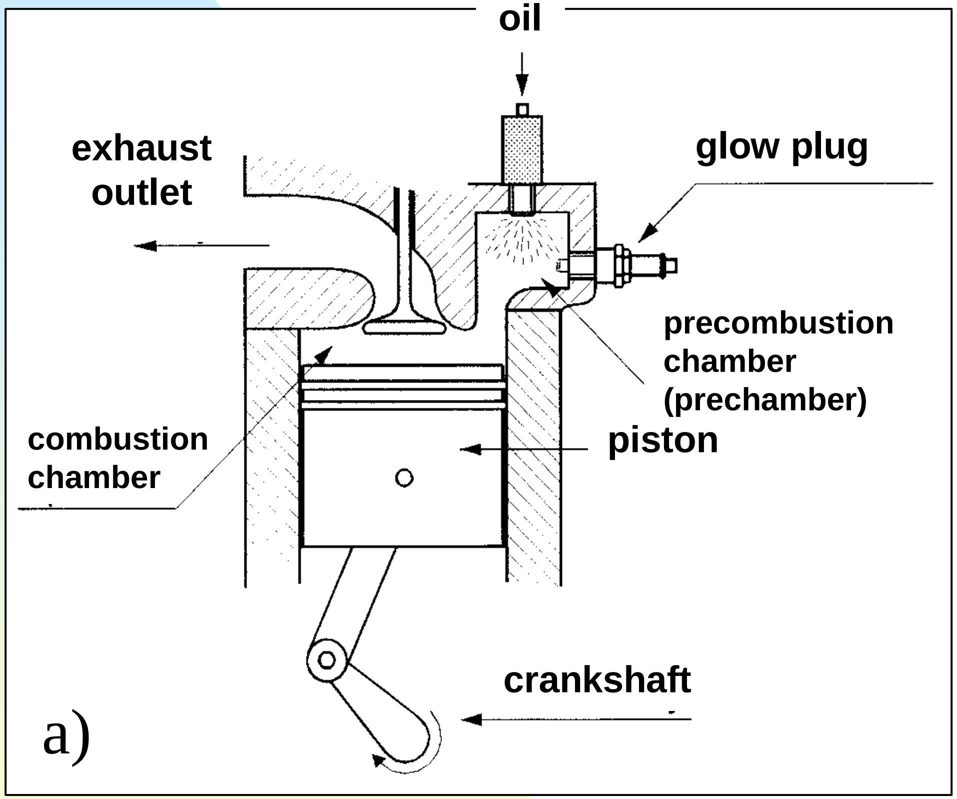
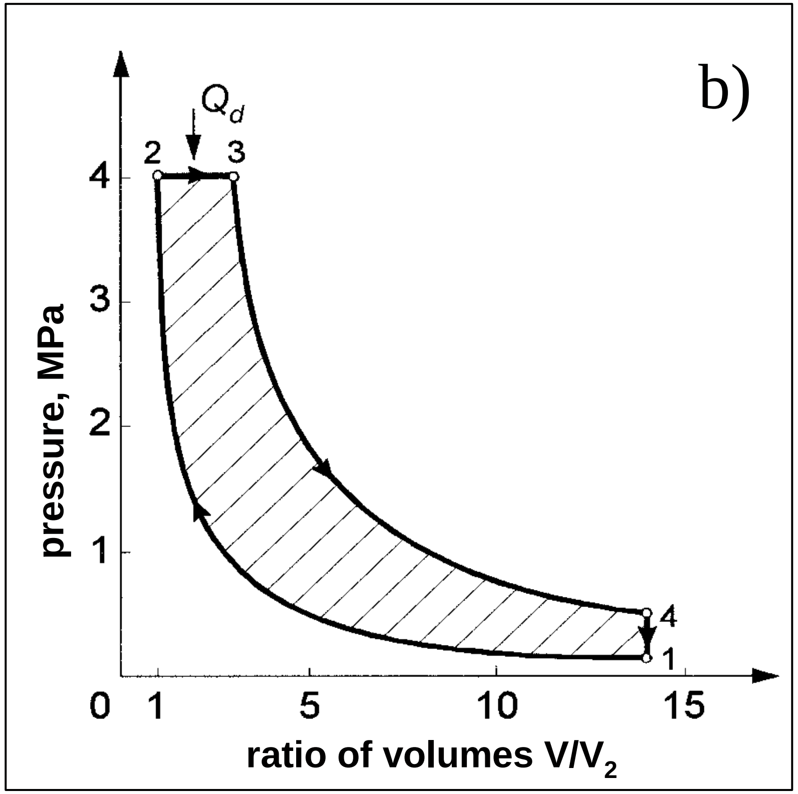
CI engine combustion

(CI - compressed – ignition)

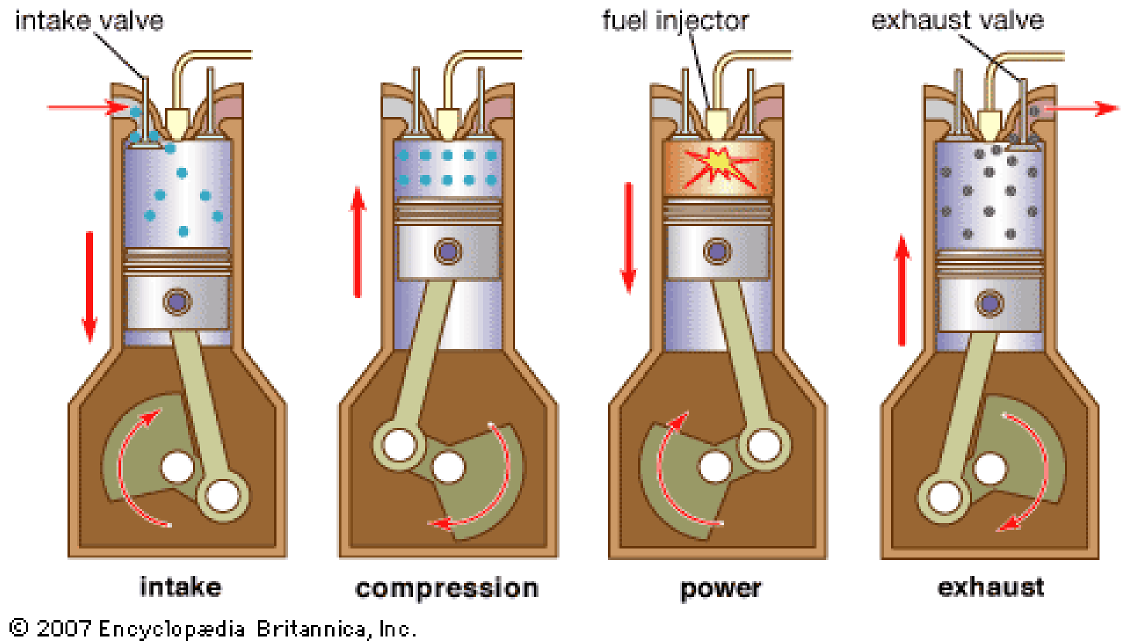
CI (Diesel) engine

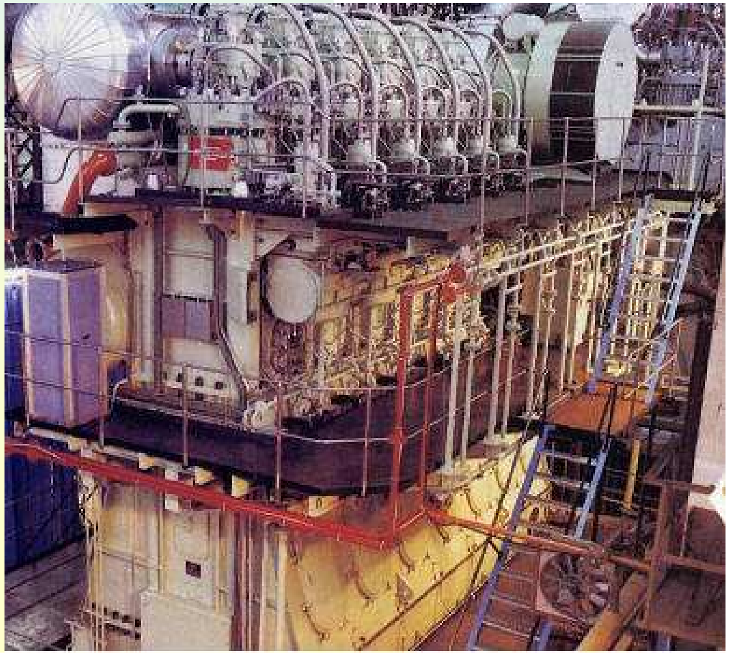




a) scheme of CI engine, b) Diesel cycle

Diesel engines 4 and 2 - stroke





Industrial Diesel engine

Selected parameters of CI engines

Compression ratio ε in Diesel engine

from 14:1 to 24:1

Passenger cars	21:1- 24:1
Trucks:	15:1-19:1

Compression pressure:	3-5 MPa
Combustion pressure:	5-8 MPa

Engine speed:	3000-5000 revolutions per minute

CI ENGINE COMBUSTION

Major processes in the combustion mechanism

I. Physical processes

1. Oil is injected into the combustion chamber
2. The oil jet is atomised to droplets
3. Droplets undergo evaporation.
4. Vapours are mixed with hot air and combustible mixture is formed.

