elements**: to move the fuel from the fuel tank to cylinder and piping etc.
- **Metering elements**: to measure and supply the fuel at the rate demanded by the load and speed.
- **Metering controls**: to adjust the rate of metering elements for changes in load and speed of the engine.
- **Distributing elements**: to divide the metered fuel equally among the cylinders.
- **Timing controls**: to adjust the start and the stop of injection.
- **Mixing elements**: to atomize and distribute the fuel within the combustion chamber.

DIESEL FUEL SYPPLY SYSTEM



COMBUSTION IN CI ENGINES

- Fuel is injected into the cylinder late in the compression stroke by one or more injectors located in each cylinder combustion chamber. Injection time is usually about 20^o of crankshaft rotation, starting at about 15^o bTDC and ending about 5^o aTDC.
- In addition to the swirl and turbulence of the air, a high injection velocity is needed to spread the fuel throughout the cylinder and cause it to mix with the air. After injection the fuel must go through a series of events to assure the proper combustion process.

- **Atomization**: the smaller the original drop size emitted by the injector the quicker and more efficient will be this atomization process.
- **Vaporization**: The small droplets of liquid fuel evaporate to vapor. This occurs very quickly due to the hot air temperature created by the high compression of CI engines. About 90% of the fuel injected into the cylinder has been vaporizes within 0.001 second after injection.
- **Fuel-air mixing**: After vaporization, the fuel vapor must mix with air to form a mixture within the AF range which is combustible.

- **Self-ignition**: At about 8^o bTDC, $6\text{-}8^o$ after the start of injection, the air-fuel mixture starts to self-ignite. Actual combustion is preceded by secondary reaches, including breakdown of large hydro carbon molecules into smaller species and some oxidation.
- **Combustion**: Combustion starts from self-ignition simultaneously at many locations in the slightly rich zone of the fuel jet, where the equivalence ratio is $\Phi = 1$ to 1.5

- Higher compression ratio can be used resulting improved thermal efficiency.
- Short delay depends on cetane no.
- Soot formation occurs if the amount of fuel injected is increased since mep (diesel) is lower than mep (petrol).
- $\gamma_{diesel} > \gamma_{petrol}$; since diesel engine works on lean AF mixture. This gives a higher fuel conversion efficiency than the spark-ignition engine, for a given expansion ratio.

  $\gamma = cp/cv$

CONSTRAINT

- Difficult to achieve rapid mixing between injected fuel and the air in the cylinder to complete combustion in the appropriate crank angle interval close to TDC.
- For commercial diesel engine

  Bore size, D = 70-900mm
- Piston speed, Sp = 2LN = const; N ≈ sp/2L;

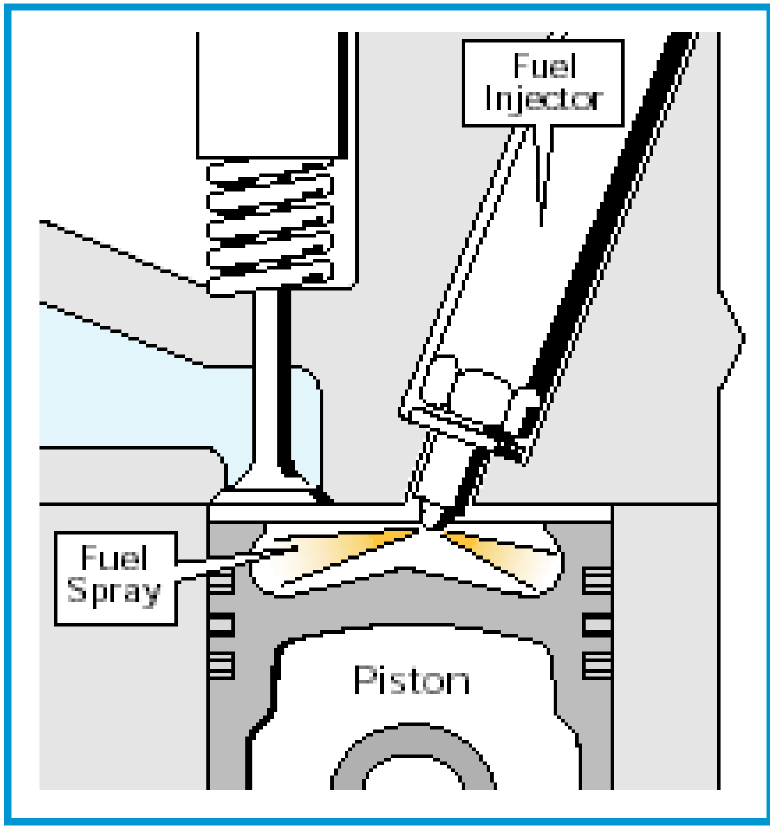
  That is, N ∞ 1/L
- Fuel-air mixing in small engine must take place on a time scale of 10 times shorter than in large engines.
- As engine size decreases more vigorous air motion is required while less fuel jet penetration is necessary.
- It is this logic that leads to the different diesel combustion chamber designs and fuel injection systems found in practice in diesel engines

COMBUSTION CHAMBER

- **Direct injection** (DI) engine has main chamber
  - Compression ratio = 15:1 to 18:1
  - Used in large engine (bus, truck)
- **Indirect injection** (IDI) engine has prechamber and main chamber
  - Compression ratio = 20:1 to 24:1
  - Used in smaller engine (utility vehicles like Pajero, Prado)

FUEL INJECTION

Direct-Injection (DI) Process



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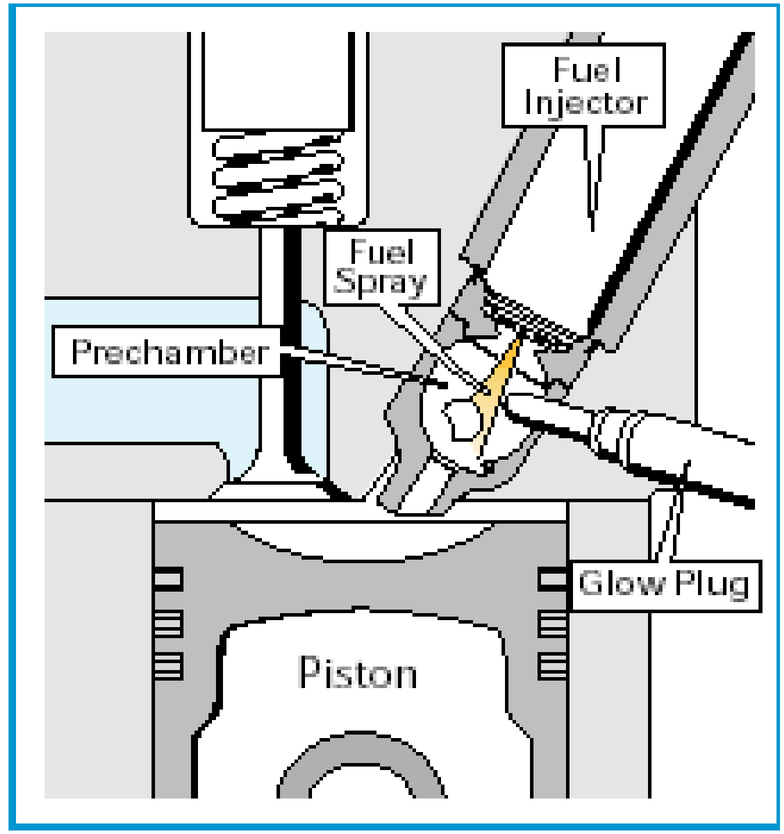
Indirect-Injection (IDI) Process



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The two fuel injection processes used in diesel engines, *direct-injection* (DI) and *indirect-injection* (IDI), are illustrated in Figures. In a DI engine, fuel is injected directly into the cylinder above the piston. In an IDI engine, fuel is injected into a small *prechamber* connected to the cylinder via a narrow passage that enters the prechamber tangentially. During the compression process, air is forced through this passage, generating a vigorous swirling motion in the prechamber. Then fuel is injected into the prechamber and ignition occurs there.

The combination of rapidly swirling air in the prechamber and the jet-like expansion of combustion gases from the prechamber into the cylinder enhances the mixing and combustion of the fuel and air. The more rapid mixing of fuel and air achieved in IDI engines comes at a price, however.

The high velocity flow of air through the narrow passage connecting the main cylinder to the prechamber, as well as the vigorous swirling motion in the prechamber itself, causes the air to lose significantly more heat during compression than it does in a DI engine. Coupled with a pressure drop from the main chamber to the prechamber, this results in an air temperature in the prechamber after compression that is lower than that in a similar DI engine.

Since rapid fuel autoignition requires a certain air temperature, an IDI engine needs a higher compression ratio to achieve the desired air temperature in the prechamber.

IDI engines operate at compression ratios of about 20:1 to 24:1; while DI engines operate at ratios of about 15:1 to 18:1. The heat losses that necessitate these higher compression ratios have another, more important effect: they decrease the efficiency of the engine. IDI engines typically achieve fuel efficiencies that are 10% to 20% lower, on a relative basis, than comparable DI engines. Even with the higher compression ratios, IDI engines may still be hard to start. Most IDI engines use glow plugs to heat the air in the prechamber in order to make starting easier. Glow plugs, which are small resistive heaters, are usually powered for only the first few minutes of engine operation.

With the negative attributes of harder starting and lower efficiency, one may wonder why IDI diesel engines are used at all. The answer is engine speed. As an engine gets smaller, generally it must operate at higher speeds to generate the desired power. As engine speed increases, there is less time *per engine cycle* to inject, vaporize, mix, and combust the fuel. As a result, the higher mixing rates afforded by IDI designs become necessary to achieve good combustion at higher engine speeds. IDI diesels most commonly are used in smaller automotive and light duty truck applications.

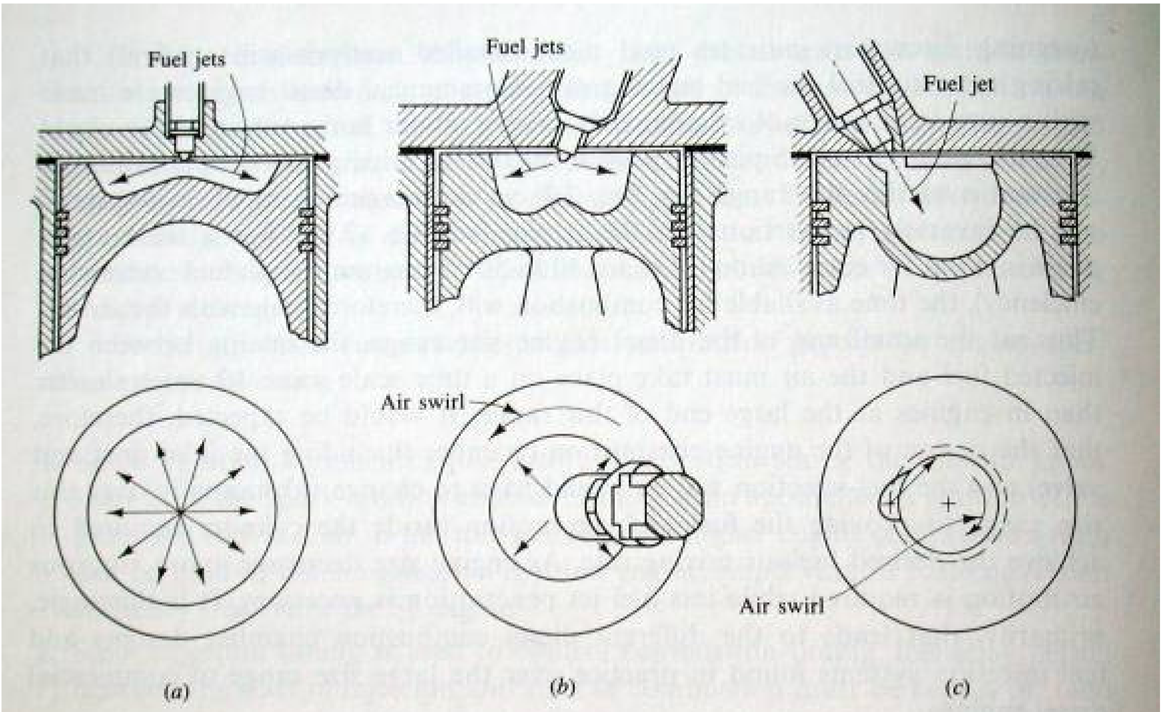
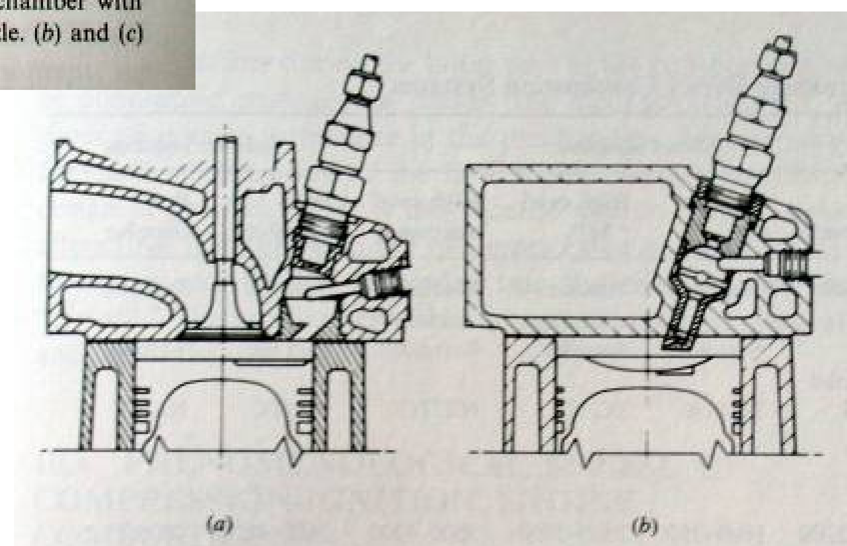


FIGURE 10-1
Common types of direct-injection compression-ignition or diesel engine combustion systems: (*a*) quiescent chamber with multihole nozzle typical of larger engines; (*b*) bowl-in-piston chamber with swirl and multihole nozzle; (*c*) bowl-in-piston chamber with swirl and single-hole nozzle. (*b*) and (*c*) used in medium to small DI engine size range.

