

Diesel injection, ignition, and fuel air mixing

1. Fuel spray phenomena
2. Spontaneous ignition
3. Effects of fuel jet and charge motion on mixing-controlled combustion
4. Fuel injection hardware
5. Challenges for diesel combustion

DIESEL FUEL INJECTION

The fuel spray serves multiple purposes:

- Atomization
- Fuel distribution
- Fuel/air mixing

Typical Diesel fuel injector

- Injection pressure: 1000 to 2200 bar
- 5 to 20 holes at ~ 0.12 - 0.2 mm diameter
- Drop size 0.1 to 10 μm
- For best torque, injection starts at about 20° BTDC

Injection strategies for NO_x control

- Late injection (inj. starts at around TDC)
- Other control strategies:
 - Pilot and multiple injections, rate shaping, water emulsion

Diesel Fuel Injection System

(A Major cost of the diesel engine)

- Performs fuel metering
- Provides high injection pressure
- Distributes fuel effectively
 - Spray patterns, atomization etc.
- Provides fluid kinetic energy for charge mixing

Typical systems:

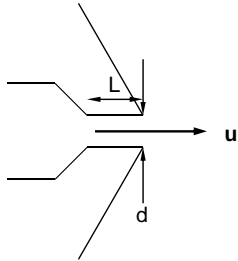
- Pump and distribution system (100 to 1500 bar)
- Common rail system (1000 to 1800 bar)
- Hydraulic pressure amplification
- Unit injectors (1000 to 2200 bar)
- Piezoelectric injectors (1800 bar)
- Electronically controlled

EXAMPLE OF DIESEL INJECTION

(Hino K13C, 6 cylinder, 12.9 L turbo-charged diesel engine, rated at 294KW@2000 rpm)

- Injection pressure = 1400 bar; duration = 40°CA
- BSFC 200 g/KW-hr
- Fuel delivered per cylinder per injection at rated condition
 - 0.163 gm ~0.21 cc (210 mm³)
- Averaged fuel flow rate during injection
 - 64 mm³/ms
- 8 nozzle holes, at 0.2 mm diameter
 - Average exit velocity at nozzle ~253 m/s

Typical physical quantities in nozzle flow



- Diesel fuel @ 100°C
 - s.g. ~ 0.78, $\mu \sim 5 \times 10^{-4}$ N-s/m²
- Nozzle diameter ~0.2 mm
- L/d ~ 5 to 10
- Reynolds No. ~ 10⁵ (turbulent)
- Pressure drop in nozzle
~30 bar \ll driving pressure
(~1000 bar)
- Injection velocity

$$u \approx \sqrt{\frac{2\Delta P}{\rho_{\text{fuel}}}} \approx 500 \text{ m/s @ } \Delta P \text{ of 1000 bar}$$

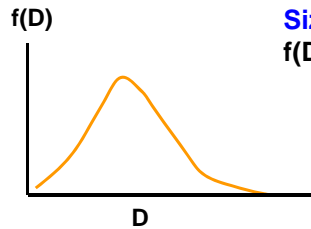
Fuel Atomization Process

- Liquid break up governed by balance between aerodynamic force and surface tension

$$\text{Webber Number } (W_b) = \frac{\rho_{\text{gas}} u^2 d}{\sigma}$$

- Critical Webber number: $W_{b,\text{critical}} \sim 30$; diesel fuel surface tension $\sim 2.5 \times 10^{-2}$ N/m
- Typical W_b at nozzle outlet $> W_{b,\text{critical}}$; fuel shattered into droplets within \sim one nozzle diameter
- Droplet size distribution in spray depends on further droplet breakup, coalescence and evaporation

Droplet size distribution



Size distribution:
 $f(D)dD$ = probability of finding particle with diameter in the range of $(D, D + dD)$

$$1 = \int_0^{\infty} f(D)dD$$

Average diameter

$$\bar{D} = \int_0^{\infty} f(D) D dD$$

Volume distribution

$$\frac{1}{V} \frac{dV}{dD} = \frac{f(D) D^3}{\int_0^{\infty} f(D) D^3 dD}$$

Sauter Mean Diameter (SMD)