II. Chemical processes

1. Low-temperature oxidation of hydrocarbons and alkylperoxy radicals formation
2. Cold flames
3. Blue flames
4. Hot flames

Major stages of combustion in CI engines

I. Induction ignition period

II. Kinetic combustion period

III. Diffusion combustion period

IV. Reburning period

Ignition delay period

I. Oil is injected when the temperature of air reaches the temperature of selfignition (approx. 250 C).

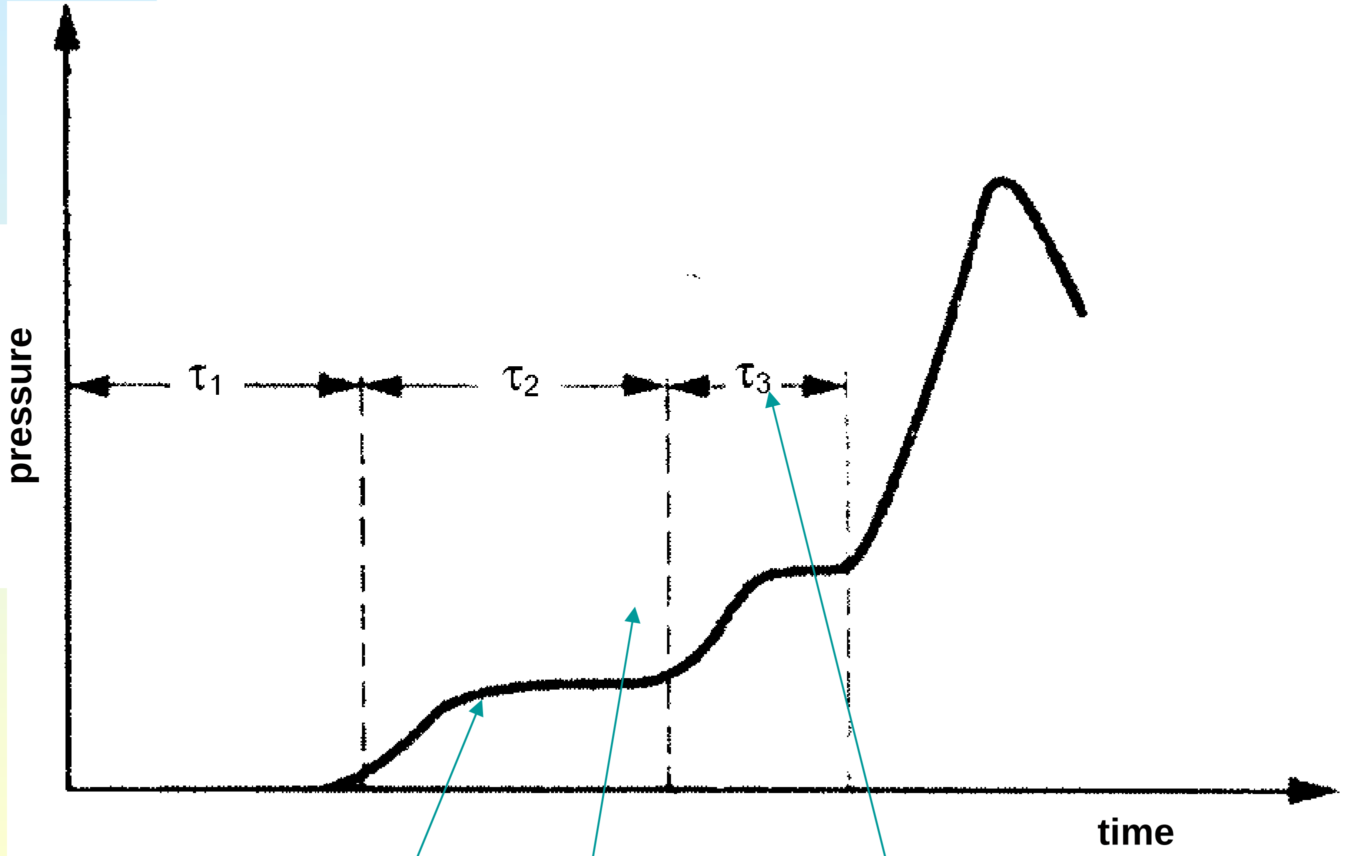
II. However, there is some delay of ignition – induction ignition delay.

III. Induction ignition delay includes physical and chemical delay periods (0.7-3 ms).

IV. The physical induction ignition period is measured from the moment of oil injection to the moment of formation of combustible oil and air mixture.

V. The chemical induction ignition period is measured to the moment of pressure indication.

Main combuston stages



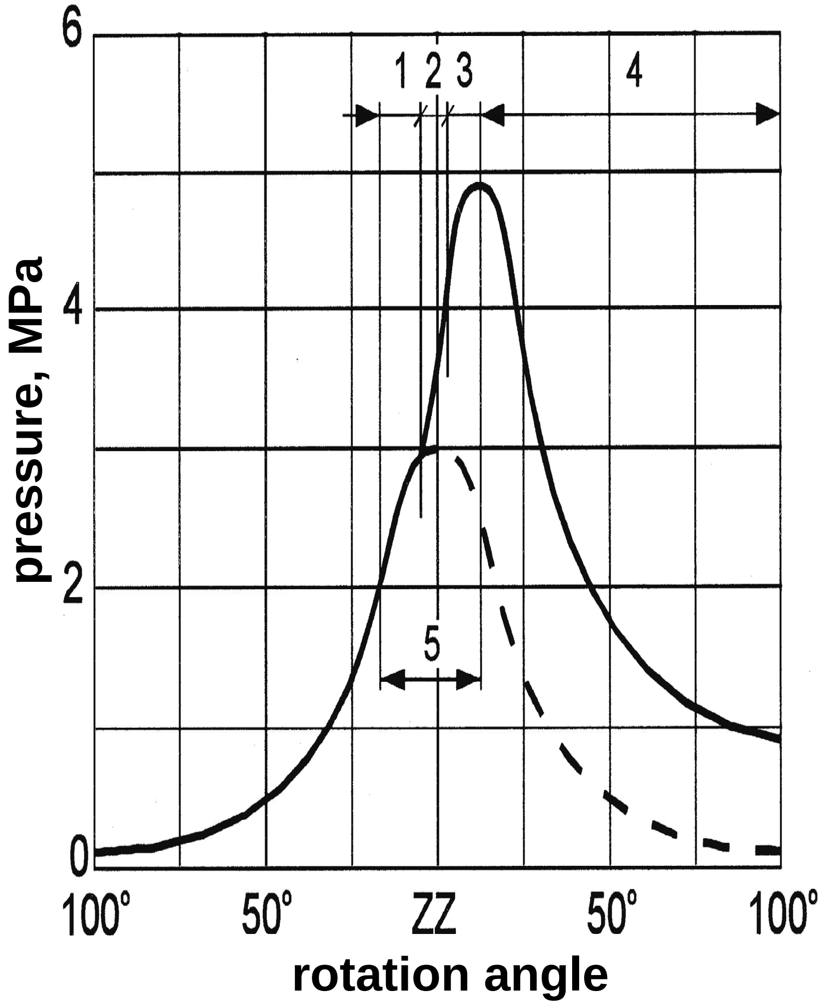
Flames: cold, blue, hot-kinetic, hot-diffusion

Selfignition temperature of selected fuels

Fuel	Temperature, ^{o}C
Diesel oil	233 (LC=41), 230 (LC=55), 225 (LC=55)
Gasoline	440-470
Ethyl alcohol	558, 426, 365
Methyl alcohol	574, 470, 464, 385
Methane	632, 537, 540
Propane	493, 450, 466, 504
n-Butane	408, 543, 477
Hydrogen	572, 400