COMBUSTION CHAMBER DESIGNS USED IN DIESEL ENGINES

Two common types of small indirect-injection diesel engine combustion system:

a) swirl prechamber; b) turbulent prechamber



Characteristics of Common Diesel Combustion Systems

System	Direct injection: Quiescent	Direct injection: Medium swirl	Direct injection: High swirl "M"	Direct injection: High swirl multispray	Indirect injection: Swirl chamber	Indirect injection: Pre-chamber
Size	Largest	Medium	Medium—smaller	Medium—small	Smallest	Smallest
Cycle	2-/4-stroke	4-stroke	4-stroke	4-stroke	4-stroke	4-stroke
Turbocharged/supercharged/naturally aspirated	TC/S	TC/NA	TC/NA	NA/TC	NA/TC	NA/TC
Maximum speed, rev/min	120–2100	1800–3500	2500–5000	3500–4300	3600–4800	4500
Bore, mm	900–150	150–100	130–80	100–80	95–70	95–70
Stroke/bore	3.5–1.2	1.3–1.0	1.2–0.9	1.1–0.9	1.1–0.9	1.1–0.9
Compression ratio	12–15	15–16	16–18	16–22	20–24	22–24
Chamber	Open or shallow dish	Bowl-in-piston	Deep bowl-in-piston	Deep bowl-in-piston	Swirl pre-chamber	Single/multi-orifice pre-chamber
Air-flow pattern	Quiescent	Medium swirl	High swirl	Highest swirl	Very high swirl in pre-chamber	Very turbulent in pre-chamber
Number of nozzle holes	Multi	Multi	Single	Multi	Single	Single
Injection pressure	Very high	High	Medium	High	Lowest	Lowest

INJECTION PUMPS

- **In-line injection pumps** are used in engines in the 40 to 100 kW per cylinder maximum power range. They contain a plunger and barrel assembly for each engine cylinder.
- **Distributor-type fuel injection pumps** are normally used in multi-cylinder engines with less than 30 kW per cylinder maximum power with injection pressures up to 750 atm. These pumps have only one plunger and barrel.
- **High pressure common rail**: Diesel fuel under high pressure, over 20,000 PSI (138,000 kPa), is applied to the injectors, which are opened by a solenoid controlled by the computer.

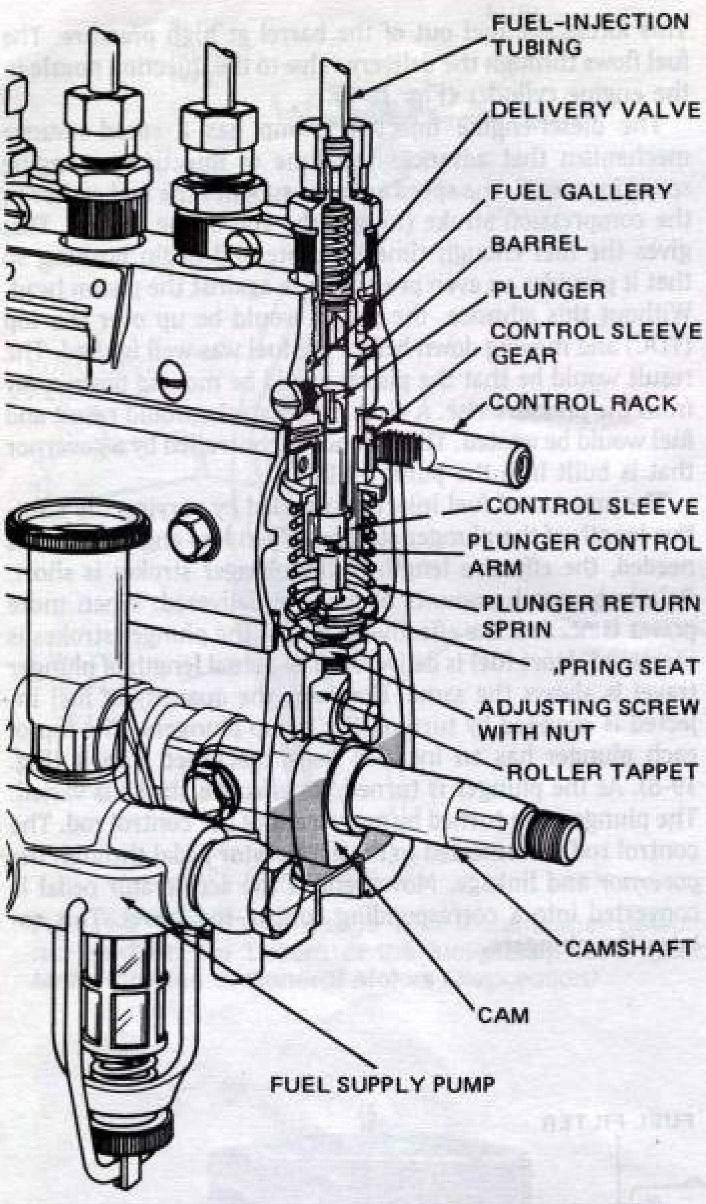


Fig. 19-7 Construction of an in-line plunger-type fuel-injection pump. *(Robert Bosch Corporation)*

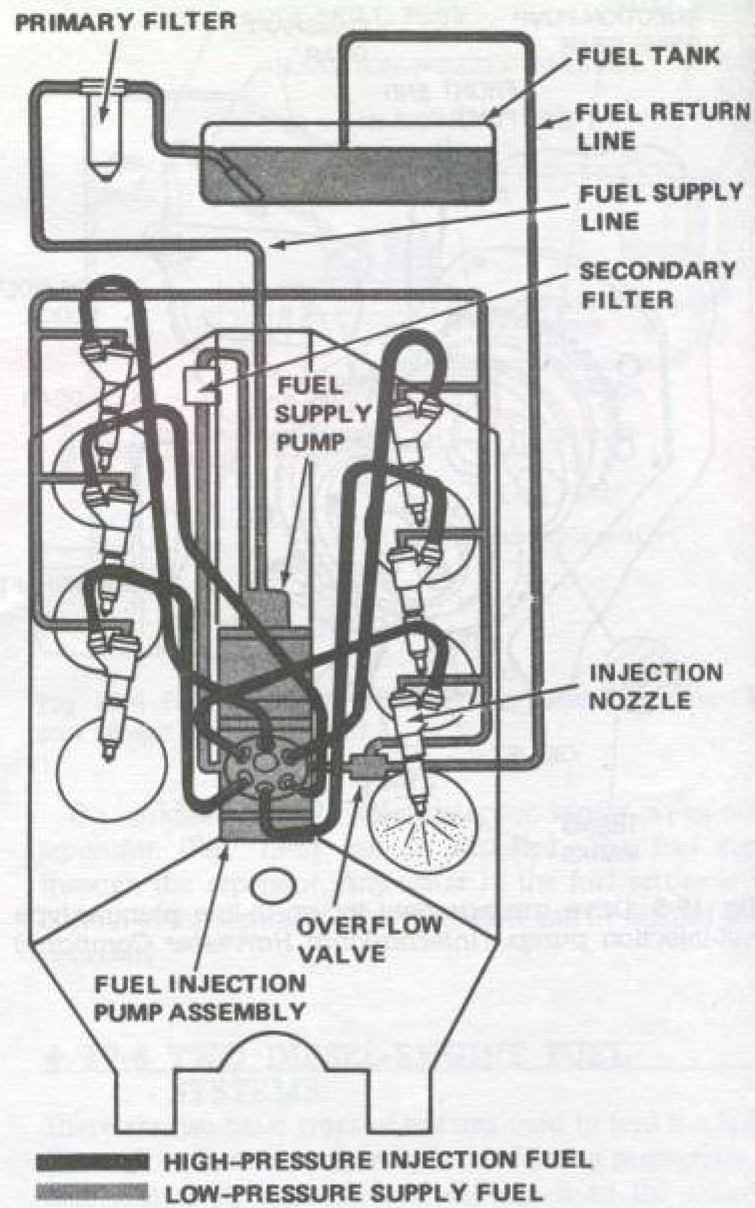


Fig. 19-9 Rotary-distributor injection-pump system for a V-6 diesel engine. *(General Motors Corporation)*

COMMON-RAIL SYSTEM (CRS)

Common-rail (accumulator) fuel-injection systems make it possible to integrate the injection system together with a number of its extended functions in the diesel engine, and thus increase the degree of freedom available for defining the combustion process.

The common-rail system's principal feature is that injection pressure is independent of engine speed and injected fuel quality.

FUEL TANK AND LIFT PUMP

High-Pressure Common Rail

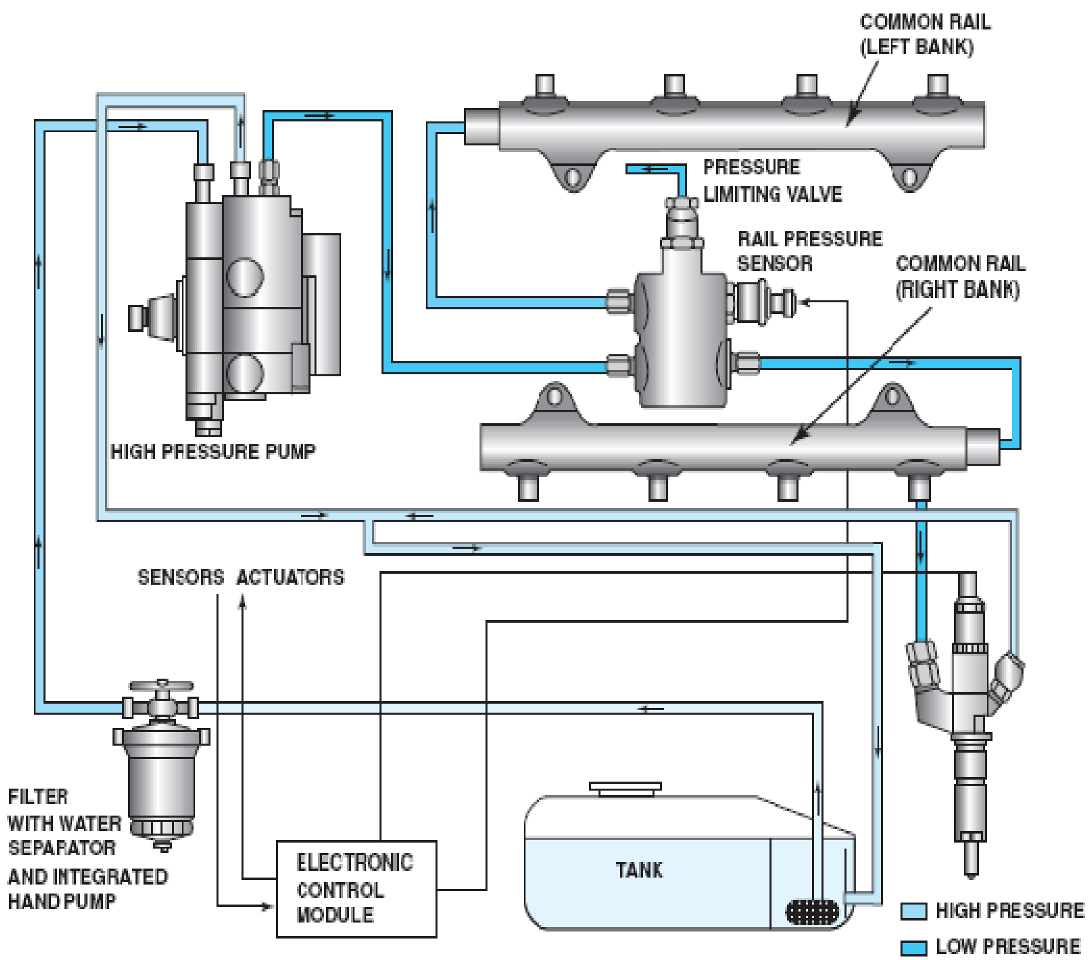
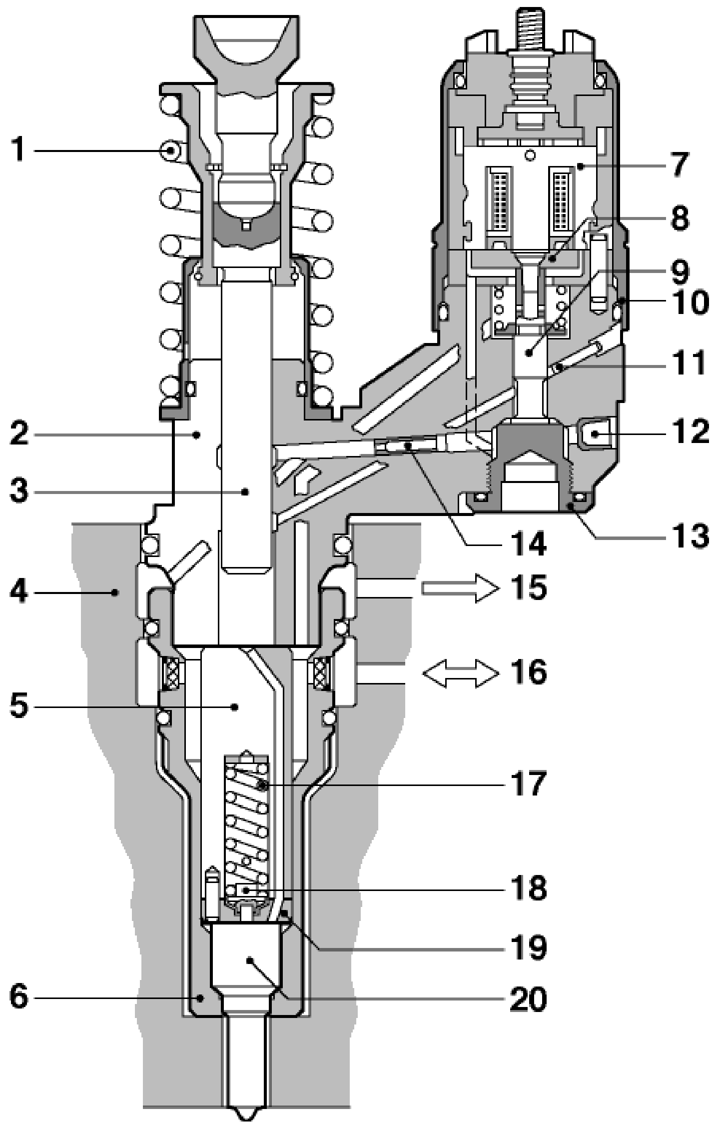


FIGURE 12-10 Overview of a computer-controlled high-pressure common rail V-8 diesel engine.