$$D_{32} = \frac{\int_0^{\infty} f(D) D^3 dD}{\int_0^{\infty} f(D) D^2 dD}$$

Droplet Size Distribution

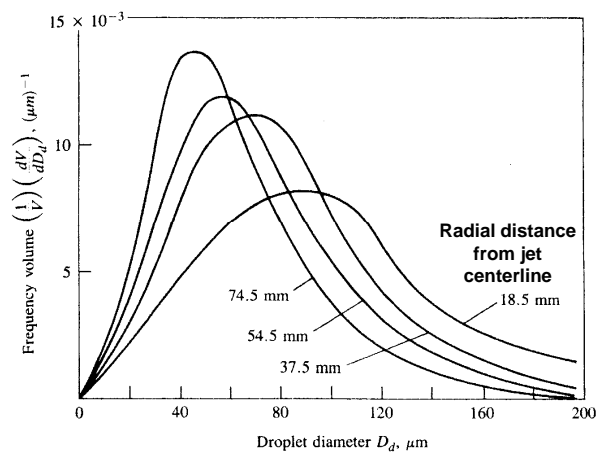
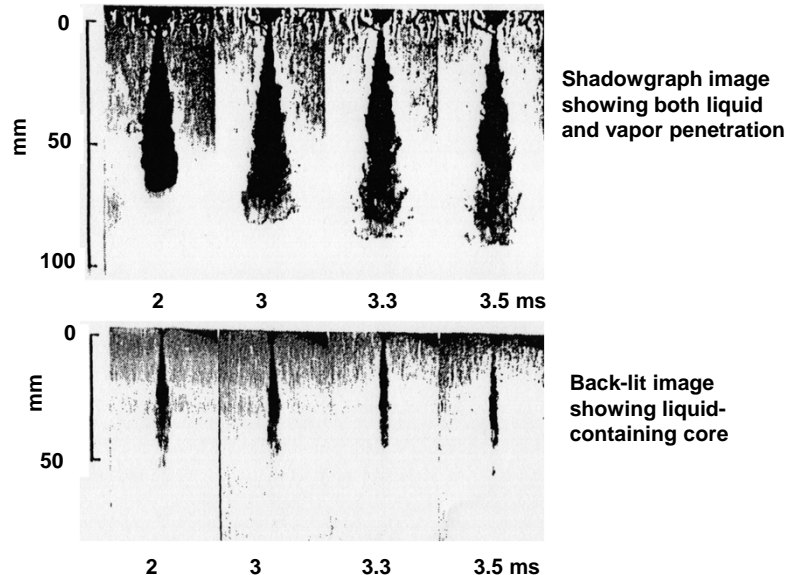


Fig. 10.28 Droplet size distribution measured well downstream; numbers on the curves are radial distances from jet axis. Nozzle opening pressure at 10 MPa; injection into air at 11 bar.

Droplet Behavior in Spray

- Small drops (~ micron size) follow gas stream; large ones do not
 - Relaxation time $\tau \propto d^2$
- Evaporation time $\propto d^2$
 - Evaporation time small once charge is ignited
- Spray angle depends on nozzle geometry and gas density : $\tan(\theta/2) \propto \sqrt{(\rho_{\text{gas}}/\rho_{\text{liquid}})}$
- Spray penetration depends on injection momentum, mixing with charge air, and droplet evaporation

Spray Penetration: vapor and liquid (Fig. 10-20)



Auto-ignition Process

PHYSICAL PROCESSES (Physical Delay)

- Drop atomization
- Evaporation
- Fuel vapor/air mixing

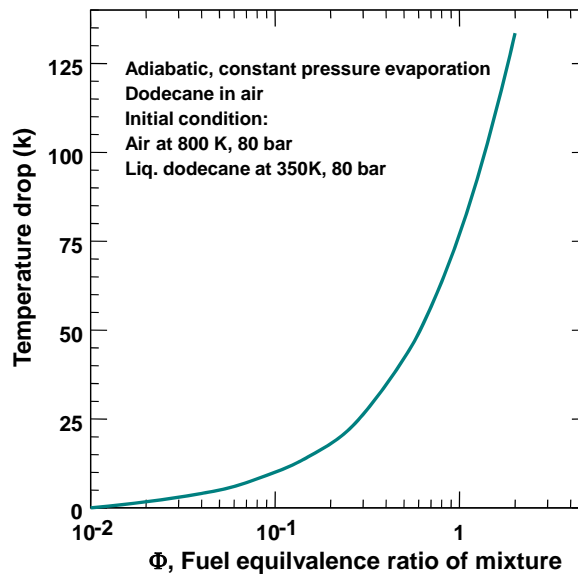
CHEMICAL PROCESSES (Chemical Delay)