Higher density, lower temperature of selfignition

Pressure record vs angle of shaft rotation angle



—— with combustion,

– – – without combustion

1 – induction ignition period,

2 – kinetic combustion period,

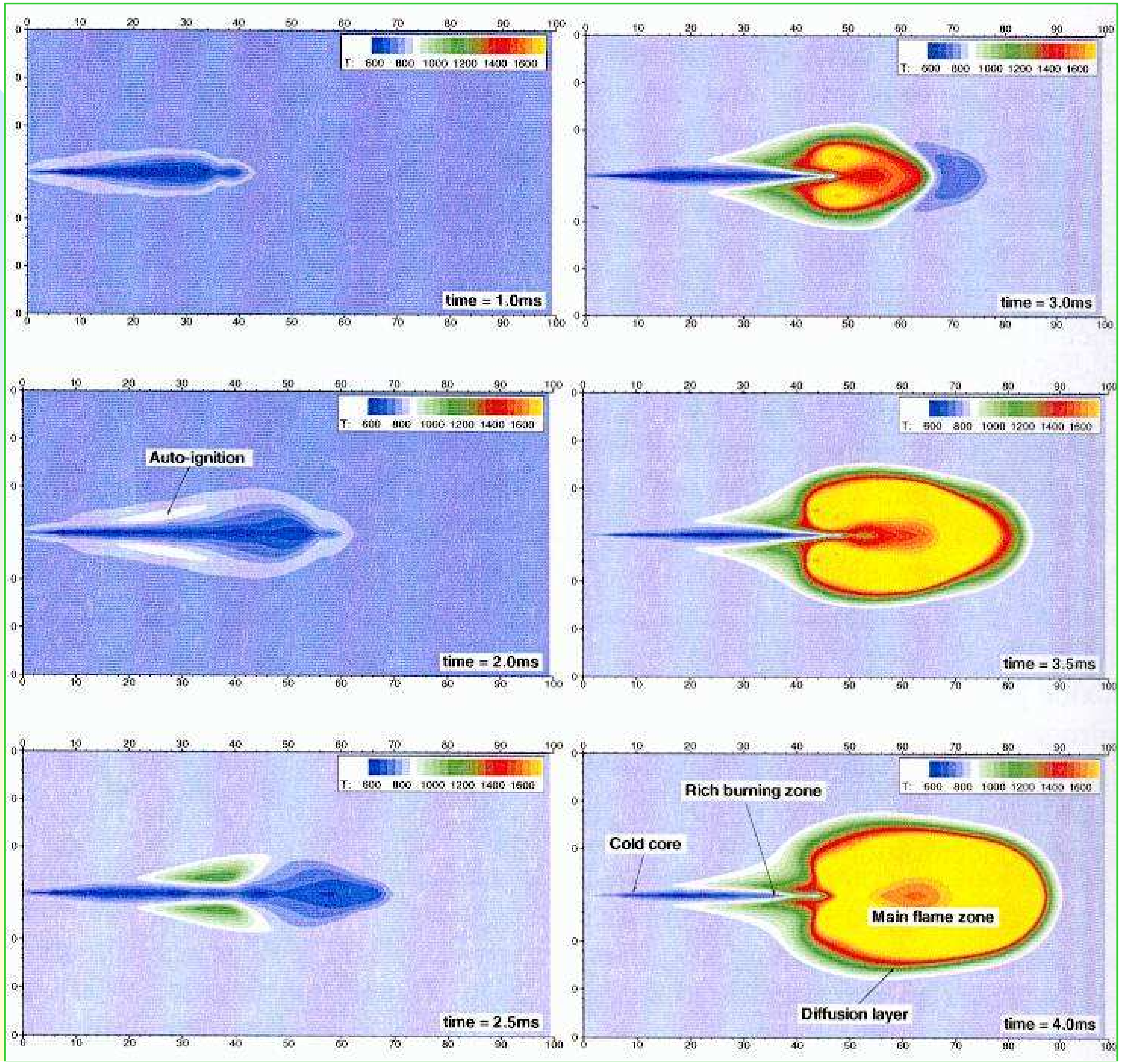
3 – diffusion combustion period,

4 – reburning period,

5– injection period,

ZZ – upper position of piston

Flame Formation



Phase of low-temperature reaction

Chemical processes

1. Formation of hydroproxides:

$$RH + O_2 = HO_2 + R,$$

$$R + O_2 = ROO$$

$$ROO + RH = ROOH + R$$

2. Formaldehyde formation (cold flames):

$$CH_3O_2 + CH_3 = CH_3O + CH_3O$$

3. Formaldehyde destruction:

$$CH_3O + M = CH_2O + H + M,\ CH_3O + O_2 = CH_2O + HO_2$$

$$CH_2O + O_2 = CHO + H_2O,\ CH_2O + OH = CHO + H_2O$$

4. Hot ignition and hot flames: $CHO + M = CO + H + M$

Hot combustion phase

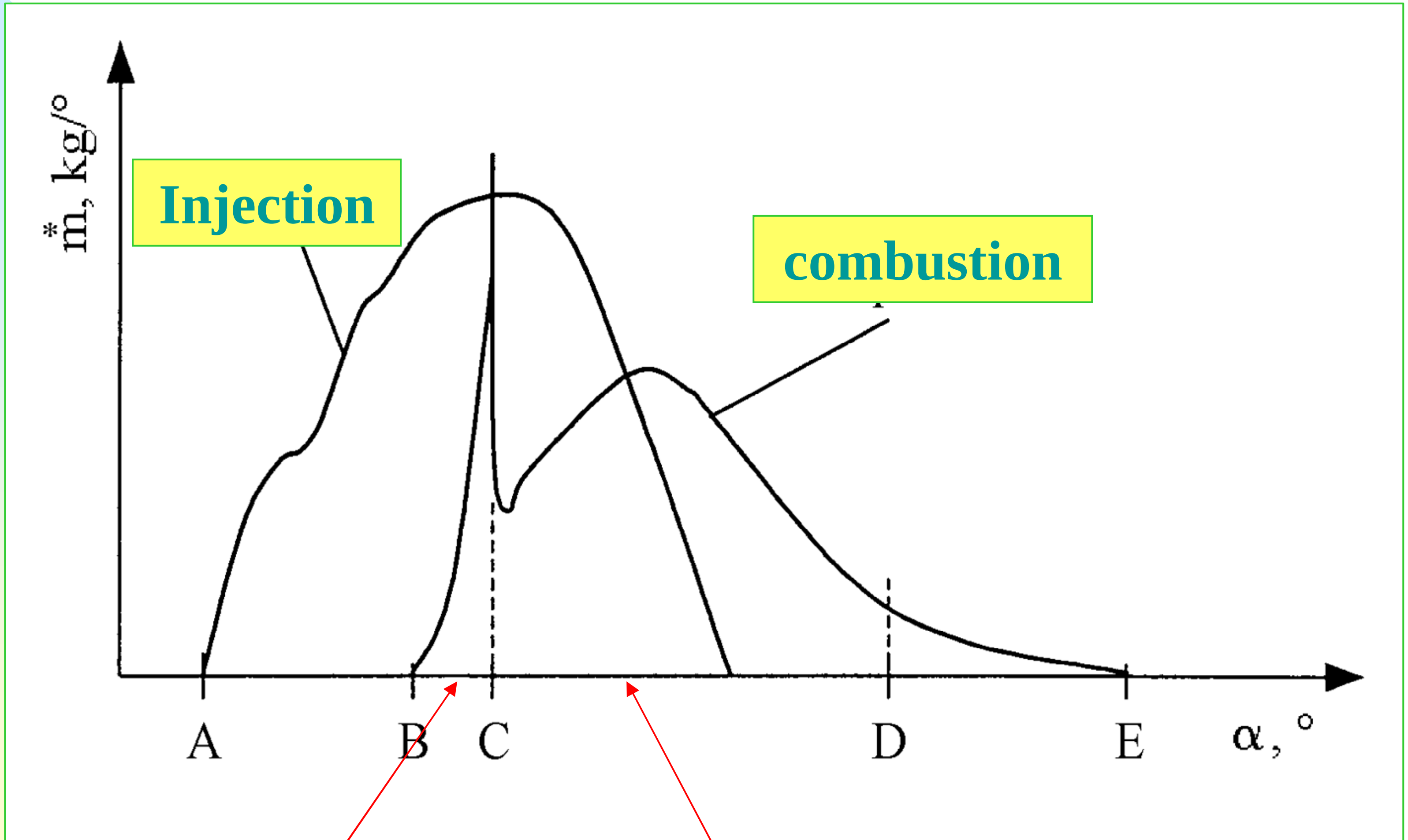
I. Kinetic phase

1. Vapour and air mixture undergoes ignition
2. Flame if formed
3. Charge is rapidly burned

II. Diffusion phase

1. Single droplets of oil undergo ignition
2. Diffusional flame is formed around the droplet
3. Droplets are burnt in diffusion regime
4. Reburning is in kinetic regime.