UNIT INJECTOR SYSTEM (UIS) FOR COMMERCIAL VEHICLES

The electronically controlled unit injector is a single-cylinder fuel-injection pump with integral nozzle and solenoid valve which is installed directly in the cylinder head of the diesel engine. Each engine cylinder is allocated its own unit injector, which is operated by a rocker arm driven by an injection cam on the engine camshaft.

UNIT INJECTOR SYSTEM (UIS) FOR COMMERCIAL VEHICLES



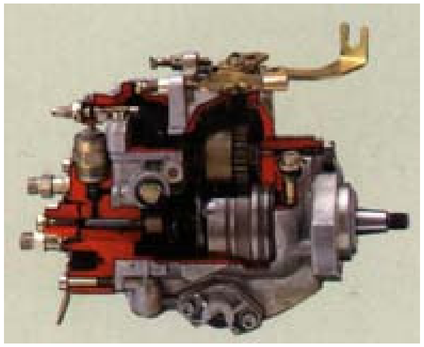
Unit Injector (UI)

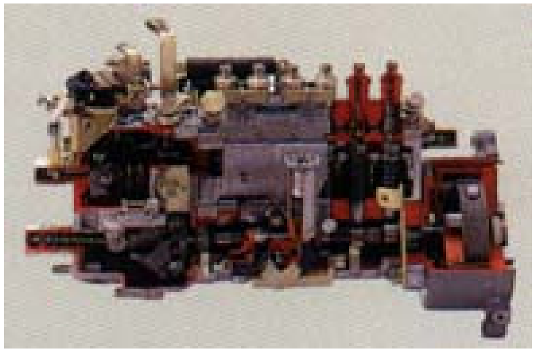
1. Return spring
2. Pump body
3. Pump plunger
4. Cylinder head
5. Spring retainer
6. Tension nut
7. Stator
8. Armature plate
9. Solenoid-valve needle
10. Solenoid-valve tension nut

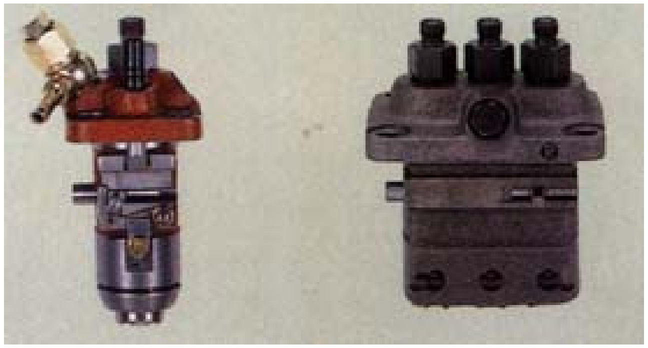
Unit Injector (UI)

11. High pressure plug
12. Solenoid travel stop
13. Restriction
14. Fuel return
15. Fuel supply
16. Injector spring
17. Pressure pin
18. Shim
19. Injector

TYPES OF FUEL INJECTION PUMP







1. VE Type Pump
(sectional area)
First developed in the world by Bosch and thirdly by DPICO, lighter and smaller than the traditional serial type

2 . PE Type Pump
(sectional area)
Used for heavy engines of buses, trucks & special vehicles, equipments and ships

3 . PER Type Pump
Used for farm equipments and low-speed hips with TAPET inside of the pump.

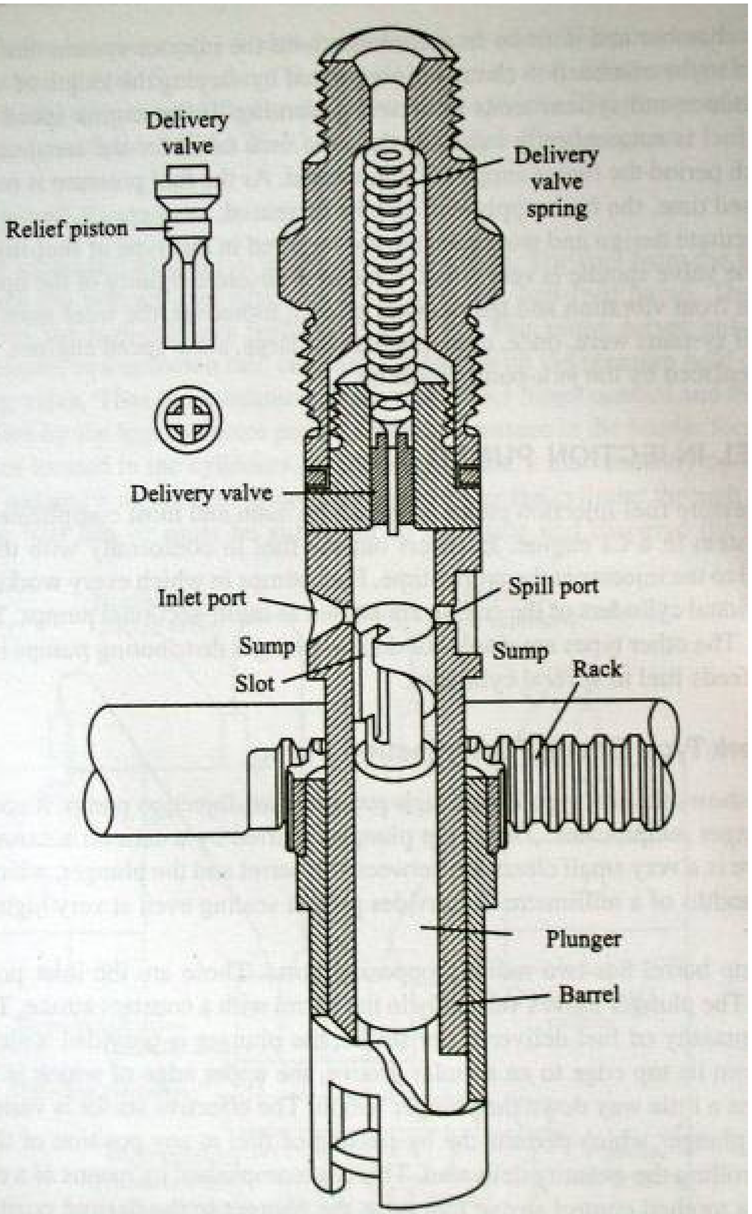


Figure 10.7 Sectional view of Bosch pump elements.

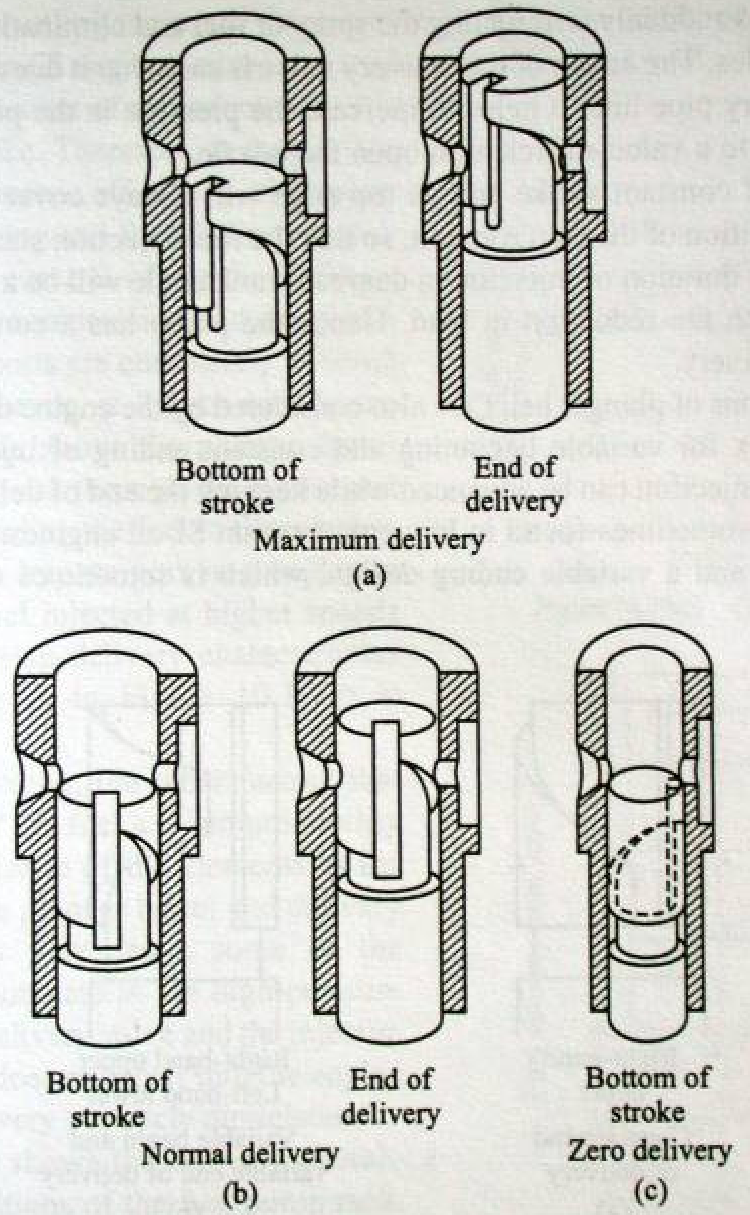
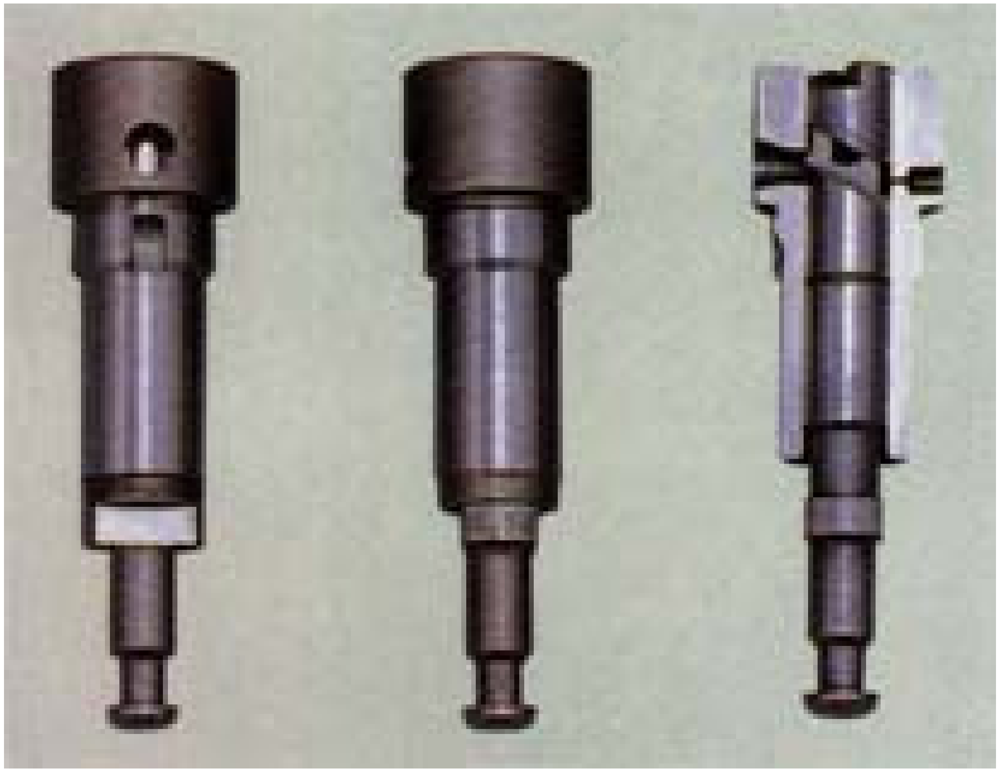


Figure 10.8 Position of the helix for various load conditions.