- Chain initiation
- Chain propagation
- Branching reactions

CETANE IMPROVERS

- Alkyl Nitrates
 - 0.5% by volume increases CN by ~10

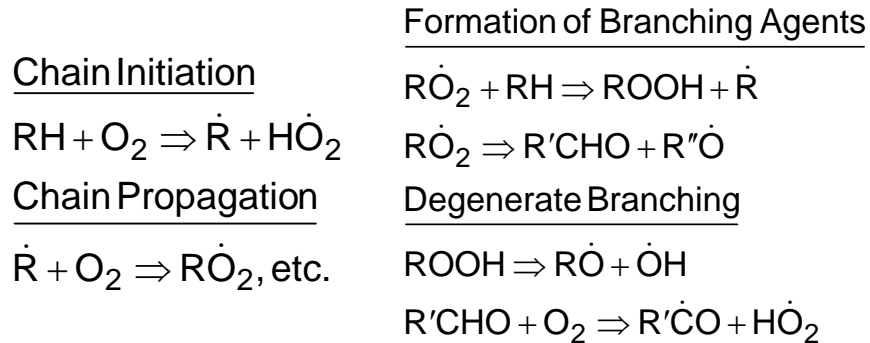
Mixture cooling from heat of vaporization



Ignition Mechanism: similar to SI engine knock

CHAIN BRANCHING EXPLOSION

Chemical reactions lead to increasing number of **radicals**, which leads to rapidly increasing reaction rates



Cetane Rating

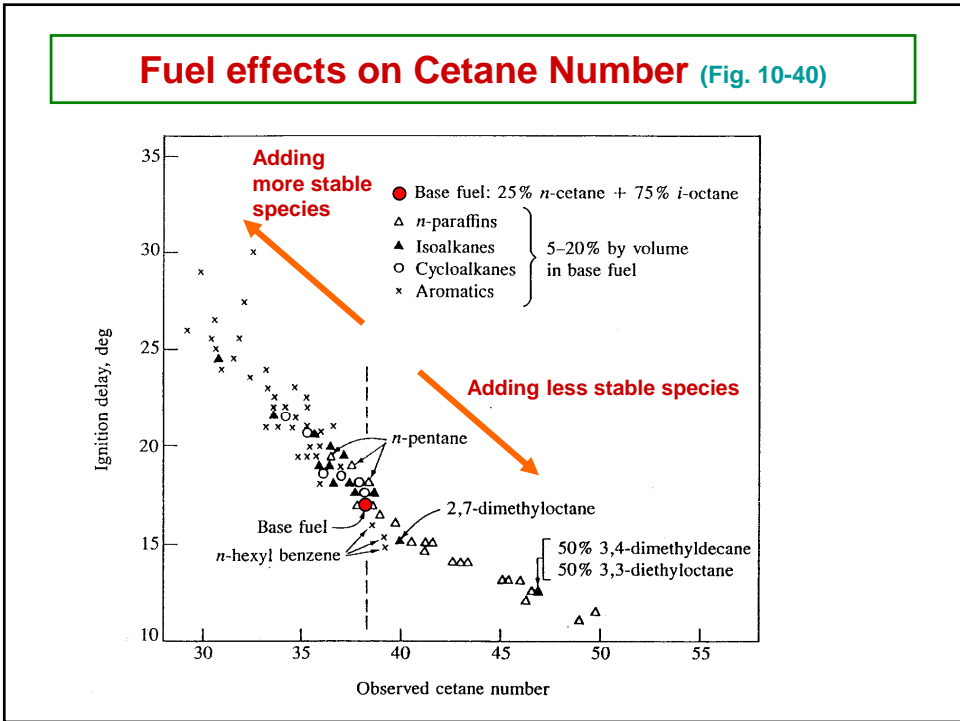
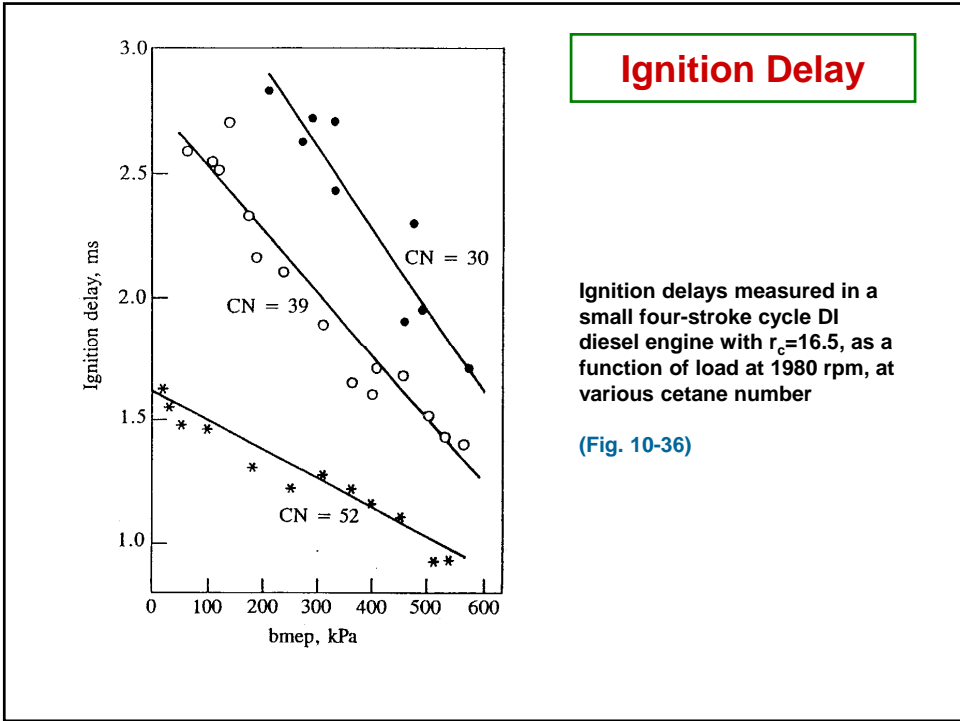
(Procedure is similar to Octane Rating for SI Engine; for details, see 10.6.2 of text)