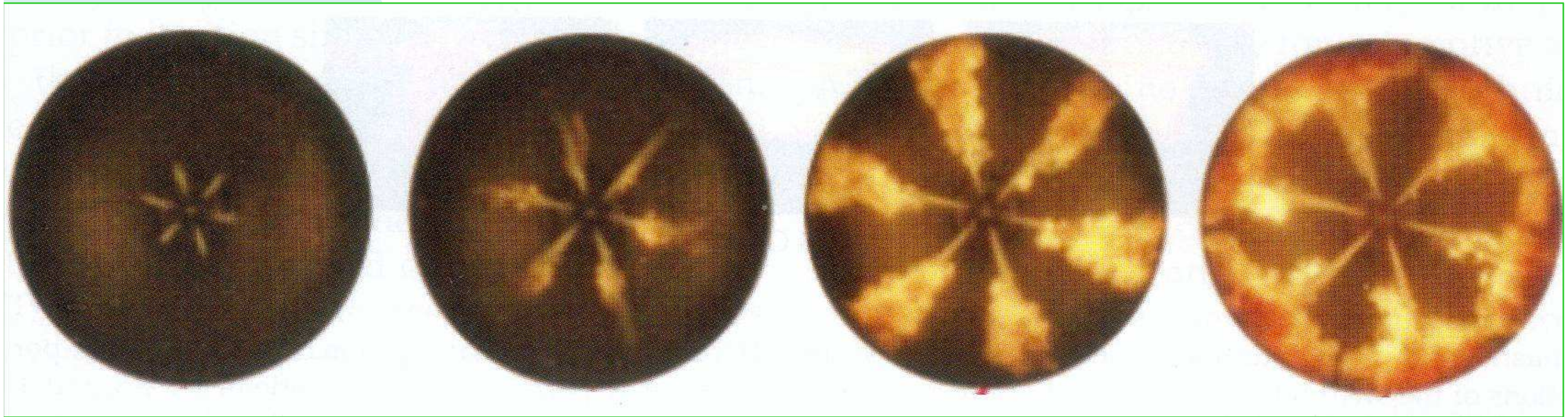
Combustion development in SC engines



Kinetic combustion

Diffusion combustion

Flame formation in CI engine



CI ENGINE COMBUSTION SYSTEMS

Types of Diesel engines

1. Low- speed engines	($n<1500$)
2. Medium-speed engines	($n = 1500\text{-}3000$)
3. High-speed engines	($n = 3000\text{-}5000$)

Combustion chambers in low- and medium speed CI engines (n < 1500)

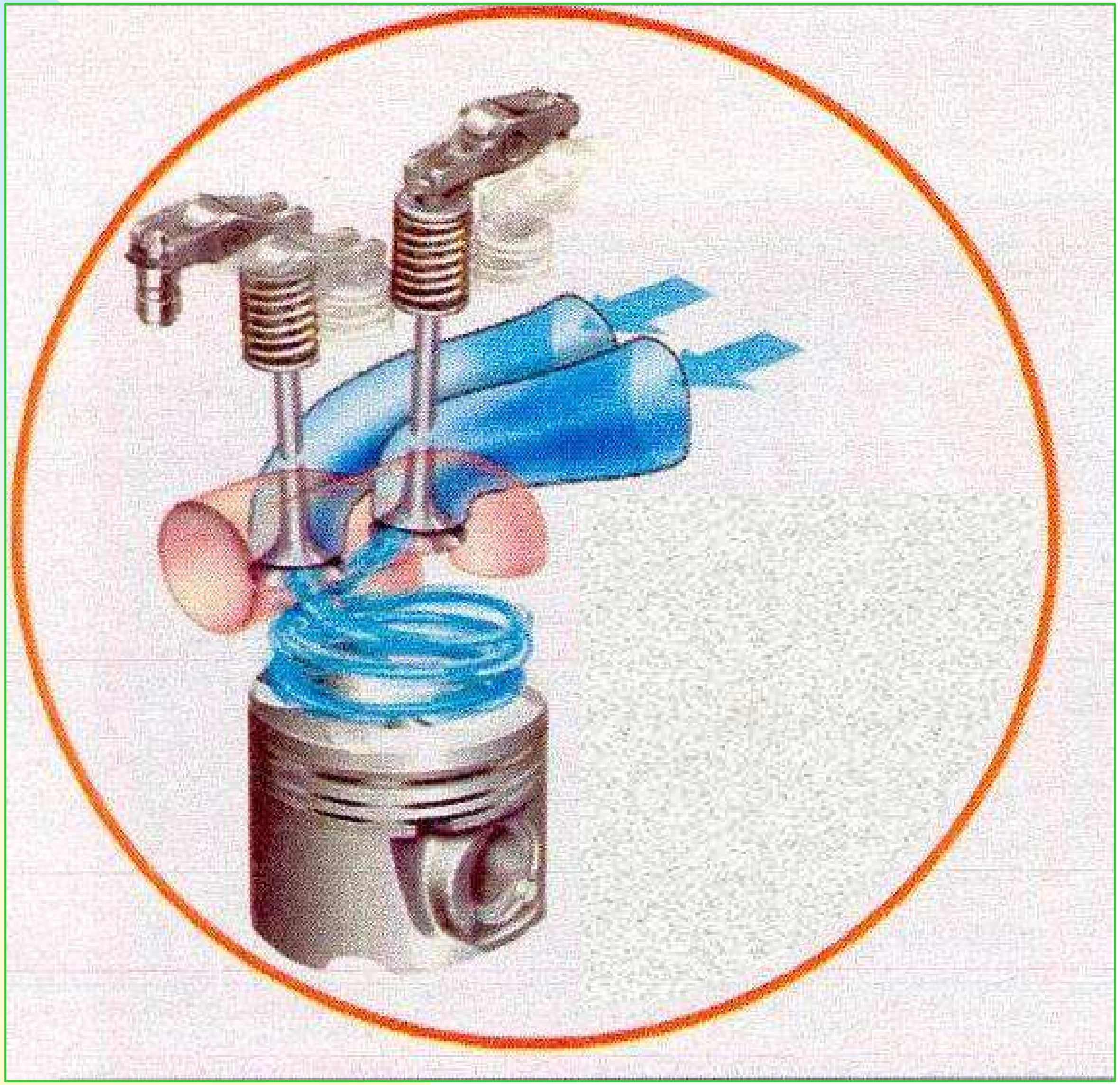
1. Shallow, swirl-less combustion chambers.

2. Direct, multi-jet fuel injection.

Medium-speed CI engines (n = 1500-3000)

1. Deep combustion chambers with intensive swirl of charge.
2. Direct injection of atomised fuel.

Intensive swirl of charge
(n = 1500-3000)



swirl
makes
the
mixture
(charge)
uniform

High-speed CI engines
(n = 3000-5000)