Plunger

Delivery valve

WORKING OF PUMP PLUNGER

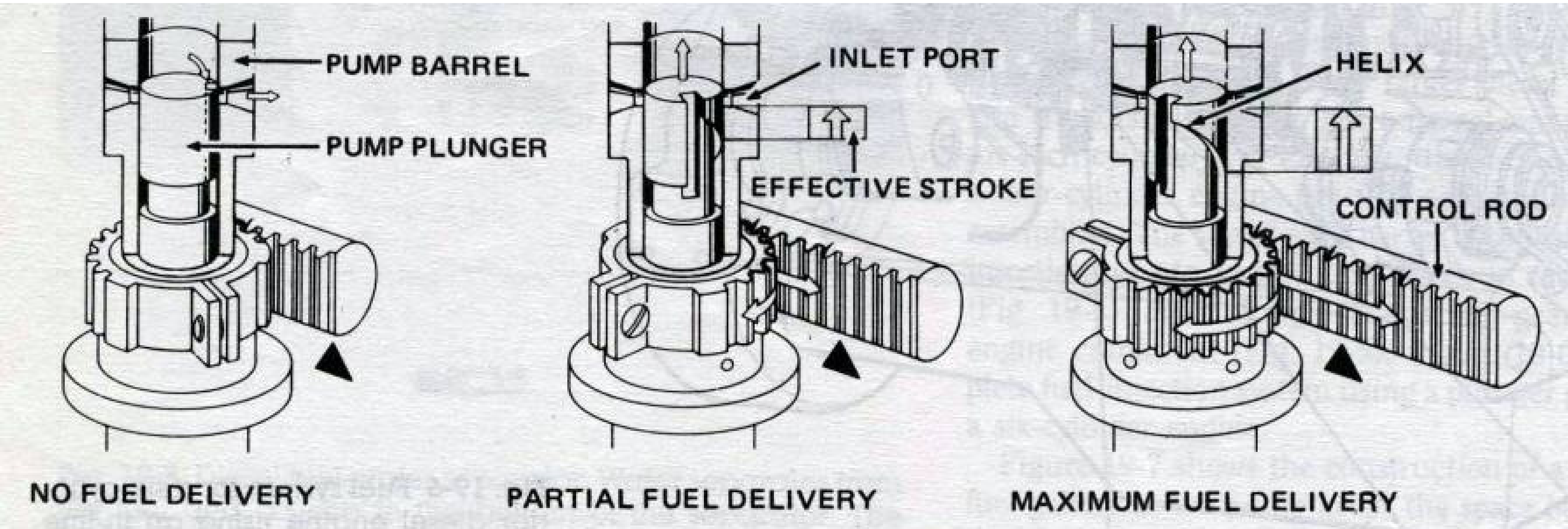


Fig. 19-8 Movement of the toothed control rod turns the pump plungers to vary the amount of fuel injected. *(Robert Bosch Corporation)*

INJECTOR AND NOZZLES

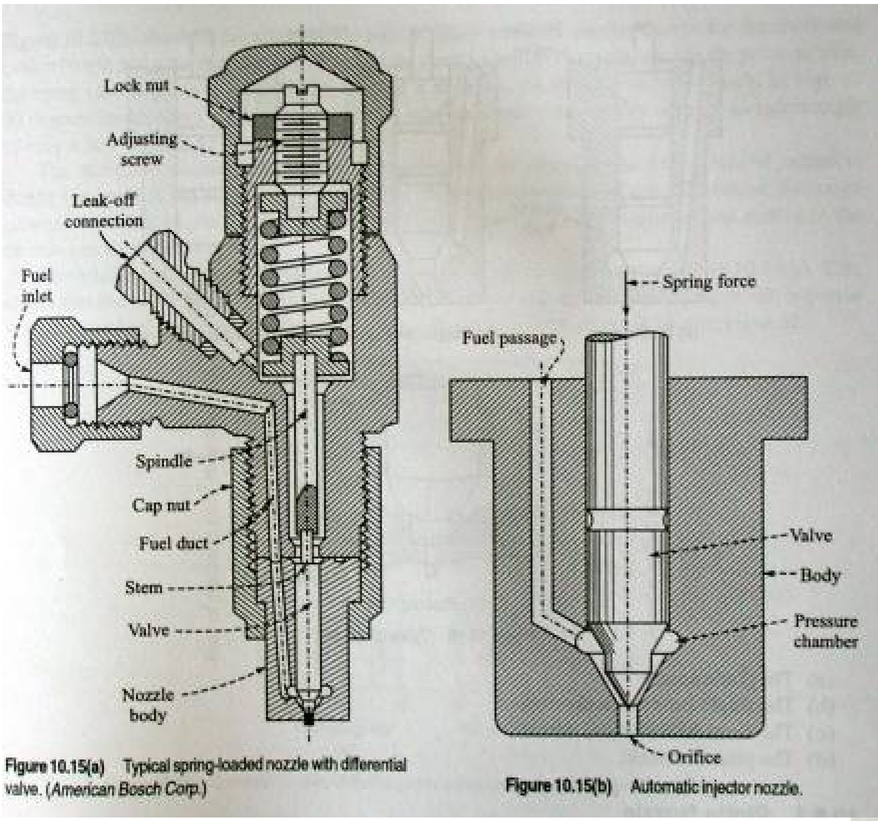


Figure 10.15(a) Typical spring-loaded nozzle with differential valve. (American Bosch Corp.)

Figure 10.15(b) Automatic injector nozzle.

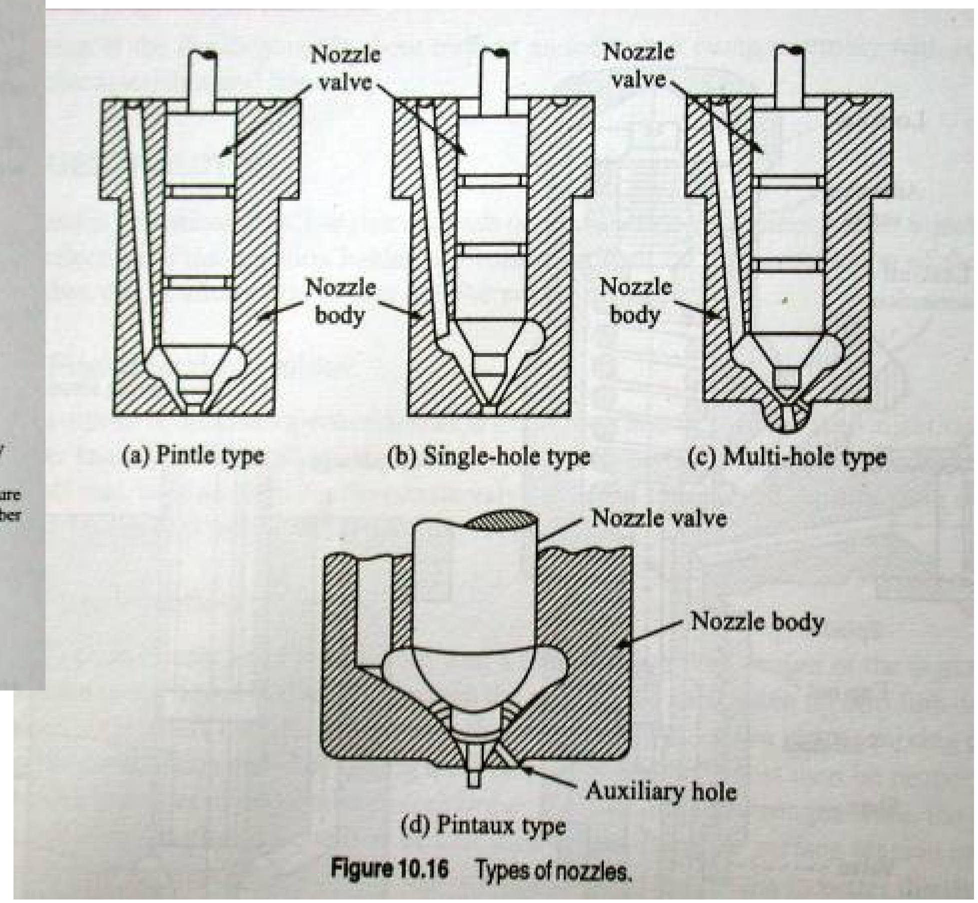


Figure 10.16 Types of nozzles.

NOZZLES

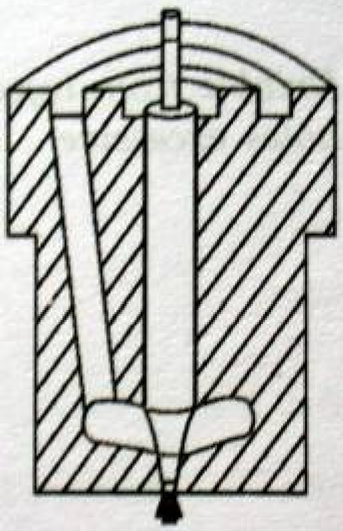


Fig. 3.37. Single hole nozzle.

Fig. 3.38. Multi-hole nozzle.

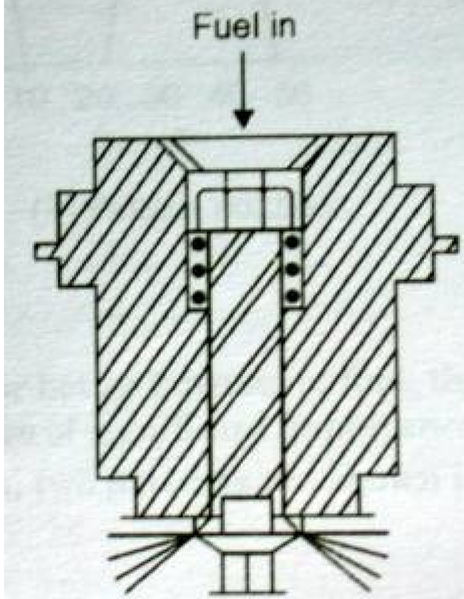
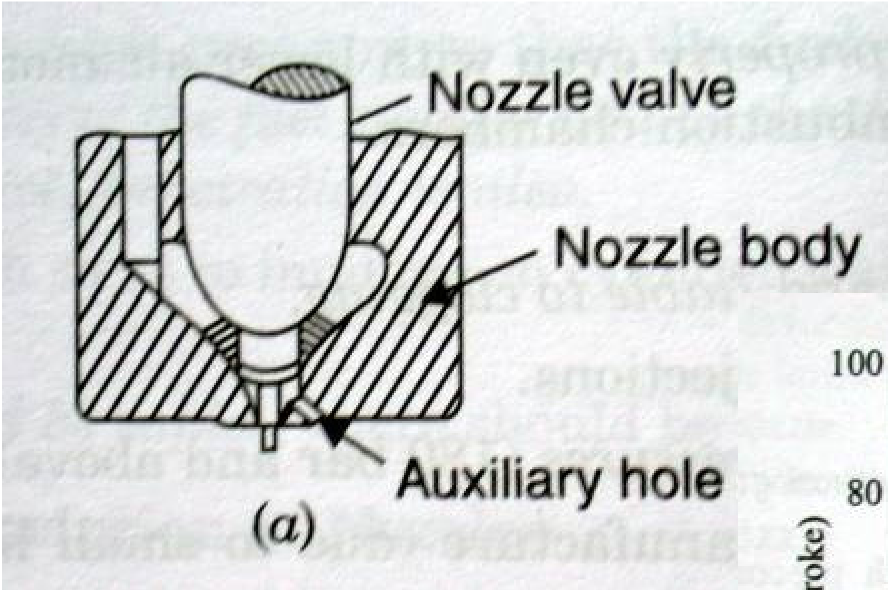


Fig. 3.39. Circumferential orifice.



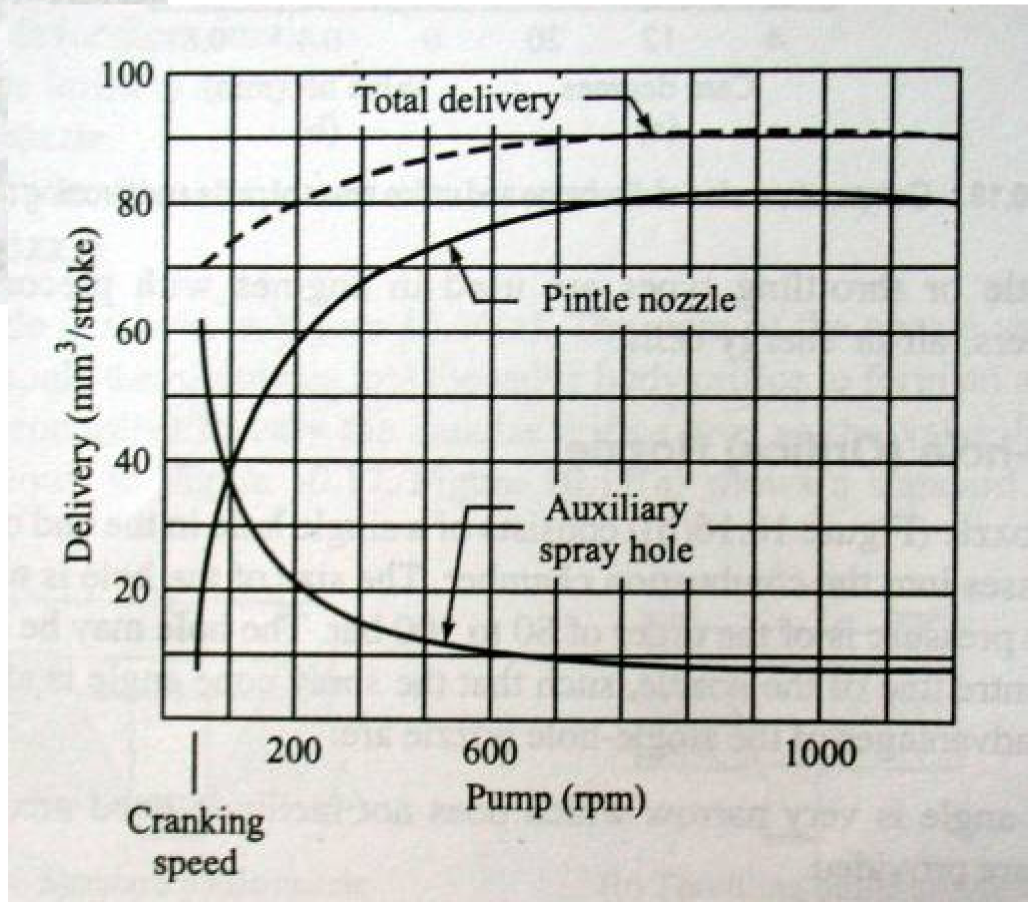
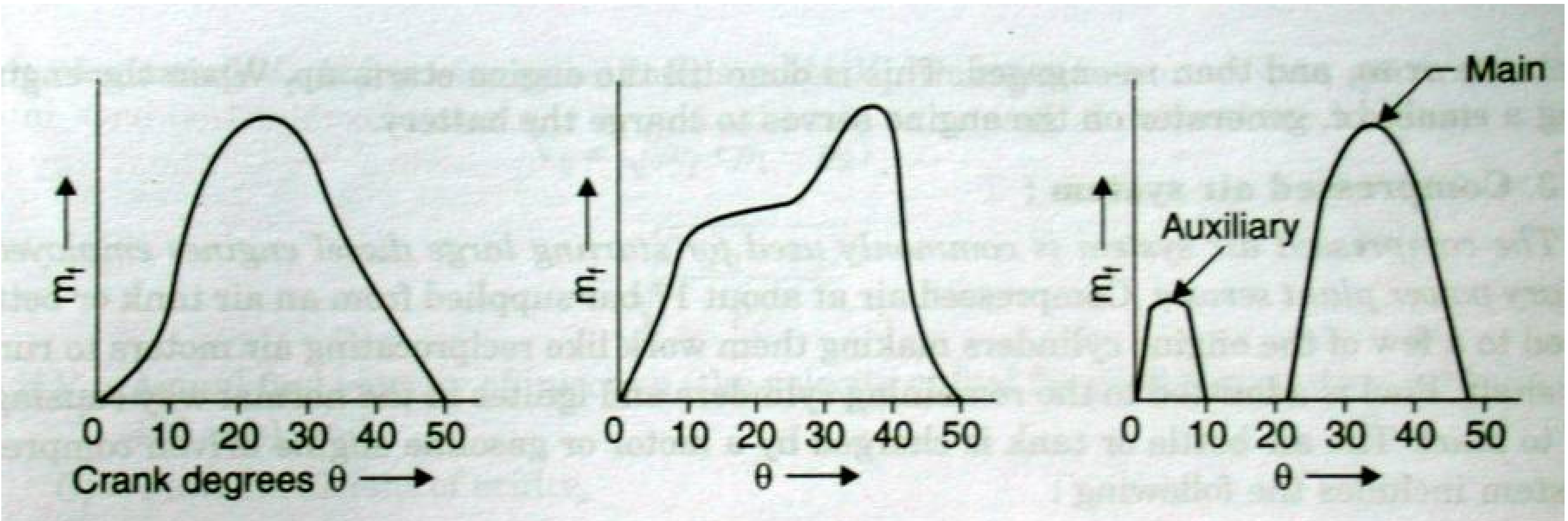


Figure 10.19 Fuel delivery characteristics of a pintaux nozzle.