Primary Reference Fuels:

- Normal cetane ($C_{16}H_{34}$): CN = 100
- Hepta-Methyl-Nonane (HMN; $C_{16}H_{34}$): CN = 15
(2-2-4-4-6-8-8 Heptamethylnonane)

Rating:

- Operate CFR engine at 900 rpm with fuel
- Injection at 13° BTC
- Adjust compression ratio until ignition at TDC
- Replace fuel by reference fuel blend and change blend proportion to get same ignition point
- $CN = \% \text{ n-cetane} + 0.15 \times \% \text{ HMN}$



Ignition Delay Calculations

- Difficulty: do not know local conditions (species concentration and temperature) to apply kinetics information

Two practical approaches:

- Use an “instantaneous” delay expression

$$\tau(T,P) = P^{-n} \exp(-E_A / T)$$

and solve ignition delay (τ_{id}) from

$$1 = \int_{t_{si}}^{t_{si} + \tau_{id}} \frac{1}{\tau(T(t), P(t))} dt$$

- Use empirical correlation of τ_{id} based on T, P at an appropriate charge condition; e.g. Eq. (10.37 of text)

$$\tau_{id}(CA) = (0.36 + 0.22 \bar{S}_p \text{ (m/s)}) \exp \left[E_A \left(\frac{1}{\bar{R}T(K)} - \frac{1}{17190} \right) + \left(\frac{21.2}{P(\text{bar}) - 12.4} \right)^{0.63} \right]$$

$$E_A \text{ (Joules per mole)} = 618,840 / (CN+25)$$

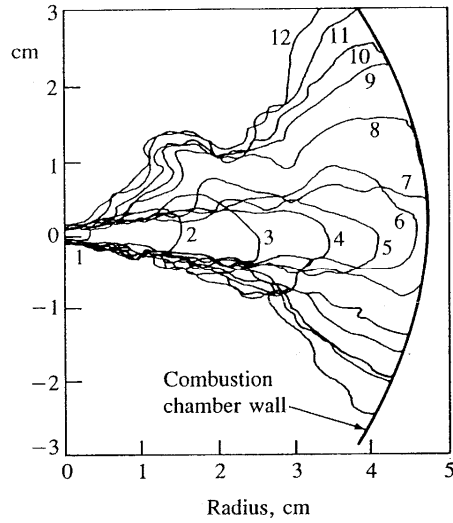
Diesel Engine Combustion Air Fuel Mixing Process

- Importance of air utilization
 - Smoke-limit A/F ~ 20
- Fuel jet momentum / wall interaction has a larger influence on the early part of the combustion process
- Charge motion impacts the later part of the combustion process (after end-of-injection)

CHARGE MOTION CONTROL

- Intake created motion: swirl, etc.
 - Not effective for low speed large engine
- Piston created motion - squish