1. Prechambers (sectional combustion chambers).

2. Indirect injection of fuel into the prechamber.

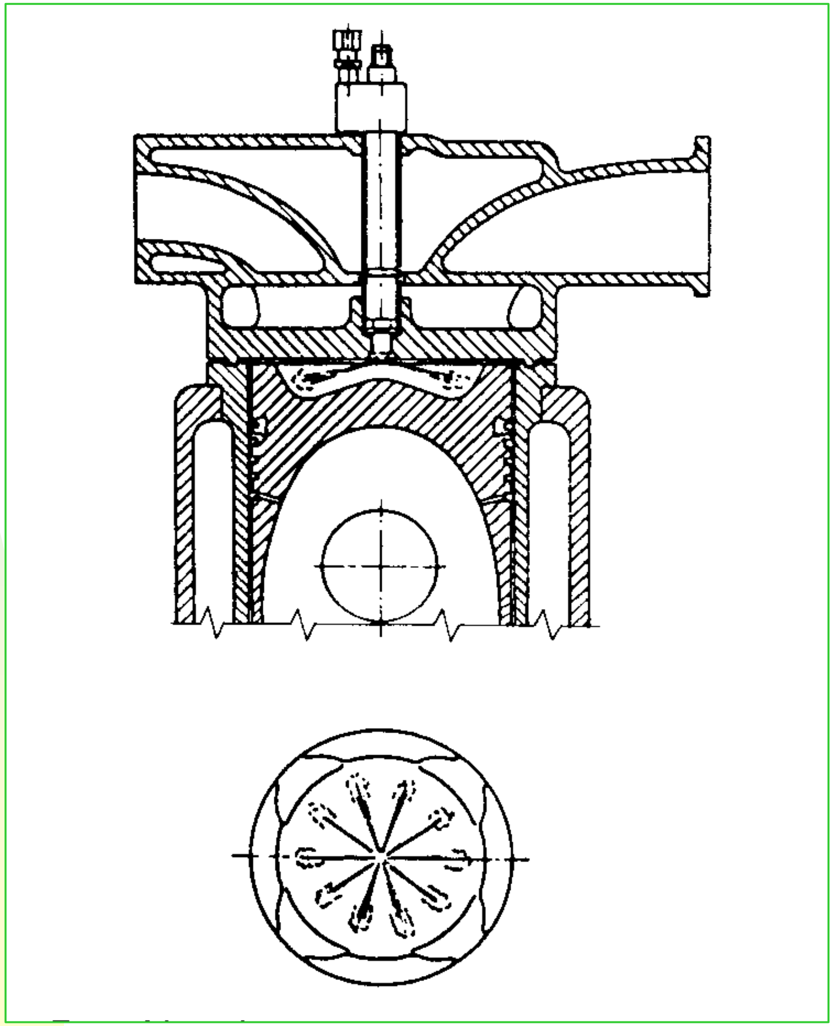
COMBUSTION CHAMBERS OF CI ENGINES

Combustion chambers of CI engines

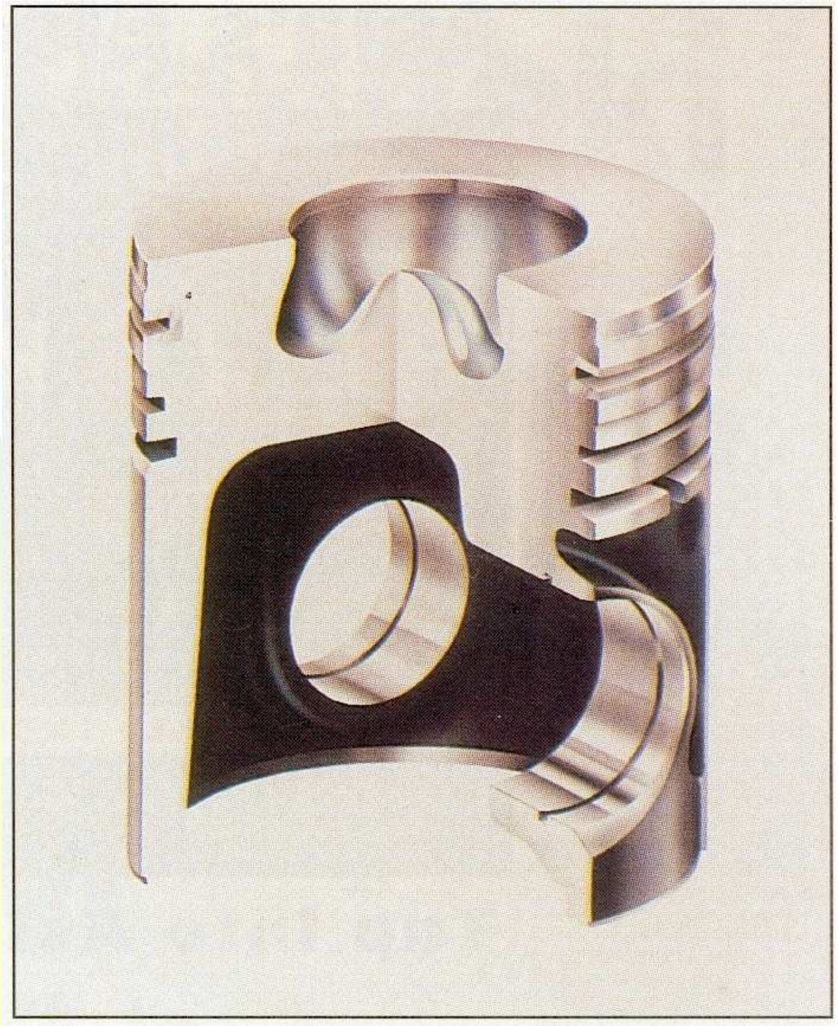
1. *Direct injection* (DI) chambers.

2. *Indirect injection* (IDI) chambers.

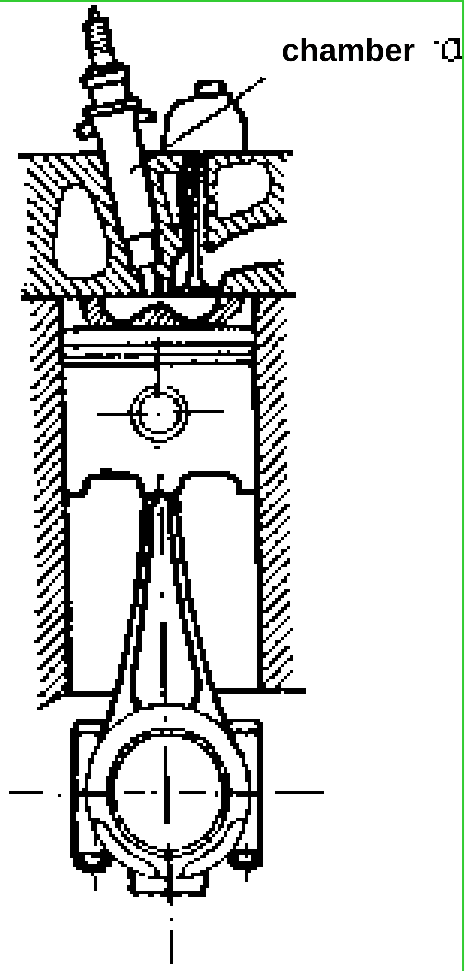
Combustion chambers of *direct injection* engines (DI)

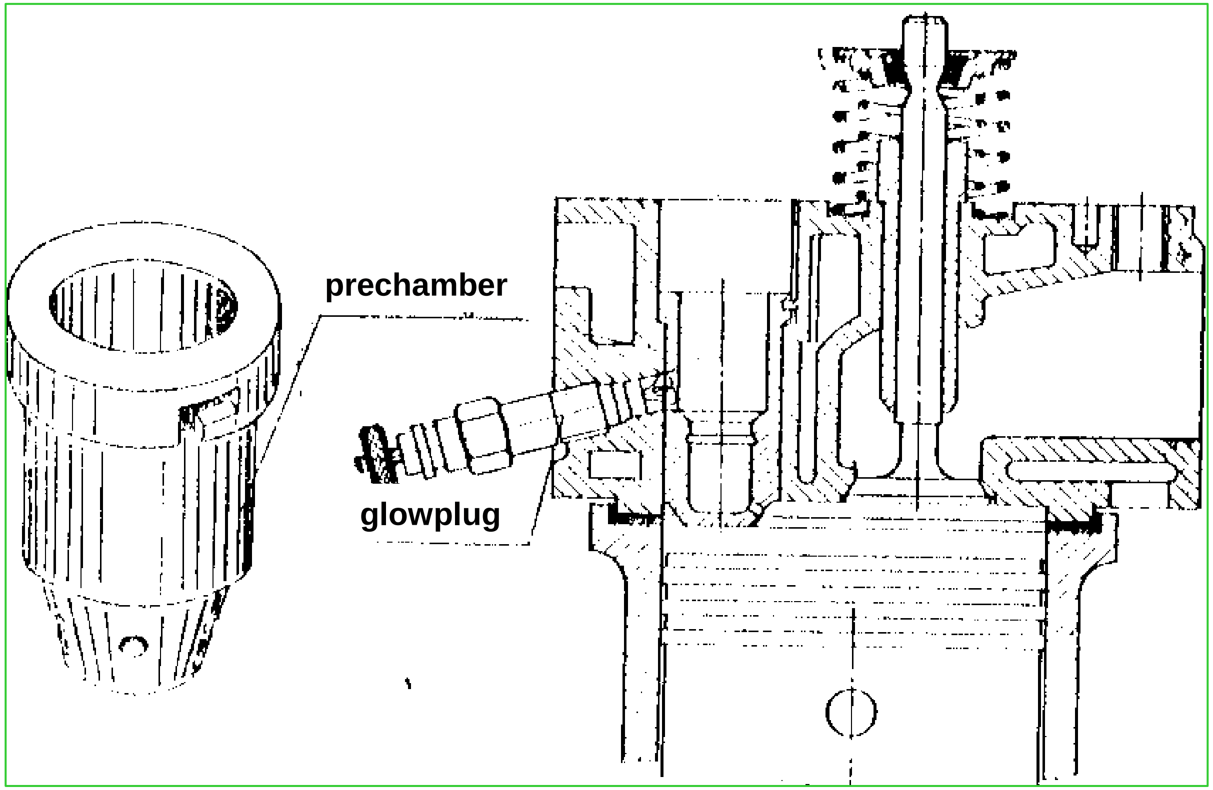


Piston of DI engine (*direct injection*)