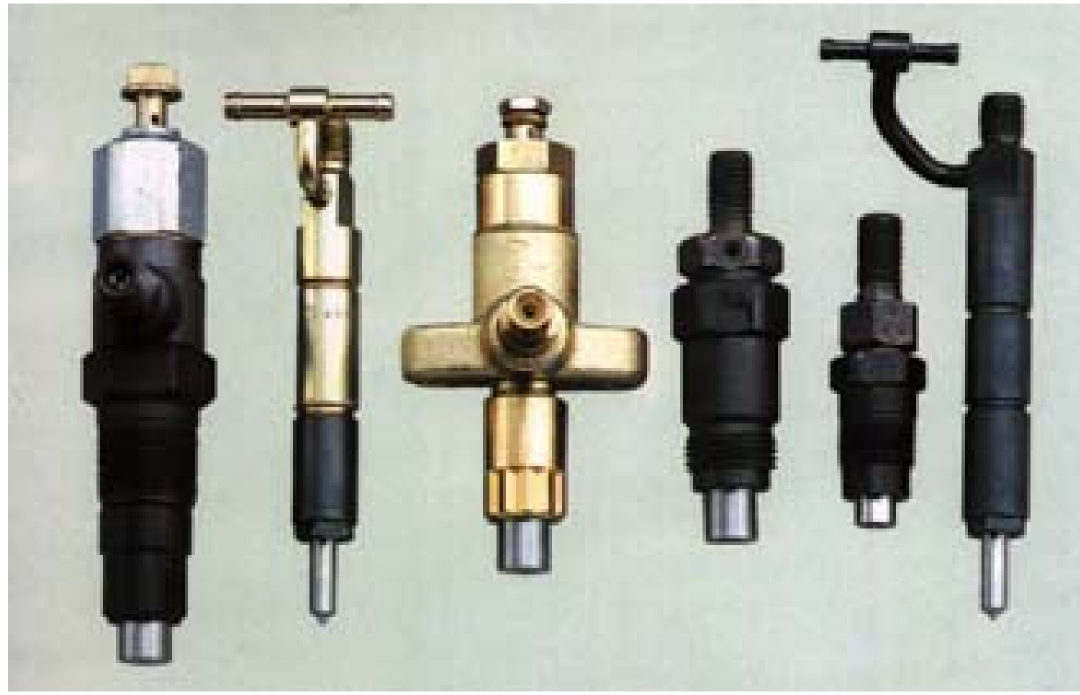
INJECTION RATE CHARACTERISTICS OF DIFFERENT NOZZLES



(*i*) Multi-hole nozzle (*ii*) Pintle nozzle (*iii*) Pintaux nozzle

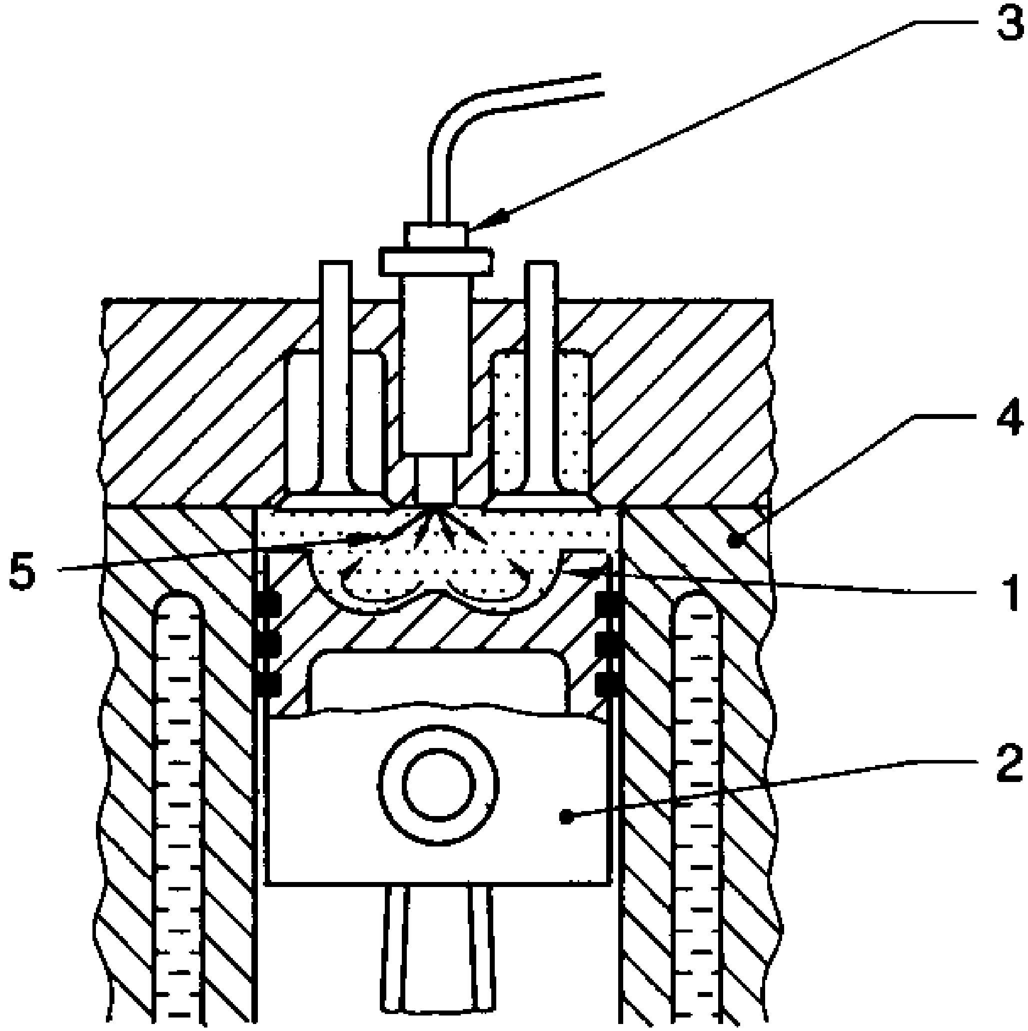
Fig. 3.42. Injection rate characteristics of nozzles.

Nozzle holder



Nozzle

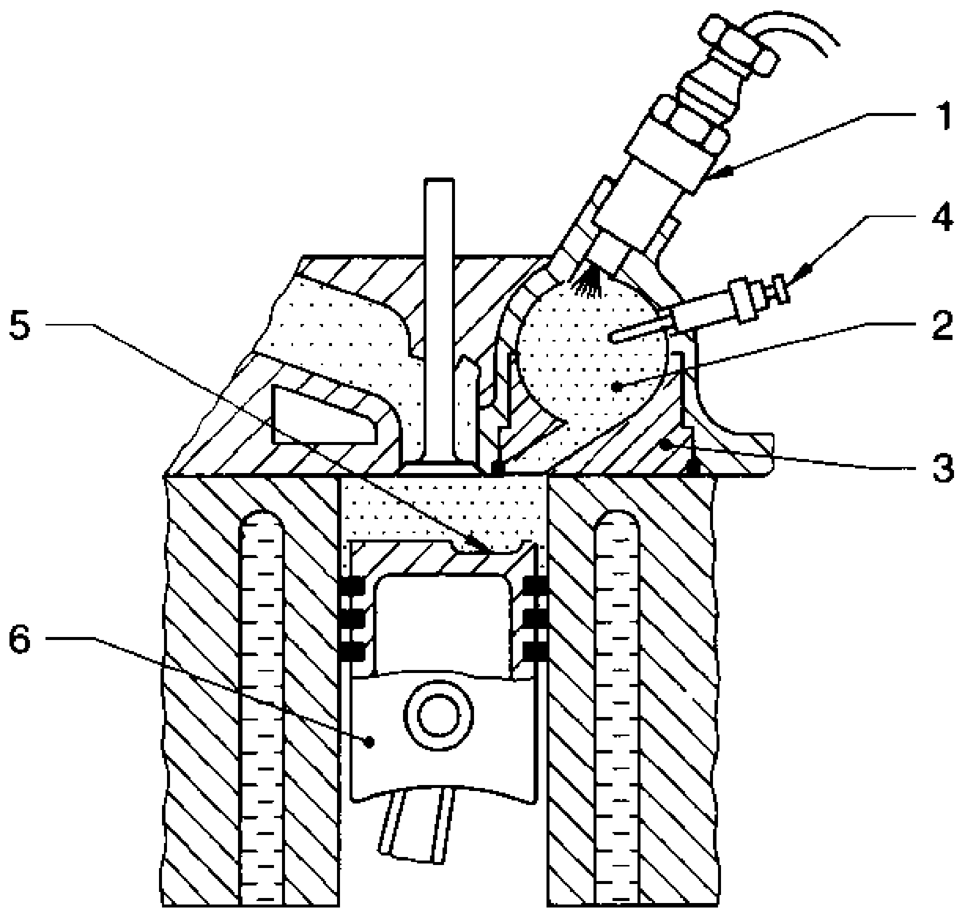
Multi-Hozzle Nozzle



Functional aspect

This nozzle works in conjunction with a Torroidal chamber.
The provision of torroidal chamber (1) on the top of the piston (2) provides a squish turbulence of air to enable fuel to mix with air fully.
The air in the cylinder (4) is compressed to a very high pressure. The fuel nozzle (3) has 4 spray (5) holes and fuel is sprayed at a very high pressure to penetrate into the highly compressed air. The fuel is ignited very quickly and combustion proceeds in the cylinder (4).
No heater or glow plug is necessary. Hence starting of engine is easy. The method is called direct injection in diesel engines. (D.I.Engines)

Pintle Nozzle



Functional aspect

The pintle nozzle (1) works in conjunction with Pre-chamber (2) provided in the cylinder head (3).
The pintle nozzle (1) provides a conical spray of fuel at a low pressure on the compressed air in the pre-combustion chamber (2).
The pre-chamber provides good turbulence of air for mixing with fuel spray. Since the air in the pre-chamber (2) is not compressed to high pressure enough heat is not available for igniting the fuel. Hence a glow plug (4) to preheat the air is provided.
The combustion of fuel takes place in two stages, i.e first in the pre-combustion chamber (2) and it is continued in the spherical chamber (5) on the top of the piston. The burnt gas and unburnt fuel particles pass to the main chamber through passage in the pre-chamber (2). During this process further atomisation of fuel takes place and all fuel is burnt out. The combustion process is continued on the top of the piston (6).
This method is called Indirect Injection in diesel engine.

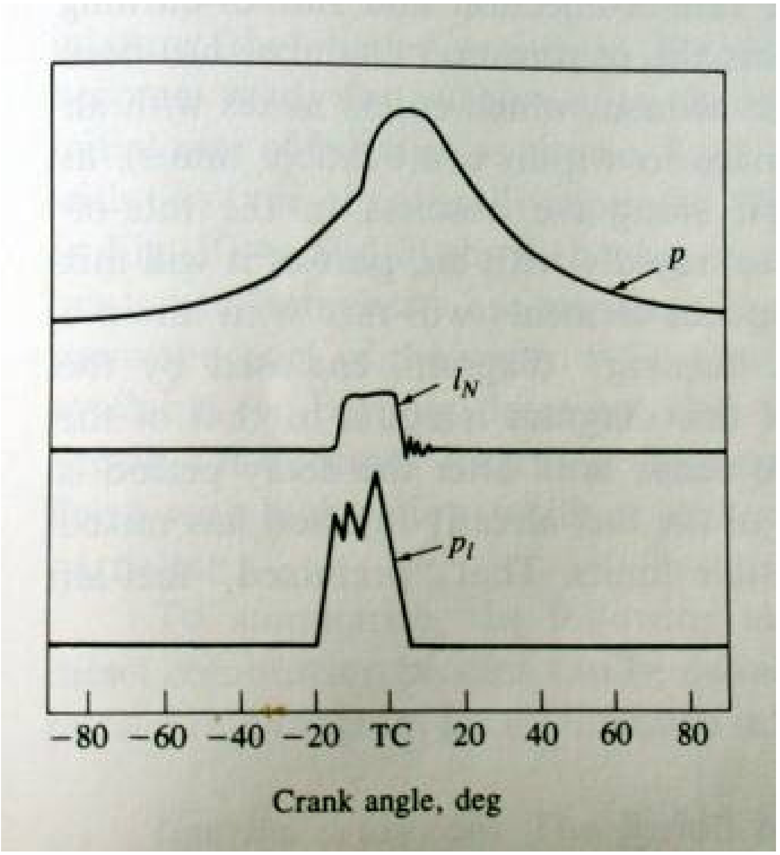
COMPARISON OF DIFFERENT TYPES OF NOZZLE

S.N.	Nozzle	Properties	Uses	Advantages	Disadvantages
1	Single hole	Diameter >0.2 mm Spray angle:5-15° Injection pressure: 80-100 bar	Open combustion chamber	Simple in operation and construction	Poor fuel mixing with air. It requires high injection pressure. It has tendency to dribble.
2	Multi-hole	No. of holes: 4-10 Dia: 0.125-0.85 mm Spray angle: 20-45° Pressure: 165-300 bar	Open combustion chamber	Good automisation. Better mixing even with slow air movement.	Very high injection pressure. Chances of nozzle hole clogging by carbon. Requires greater maintenance and operation expenses.
3	Circumferential orifice	Large spray angle		Large spray angle for better mixing of fuel with air.	
4	Pintle nozzle	Variable spray angle up to 60° Pressure: 110-135 bar	Pre-chamber	Spray angle can be varied by changing the section of pin along its length.	Distribution and penetration poor, hence not suitable for open combustion chamber.
5	Pintaux (Pintle+auxilliary)	Auxilliary hole dia: 0.2mm Spary angle: 30°	Pre-chamber	Better performance in cold starting.	Tendency for the auxilliary hole to choke. The injection characteristic of the pintaux nozzle is poorer than that of the multi-hole nozzle.