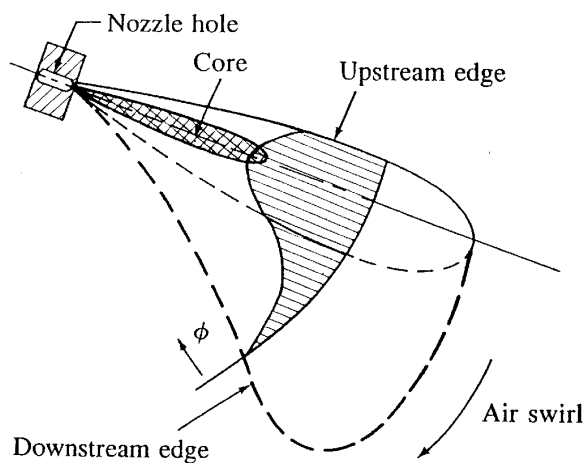
Interaction of fuel jet and the chamber wall



Sketches of outer vapor boundary of diesel fuel spray from 12 successive frames (0.14 ms apart) of high-speed shadowgraph movie. Injection pressure at 60 MPa.

Fig. 10-21

Interaction of fuel jet with air swirl

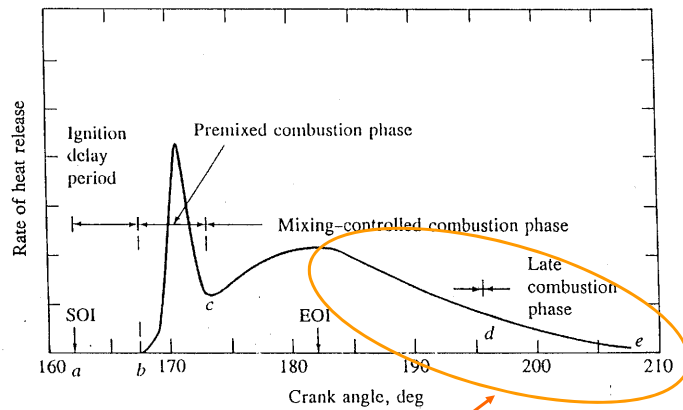


Schematic of fuel jet – air swirl interaction; Φ is the fuel equivalence ratio distribution

Fig. 10-22

Rate of Heat Release in Diesel Combustion

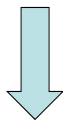
(Fig. 10.8 of Text)



Part of combustion affected most by the charge motion

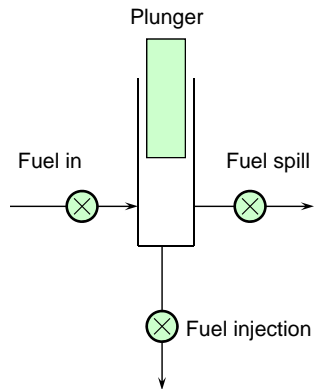
DIESEL FUEL INJECTION HARDWARE

- High pressure system
 - precision parts for flow control
- Fast action
 - high power movements



Expensive system

FUEL METERING AND INJECTION SYSTEM - CONCEPT

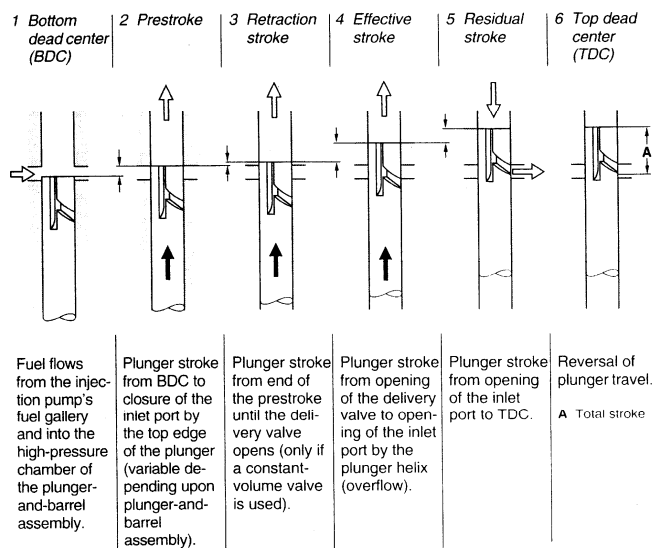


Process:

- Fill
- Pressurize
- Inject
- Spill

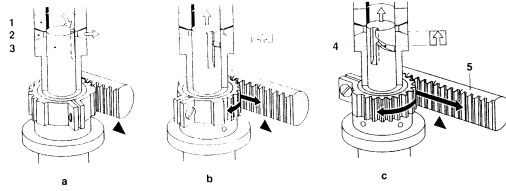
Fuel Delivery Control

Fig. 3: Plunger-stroke phases



From *Diesel Fuel Injection*, Robert Bosch GmbH, 1994

Fig. 4: Fuel-delivery control
Using a toothed control rack. a) Zero delivery, b) Partial delivery, c) Maximum delivery.
1 Pump barrel, 2 Inlet port, 3 Pump plunger, 4 Helix, 5 Control rack.