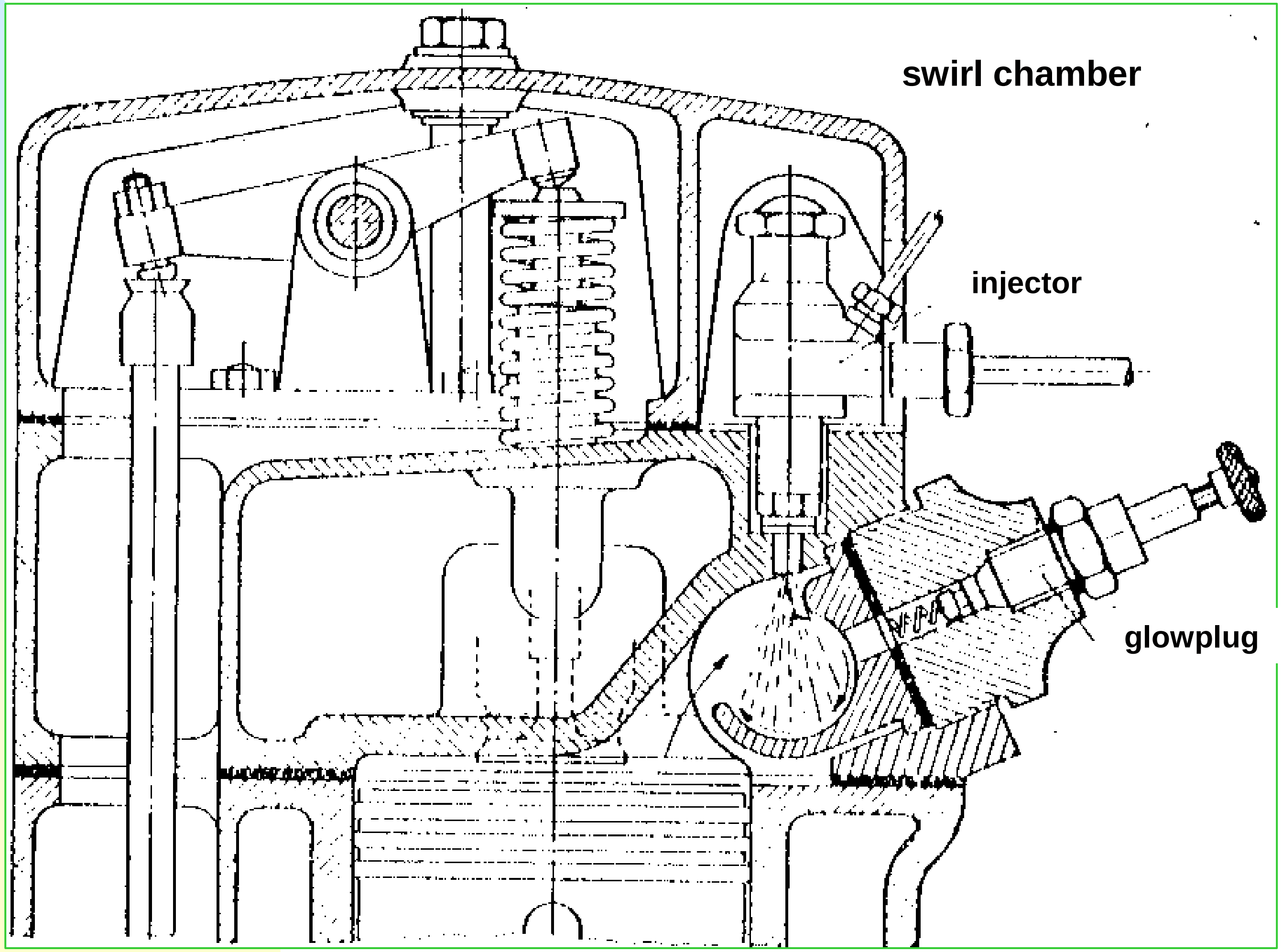
Combustion chamber of *indirect injection* (IDI)





prechamber

Combustion chamber of *indirect injection* (IDI)



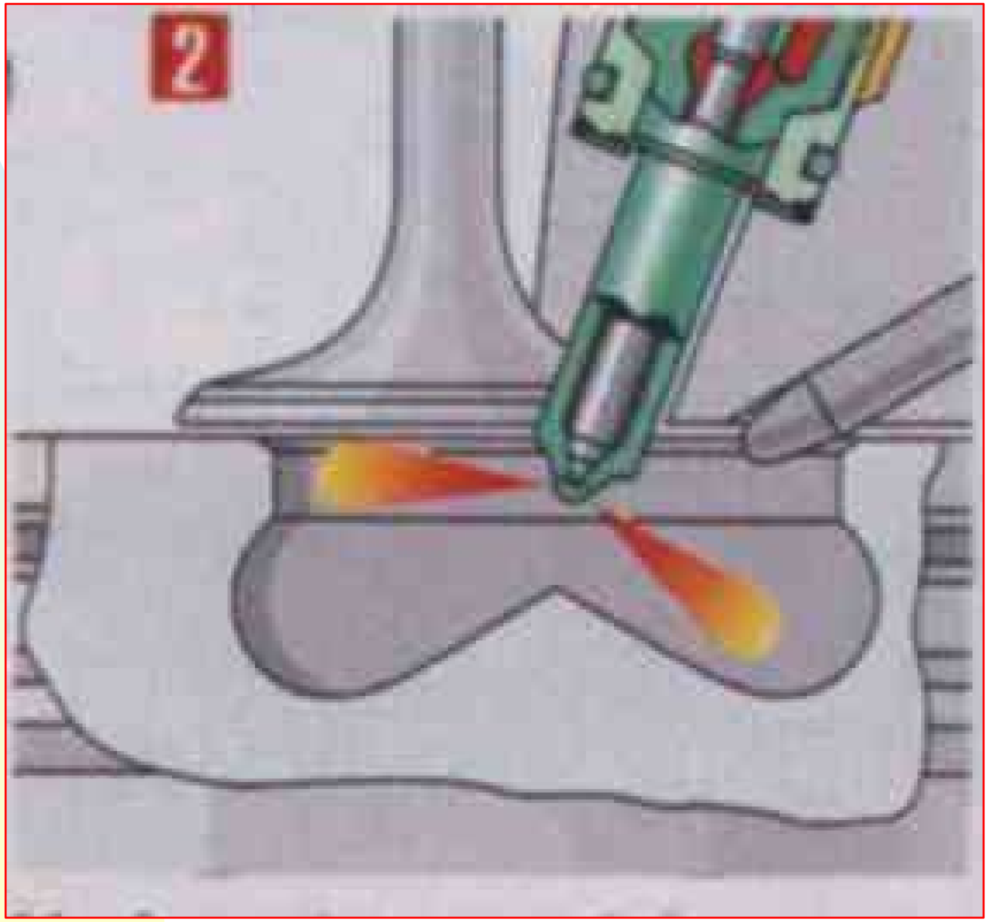
CI ENGINE FUEL INJECTION SYSTEMS

Injection systems of CI engines

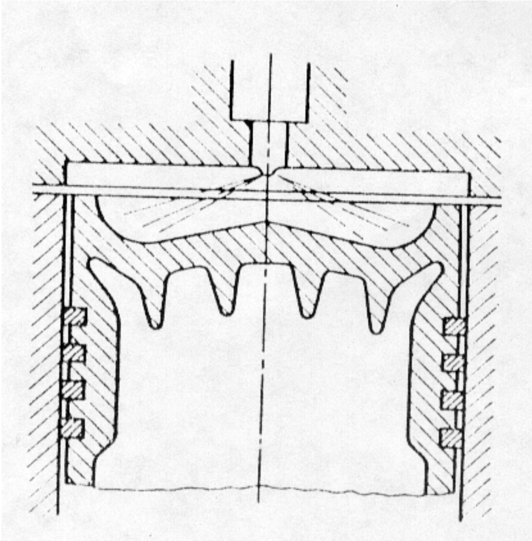
1. Direct injection systems DI.

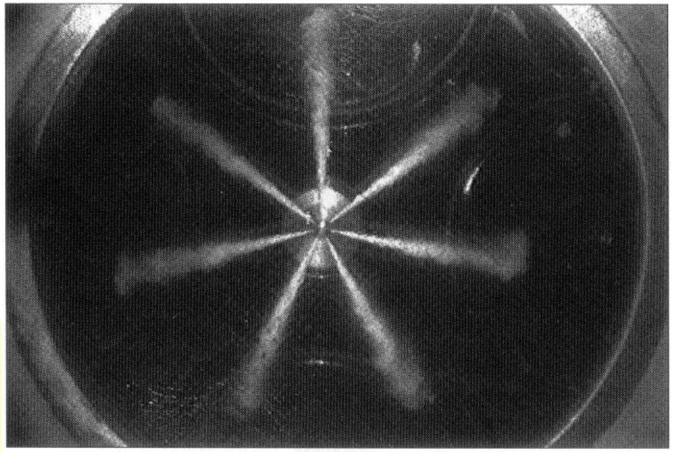
2. Indirect injection IDI.

Direct injection DI

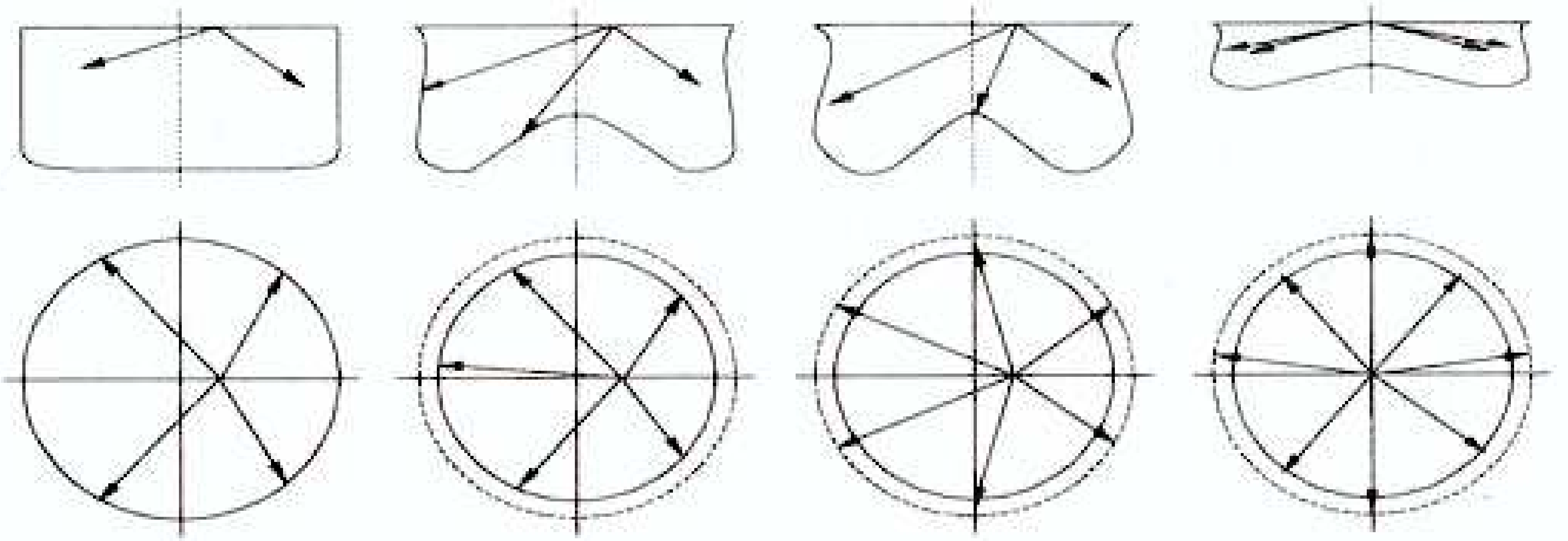


DI (*direct injection*)