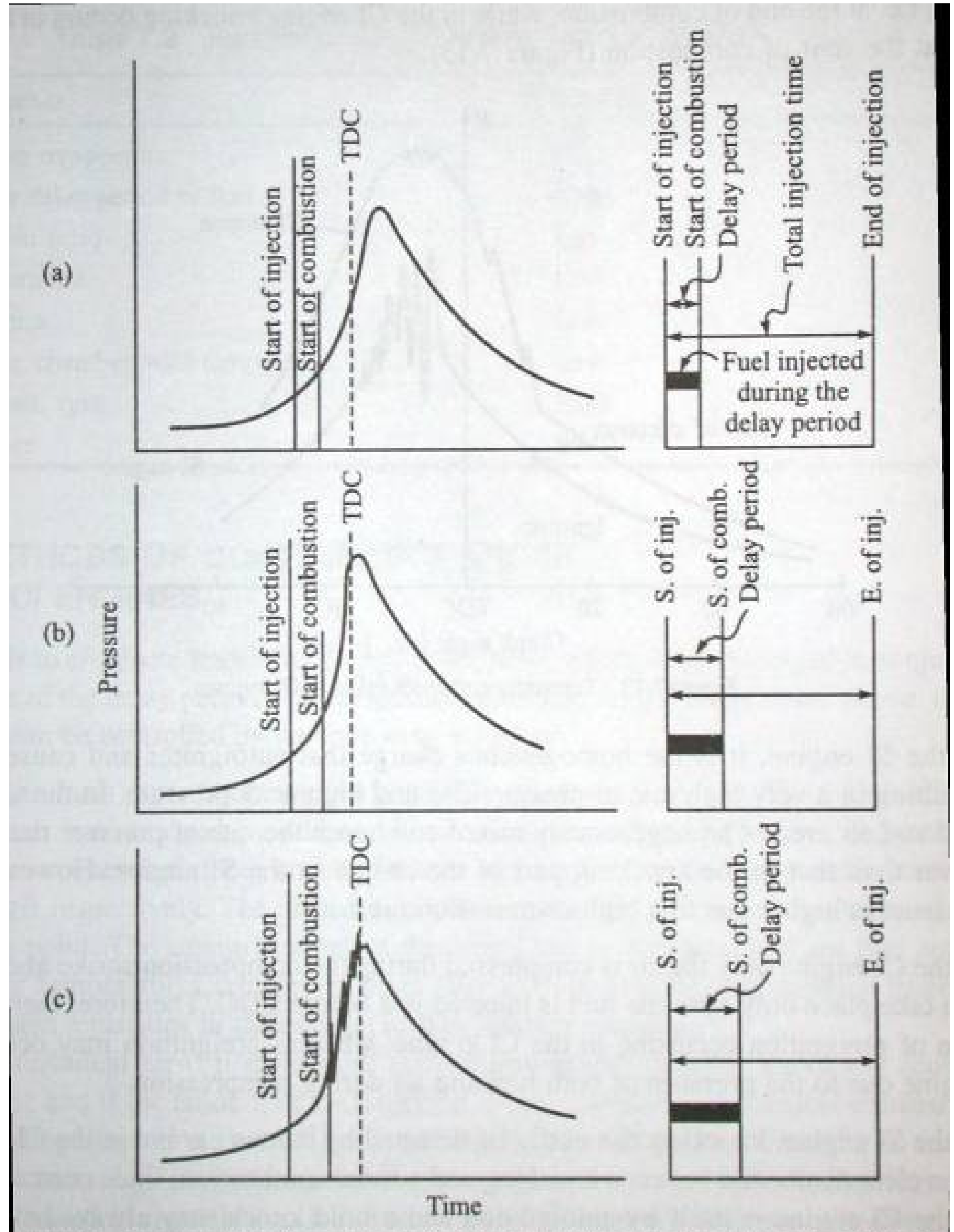
diesel fuel injector - how it works.flv

IGNITION DELAY

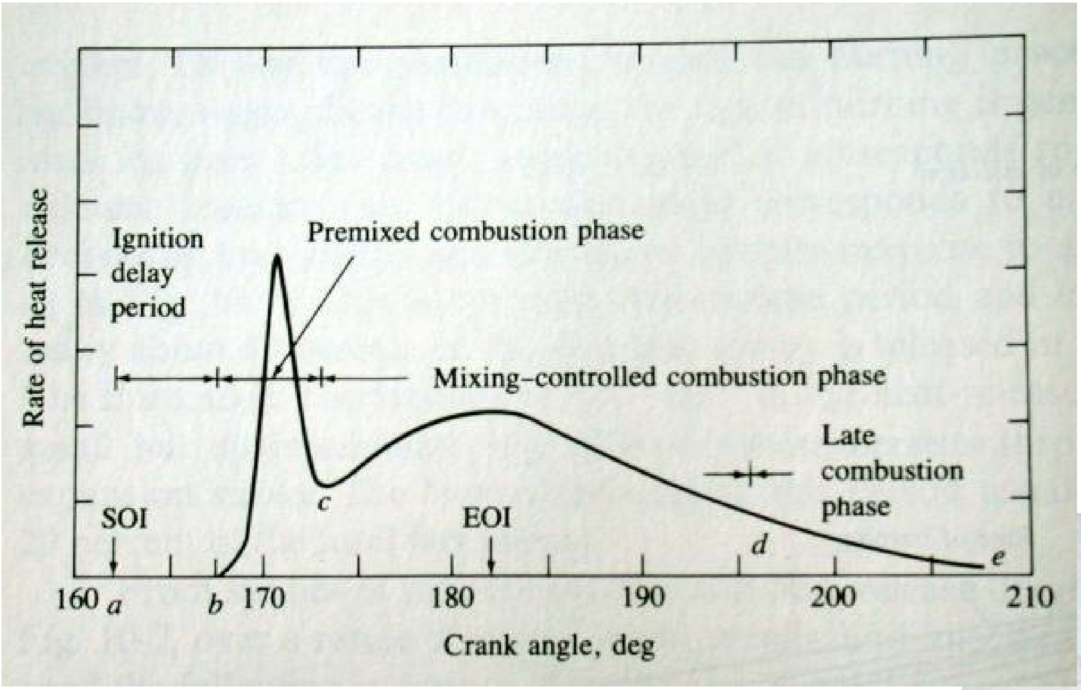
- The ignition delay in a diesel engine is defined as the time (or crank angle) interval between the start of injection and the start of combustion. The start of injection is taken as the time when the injector needle lifts off its seat.
- The combustion of injected fuel depends on:
  - The physical processes are: the atomization of the liquid fuel jet; the vaporization of the fuel droplets; the mixing of fuel vapor with air.
  - The chemical processes are the pre-combustion reactions of the fuel, air, residual gas mixture which lead to autoignition.
- These processes are affected by engine design and operating variables, and fuel characteristics.



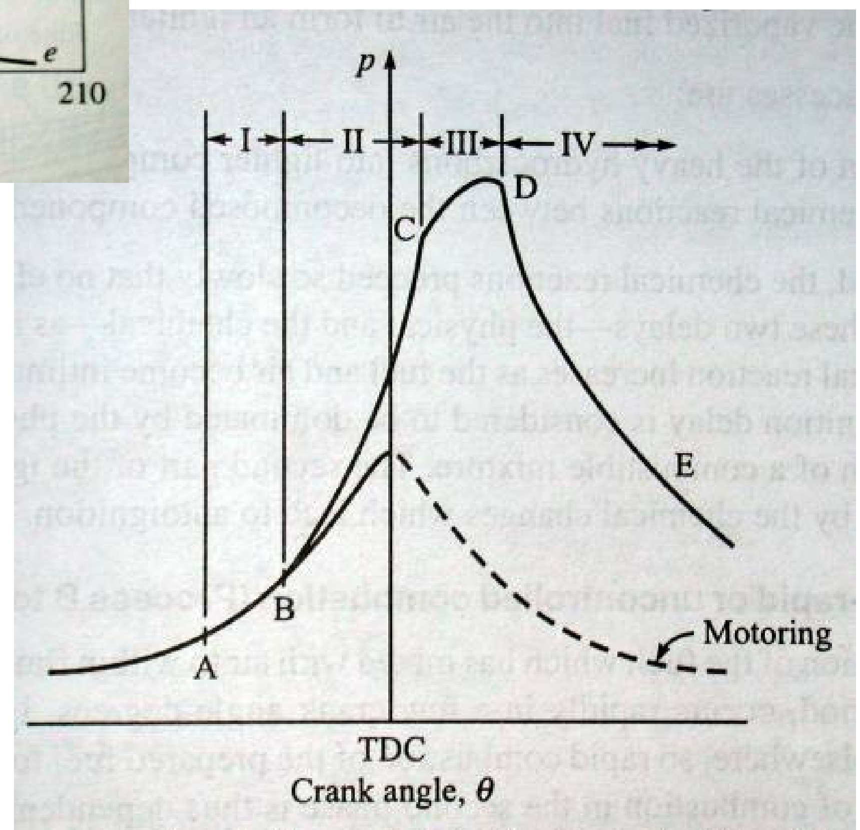
Cylinder pressure p, injector needle lift l_N, and injection-system fuel-line pressure p_1, as functions for crank angle for small DI engine



ure 7.12 Diagrams illustrating the effect of ignition delay on the rate of pressure rise in a CI engine



Typical DI engine heat-release-rate diagram identifying different diesel combustion phases.



A-Start of fuel injection
AB-Delay period (mixture formation)
B-Start of ignition (combustion)
C-End of ignition
BC-Rapid or uncontrolled combustion
D-Combustion
CD-Mixing-Controlled combustion
DE-Late combustion (products)

INFLUENCE OF VARIOUS FACTORS ON DELAY PERIOD

- Ignition quality of fuel (cetane no.)
- Injection timing
- Compression ratio
- Injection pressure, rate of injection and drop size
- Intake, water jacket and fuel temperature
- Intake pressure
- Engine speed
- Air-fuel ratio
- Injection quantity or Load
- Engine size
- Combustion chamber wall effects
- Swirl rate
- Exhaust gas recirculation
- Types of combustion chamber

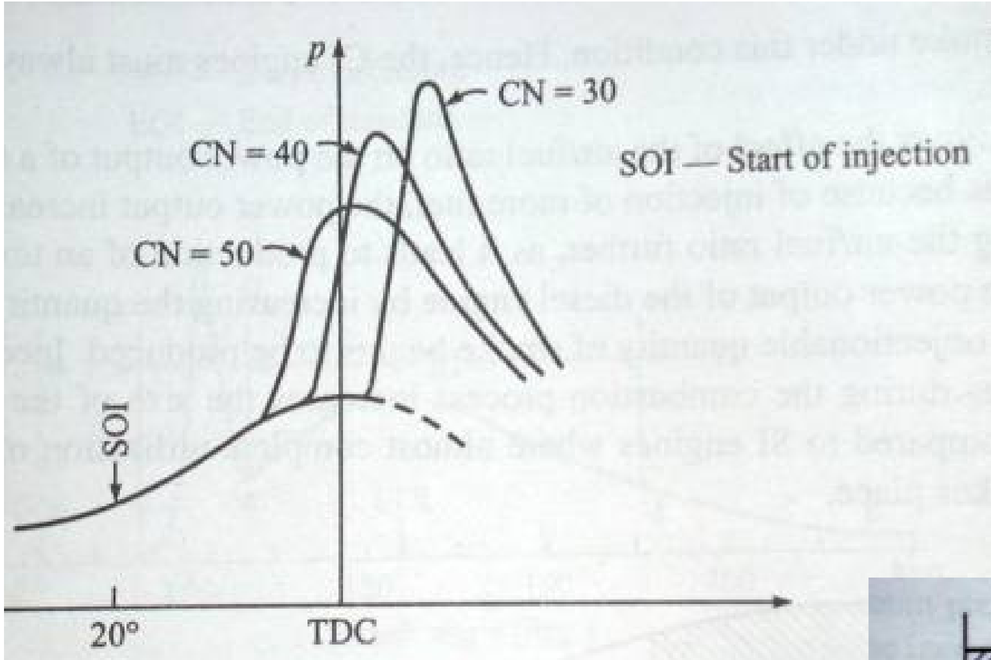


Figure 7.9 Effect of Cetane number (CN) on the *p*–*θ* diagram.