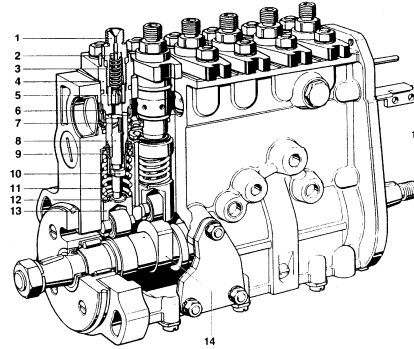
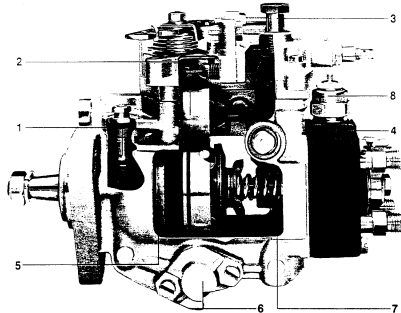


Fuel Rack and In-line Pump

From *Diesel Fuel Injection*,
Robert Bosch GmbH, 1994

Fig. 1: PES in-line fuel-injection pump
1 Delivery-valve holder, 2 Filler piece, 3 Delivery-valve spring, 4 Pump barrel, 5 Delivery valve, 6 Inlet port and spill port, 7 Control helix, 8 Pump plunger, 9 Control sleeve, 10 Plunger control arm, 11 Plunger spring, 12 Spring seat, 13 Roller tappet, 14 Cam, 15 Control rack.

Distributor pump



Diesel Injector

Fig. 2: Nozzle shapes

- 1 Throttling pintle nozzle,
- 2 Throttling pintle nozzle with flat-cut pintle,
- 2a Side view, 2b Front view,
- 3 Hole-type nozzle with conical blind hole,
- 4 Hole-type nozzle with cylindrical blind hole,
- 5 Seat-hole nozzle.

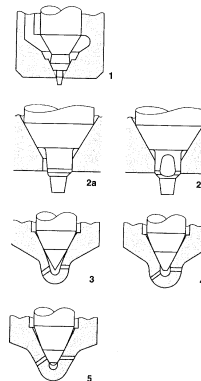
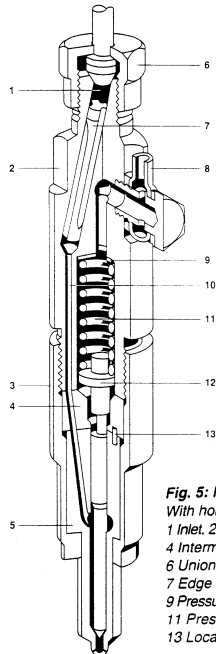
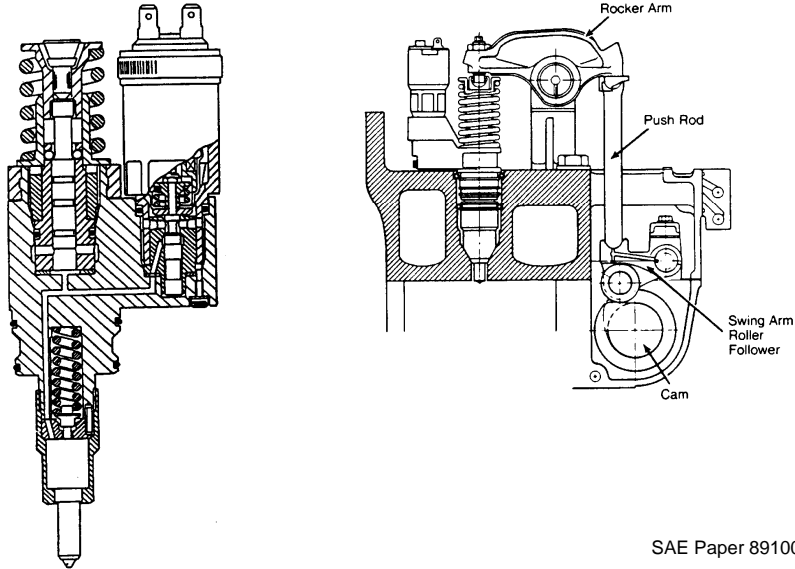