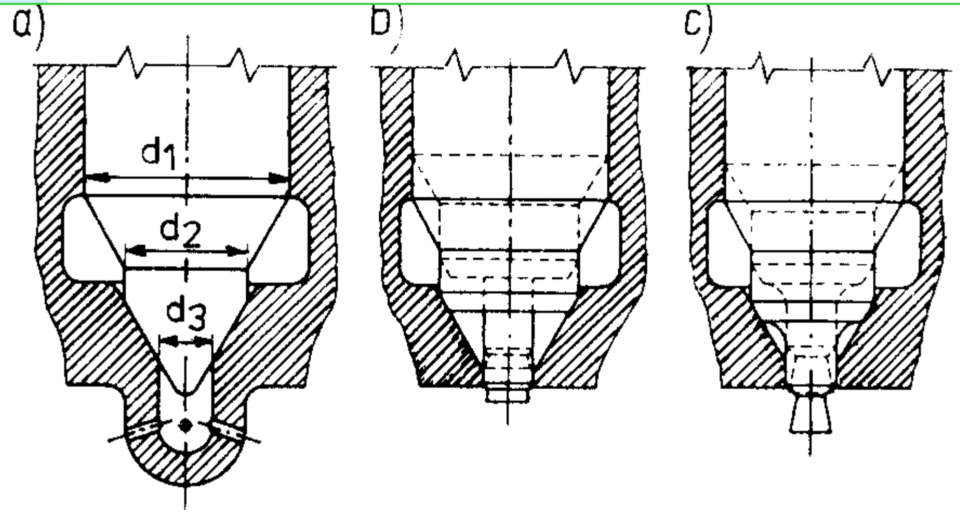
Direct injection systems DI



4-holes injector | 5-holes injector | 6-holes injector | 8-holes injector

Shape of combustion chamber in piston

Diesel oil injectors

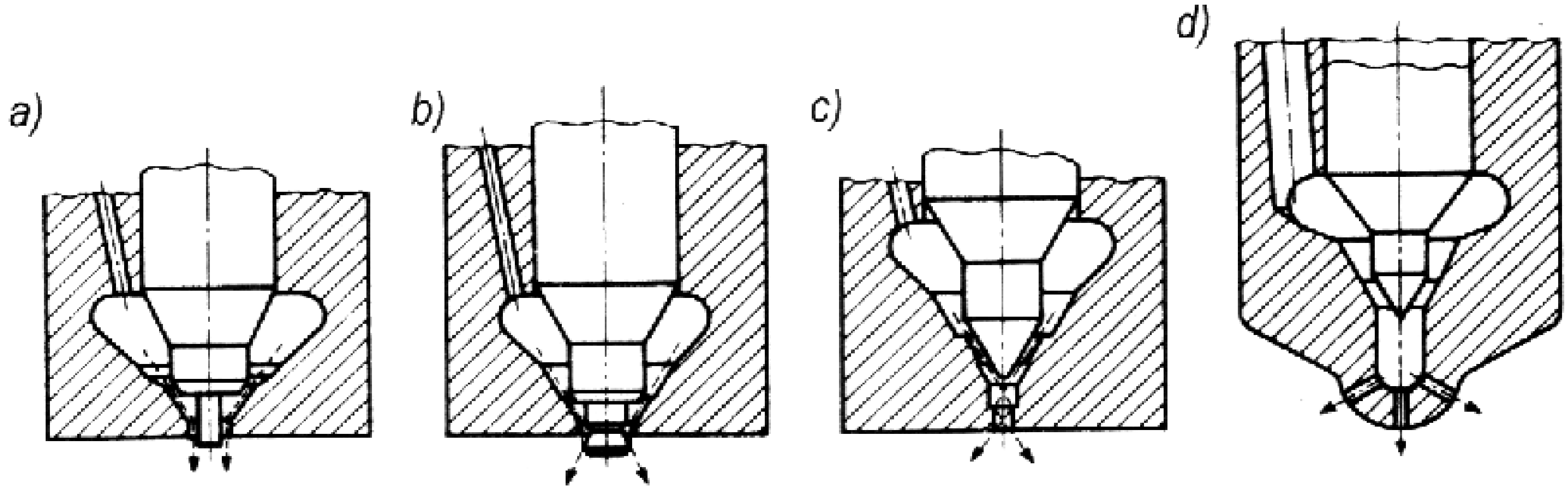


Rys. 11.7. Typowe końcówki wtryskiwaczy do silników Diesla: a) wielootworkowego, b) standardowego czopikowego, c) czopikowego dławiącego [2]

Typical injector nozzels

- **multihole**
- **standard with needle**
- **chocking with needle**

Types of Diesel oil nozzles



Types of injector
a) with cylindrically ended needle, b) with conically ended needle,
c) single-hole, d) multi-hole

Typy rozpylaczy:
a) czopikowy z cylindrycznym zakończeniem iglicy, b) czopikowy ze stożkowym zakończeniem iglicy, c) jednootworowy, d) wielootworowy