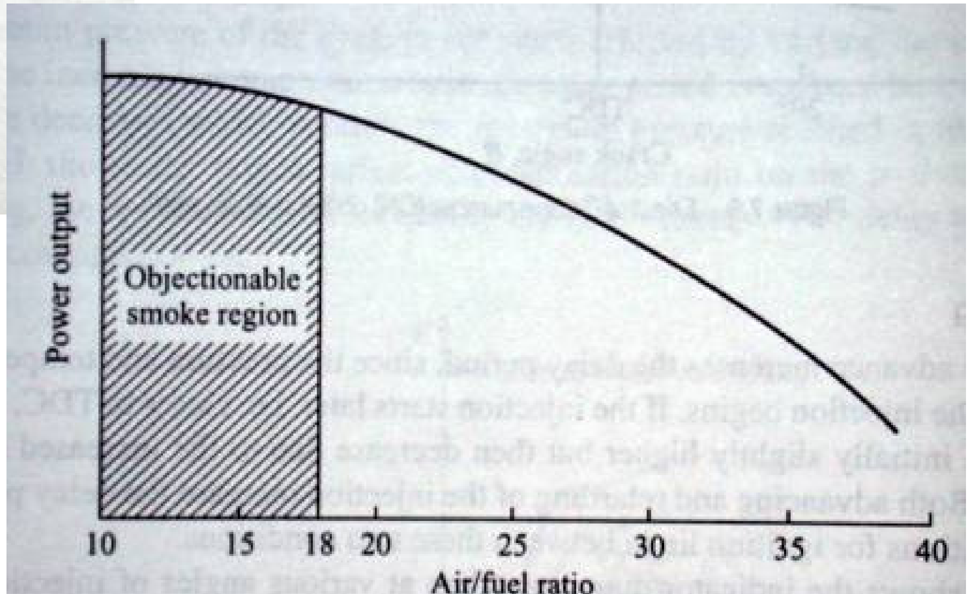


Figure 7.8 Effect of air/fuel ratio on the power output of a CI engine.

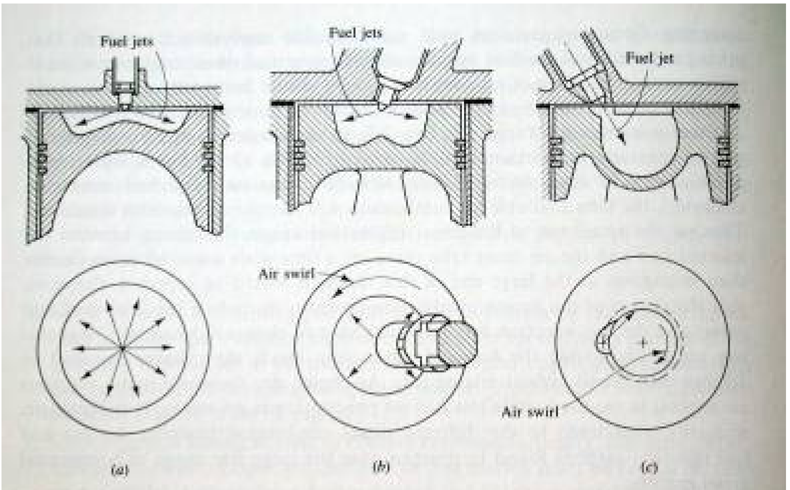
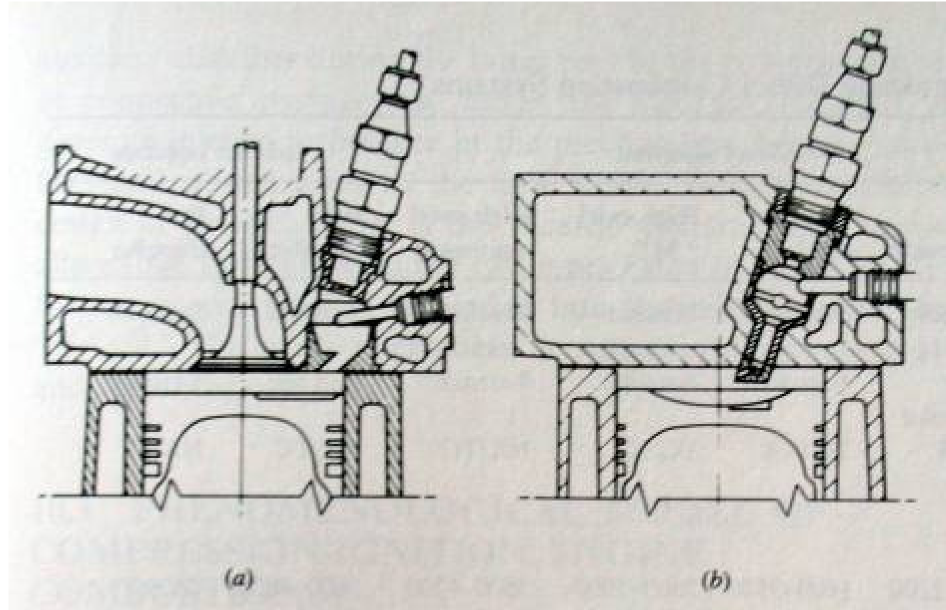
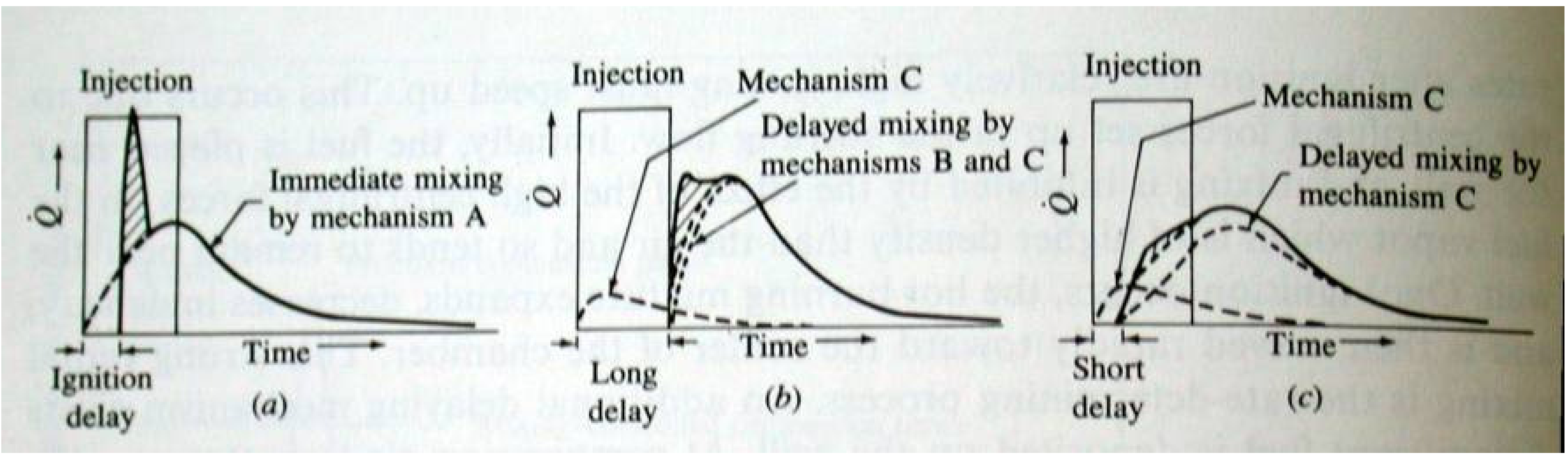


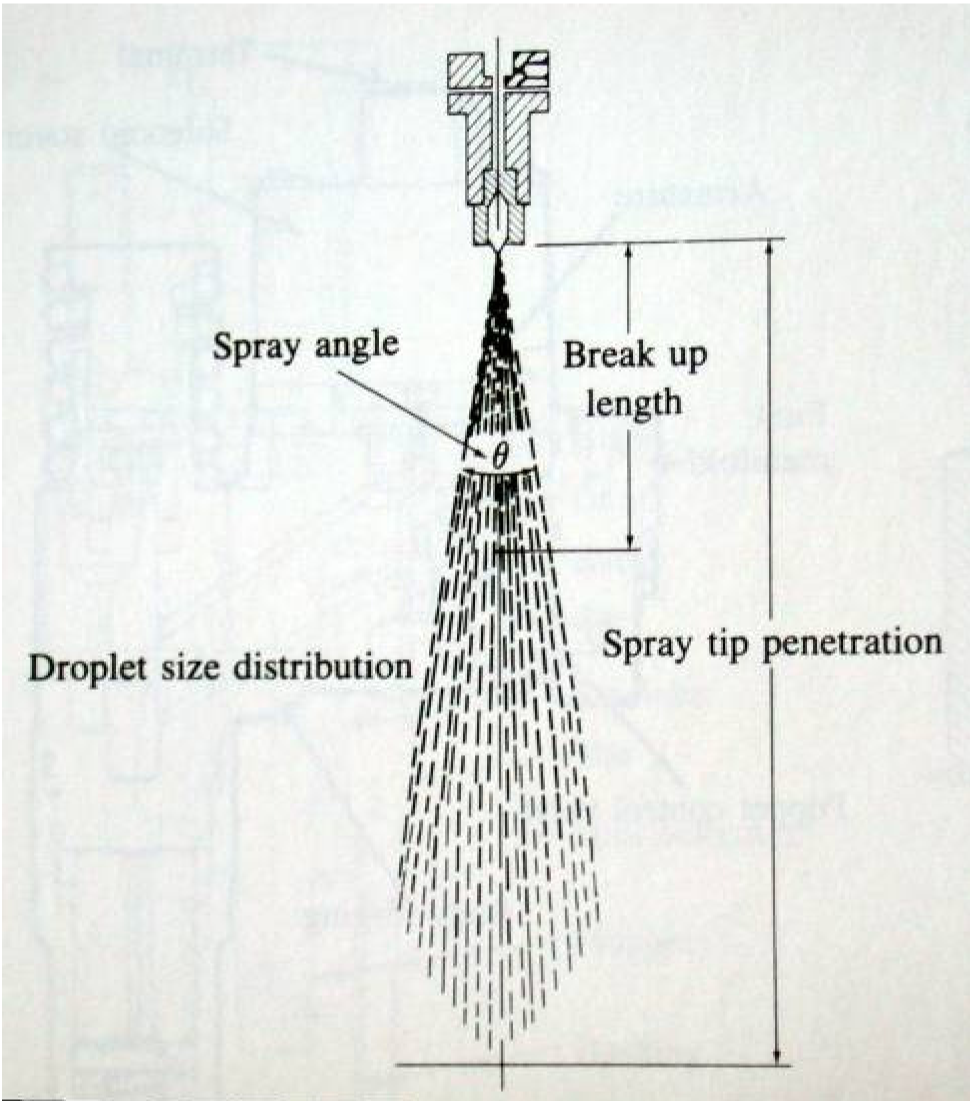
FIGURE 10-1
Common types of direct-injection compression-ignition or diesel engine combustion systems: (a) quiescent chamber with multihole nozzle typical of larger engines; (b) bowl-in-piston chamber with swirl and multihole nozzle; (c) bowl-in-piston chamber with swirl and single-hole nozzle. (b) and (c) used in medium to small DI engine size range.