Fig. 5: Nozzle-and-holder assembly

- With hole-type nozzle.
- 1 Inlet, 2 Nozzle-holder body, 3 Nozzle-retaining nut,
- 4 Intermediate element, 5 Injection nozzle,
- 6 Union nut with high-pressure line,
- 7 Edge filter, 8 Leak-off connection,
- 9 Pressure-adjusting shims, 10 Pressure passage,
- 11 Pressure spring, 12 Pressure pin,
- 13 Locating pins.



Electronic Unit Injector

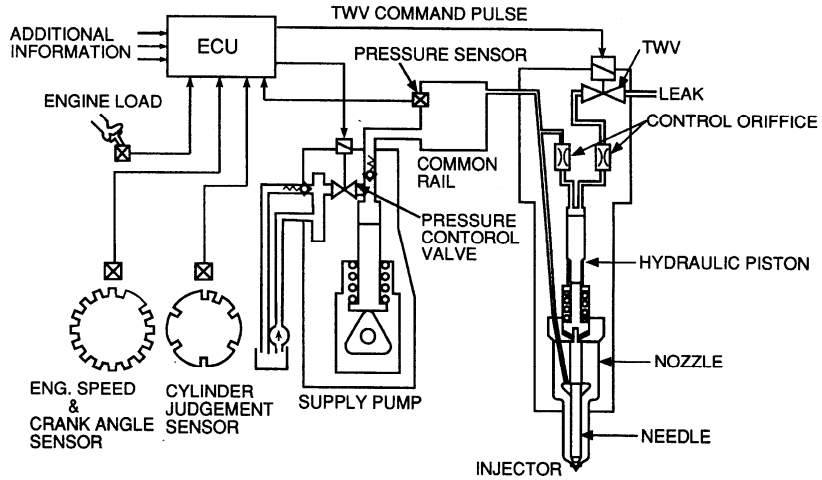


SAE Paper 891001

Injection pressure

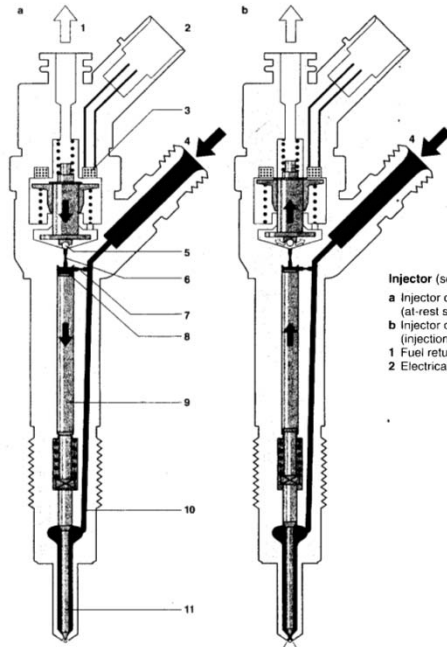
- Positive displacement injection system
 - Injection pressure adjusted to accommodate plunger motion
 - Injection pressure $\propto \text{rpm}^2$
- Injection characteristics speed dependent
 - Injection pressure too high at high rpm
 - Injection pressure too low at low rpm

Common Rail Fuel Injection System



SAE Paper 1999-01-0833

Common Rail Injector



Injector (schematic)

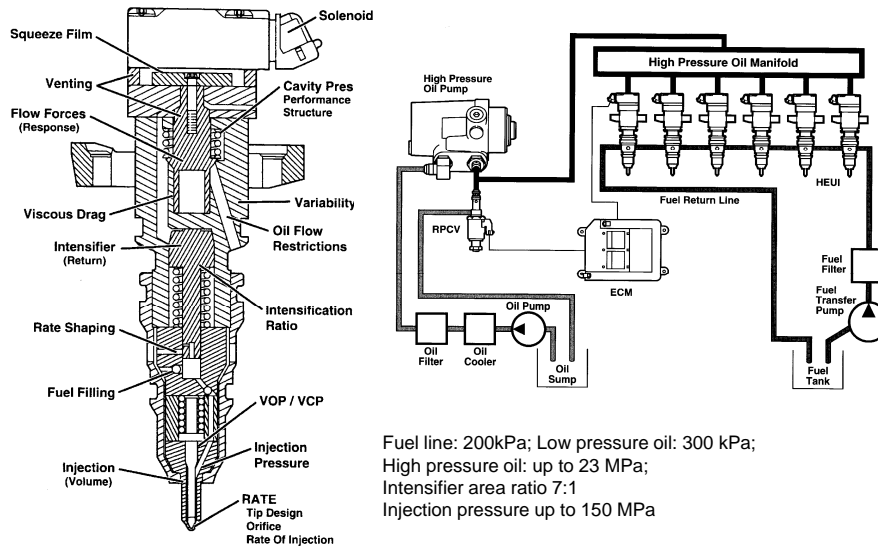
- a injector closed (at-rest status),
- b injector opened (injection).
- 1 Fuel return,
- 2 Electrical connection,

- 3 Triggering element (solenoid valve),
- 4 Fuel inlet (high pressure) from the rail,
- 5 Valve ball,
- 6 Bleed orifice,
- 7 Feed orifice,
- 8 Valve control chamber,
- 9 Valve control plunger,
- 10 Feed passage to the nozzle,
- 11 Nozzle needle.

Nozzle opening speed controlled by the flow rate difference between the Bleed (6) and Feed (7) orifices

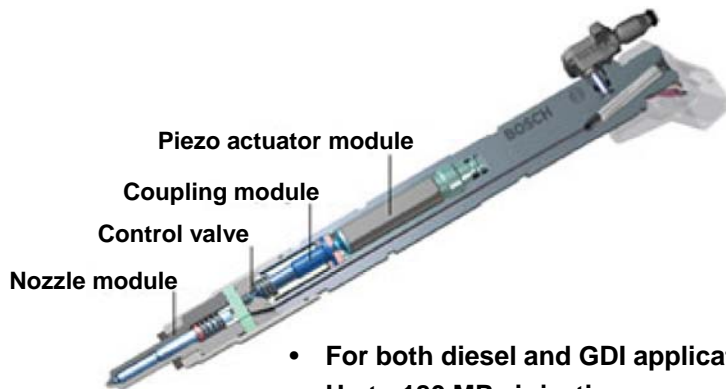
From Bosch: Diesel Engine Management

Caterpillar Hydraulic Electronic Unit Injector (HEUI)



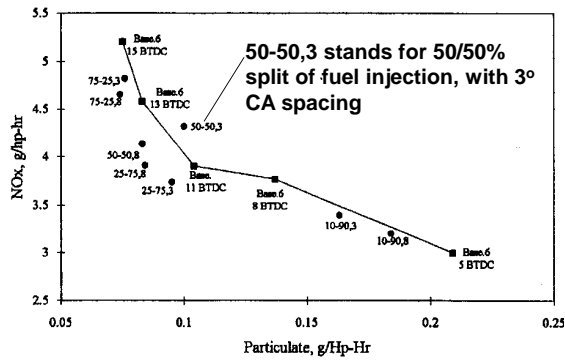
SAE Papers 930270, 930271

Piezoelectric injectors

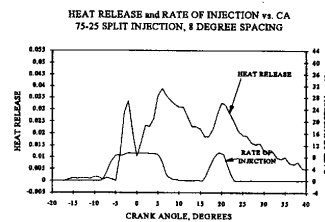
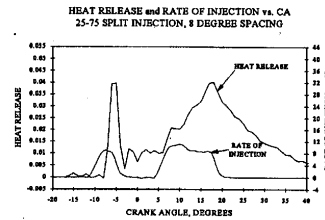


- For both diesel and GDI applications
- Up to 180 MPa injection pressure
- 5 injections per cycle
- In vehicle production already
- Suppliers: Bosch; Delphi; Denso; Siemens; ...

Split Injection (SAE Paper 940668)



1600 rpm, 184 KPa manifold pressure, overall fuel equivalence ratio = 0.45;



CHALLENGES IN DIESEL COMBUSTION

Heavy Duty Diesel Engines

- NOx emission
- Particulate emission
- Power density
- Noise

High Speed Passenger Car Diesel Engines

- All of the above, plus
 - Fast burn rate

Cavitation in Injection Nozzle

- Cavitation happens when local pressure is lower than the fluid vapor pressure
- Effects
 - Affects the spray angle
 - Damage to the nozzle passage
- Factors affecting cavitation
 - Combustion chamber pressure
 - Local streamline curvature within the nozzle

Flow process that leads to cavitation