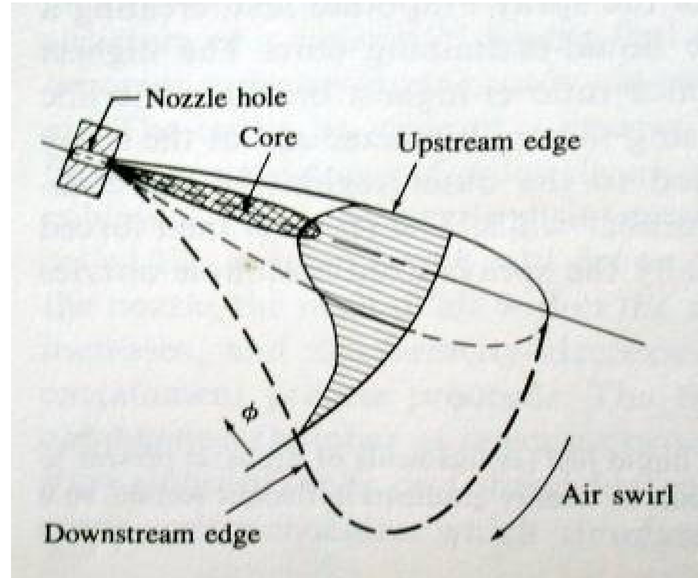


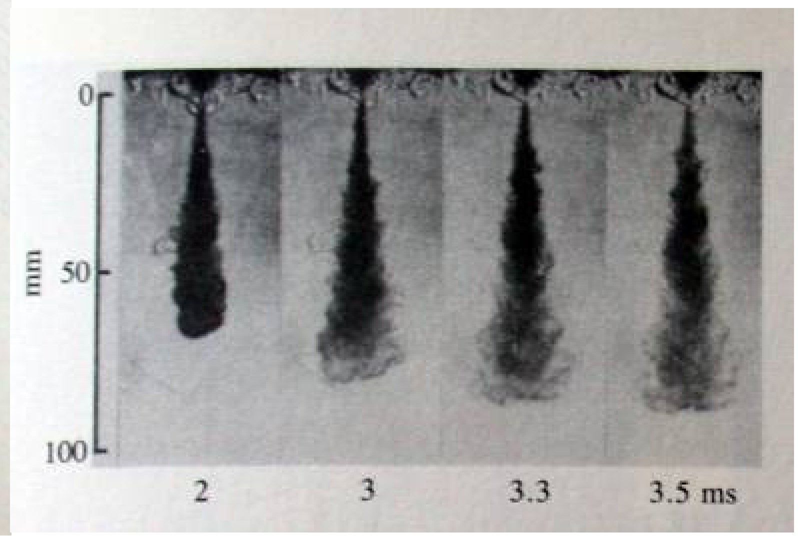


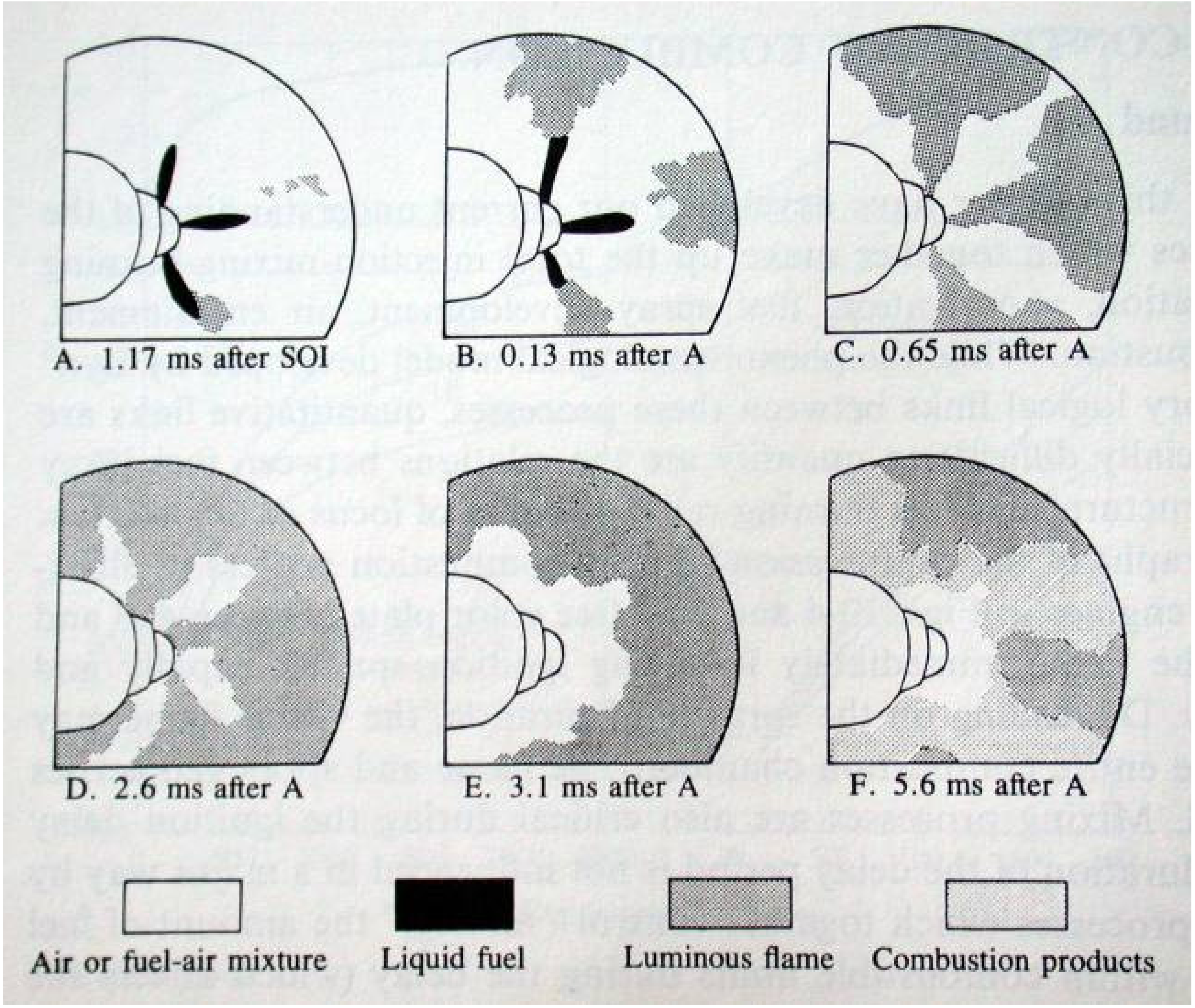
Schematic injection-rate and burning-rate diagrams in three different types of naturally aspirated diesel combustion system: a) DI engine with central multihole nozzle; b) DI “M” type engine with fuel injected on wall; c) IDI swirl chamber engine.

FUEL SPRAY


Spray angle
θ
Break up
length
Spray tip penetration
Droplet size distribution


Nozzle hole
Core
Upstream edge
ϕ
Air swirl
Downstream edge


0
50
100
mm
2
3
3.3
3.5 ms



Tracing of outer boundary of liquid fuel spray and flame from high-speed movies of diesel combustion taken in a rapid-compression machine, looking down on piston through transparent head.

TEST BENCH

GOVERNOR

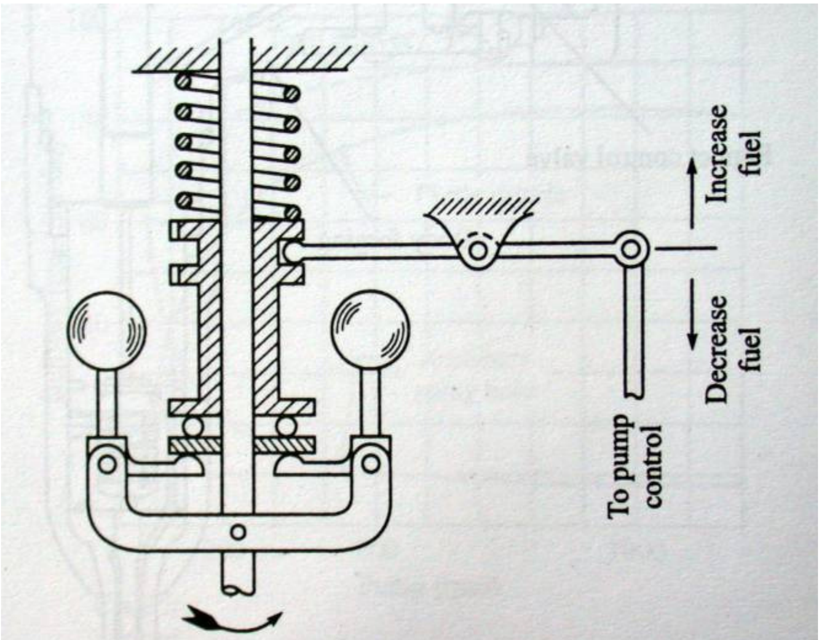


Figure 10.21 Simple mechanical governor.

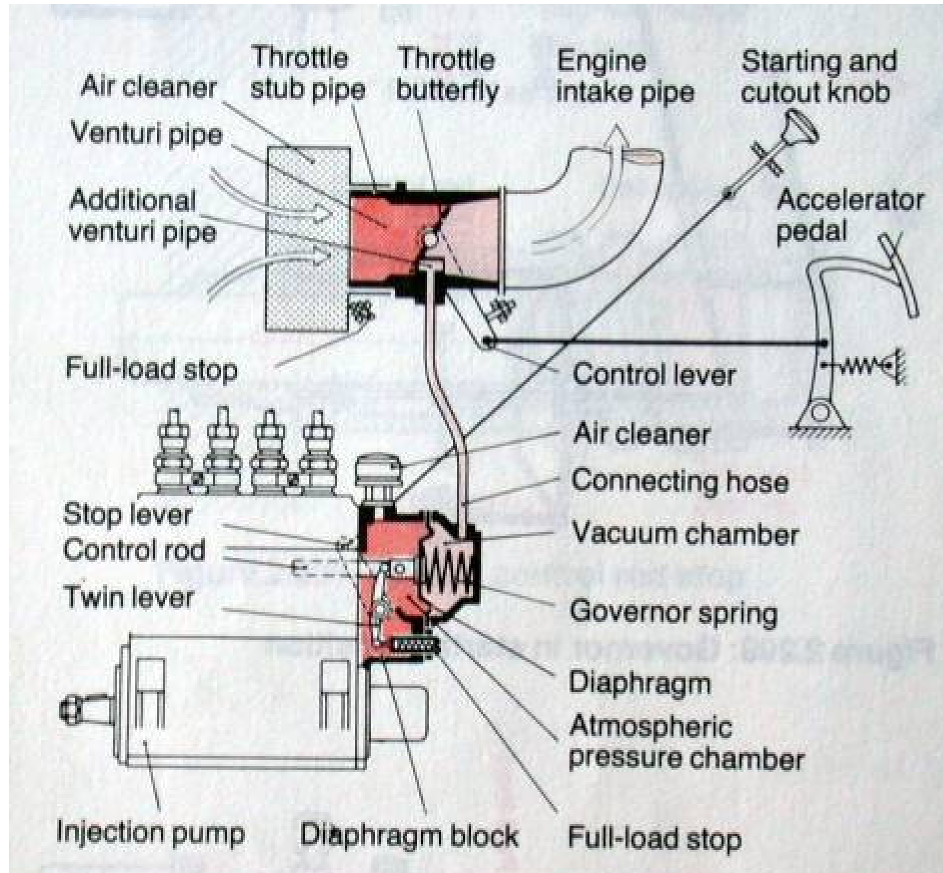


Figure 2.212: Pneumatic governor (schematic)

MECHANICAL GOVERNOR

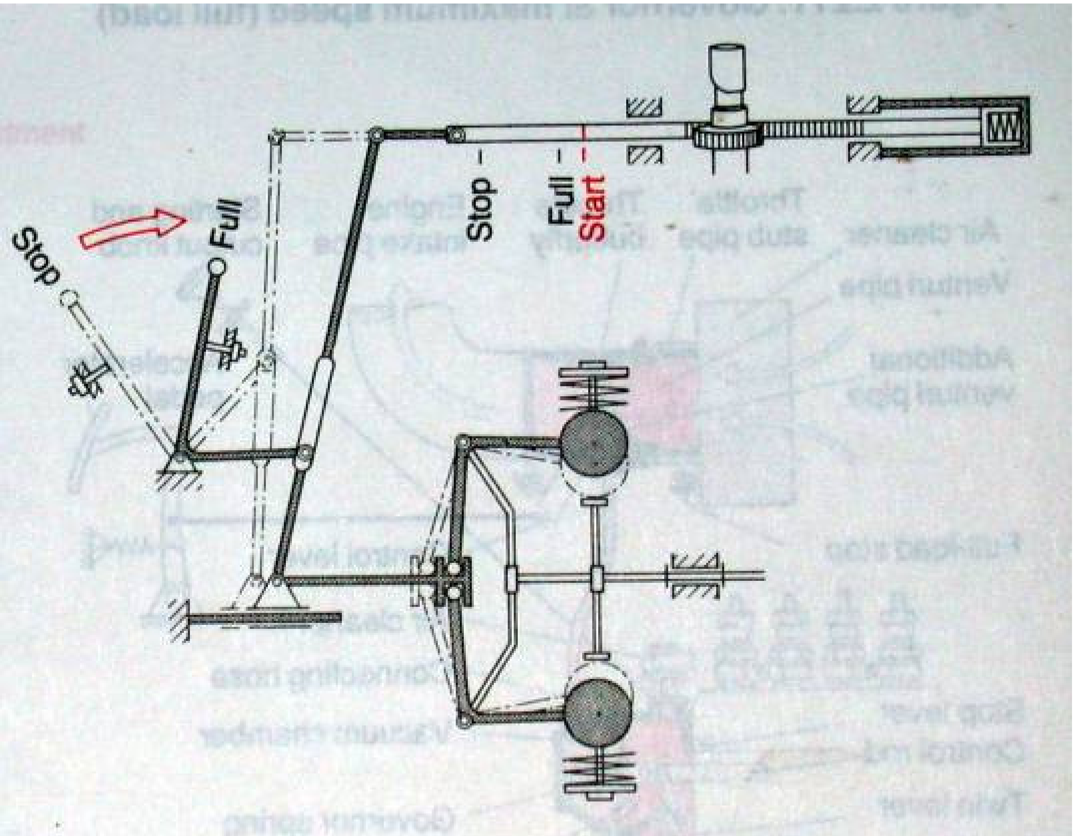


Figure 2.209: Governor in starting position

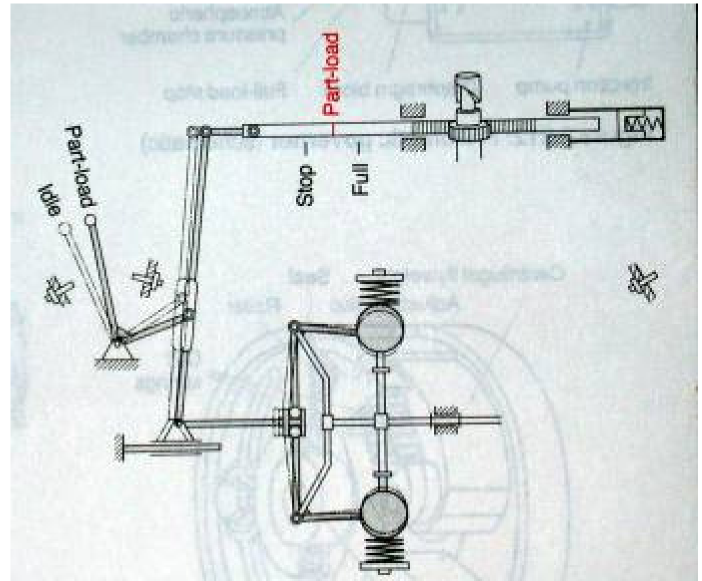


Figure 2.210: Governor at part-load

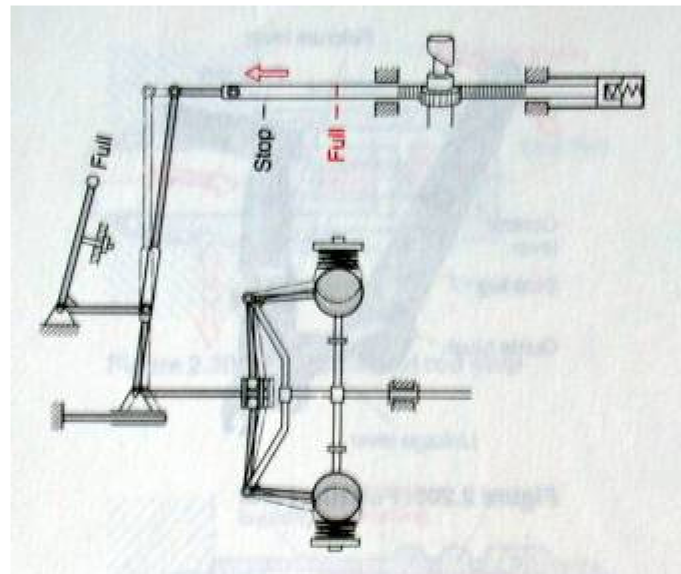


Figure 2.211: Governor at maximum speed (full load)

CONCLUSIONS

- Diesel fuel supply system depends on the type of injection. It may be either DI or IDI.
- DI system is used in slow running large engines whereas IDI is used in smaller but fast running engines.
- Glow plugs are used to enhance the cold starting.
- Care should be taken to use clean diesel fuel.
- Diesel engines running at low rpm emit more health damaging smoke.
- Periodic servicing of fuel system is very important; such as changing of filters, calibration of injection pump etc.
- Only a trained and skilled technician should handle the injection pump.