Z pracy dypl. S. Dąbrowy

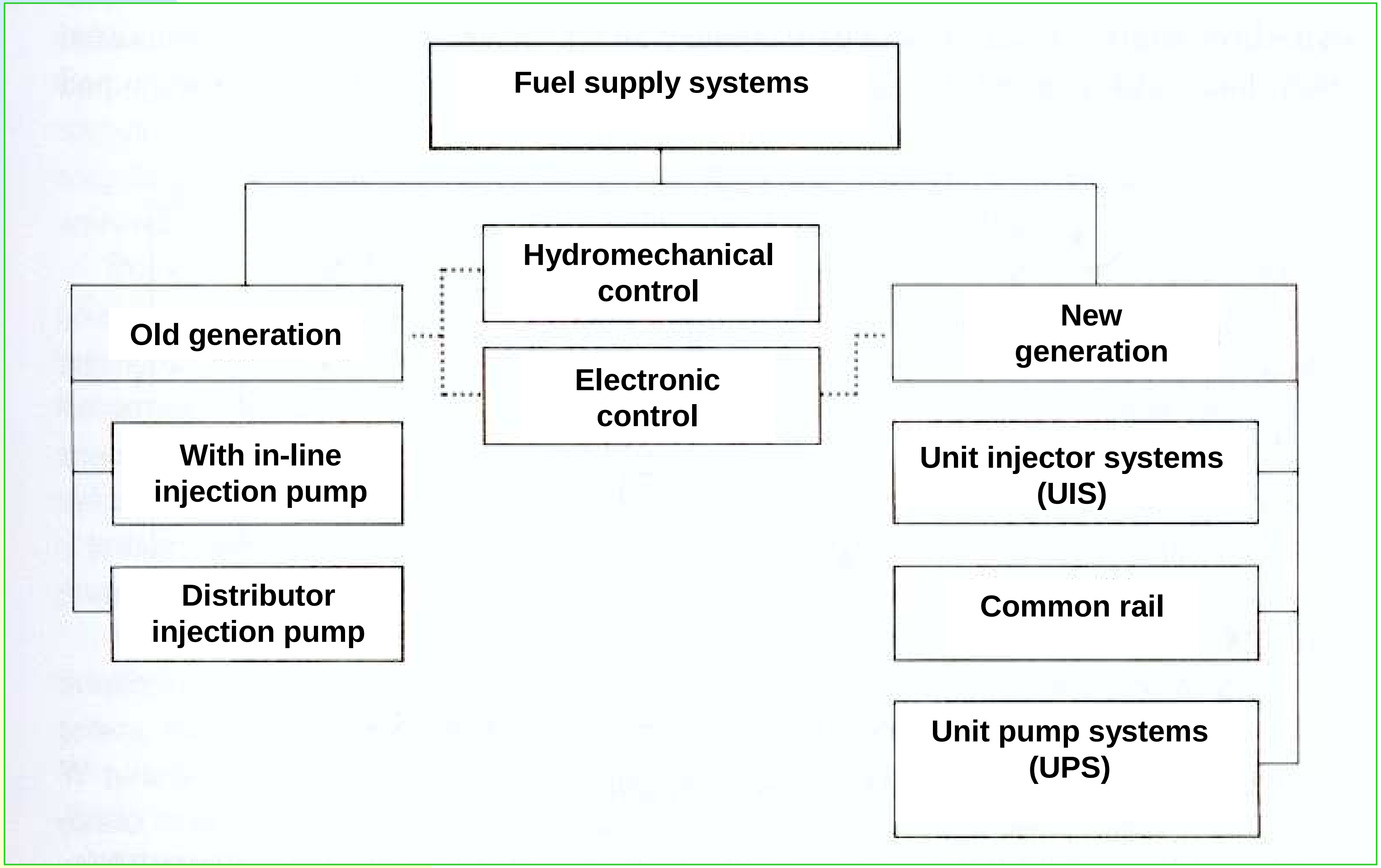
DI and IDI nozzles

Delphi DI injectors

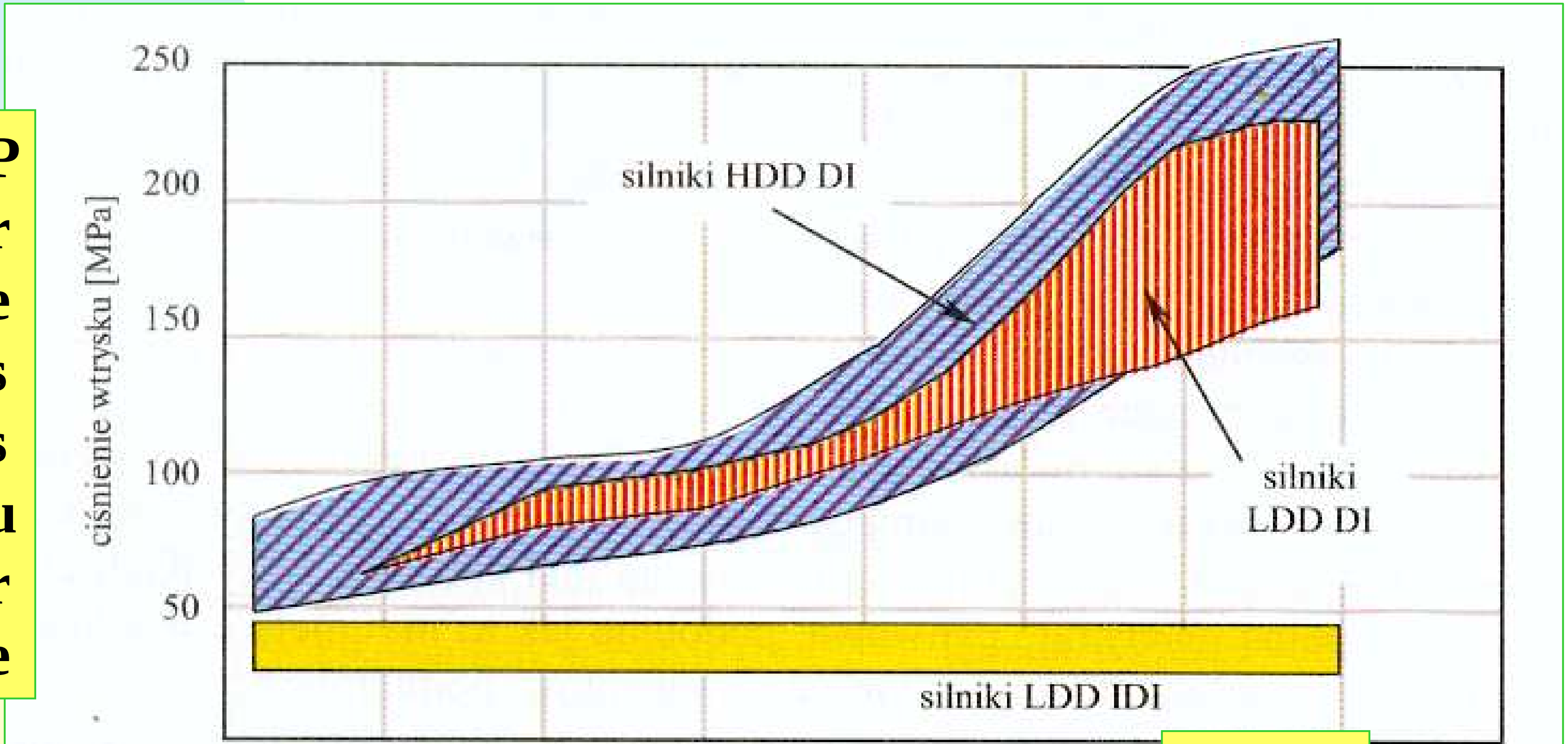
DelphiIDI injectors
with needle

FUEL SUPPLY SYSTEMS IN CI ENGINES

Types of fuel supply systems in CI engines



Change of injection pressure of fuel in CI engines



Pressure

Time

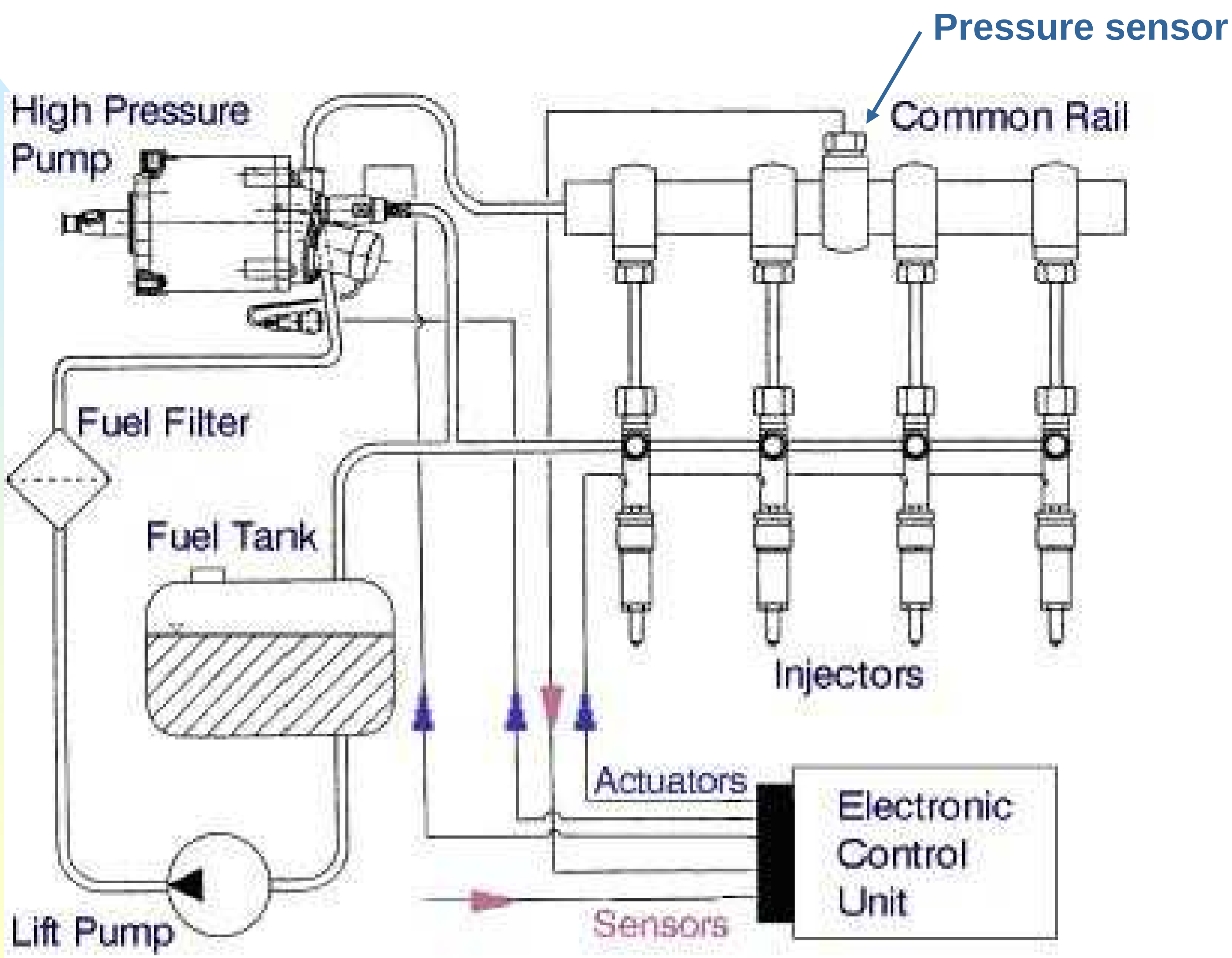
HDD- heavy duty Diesel, LDD- light duty Diesel

Current Diesel oil injection systems

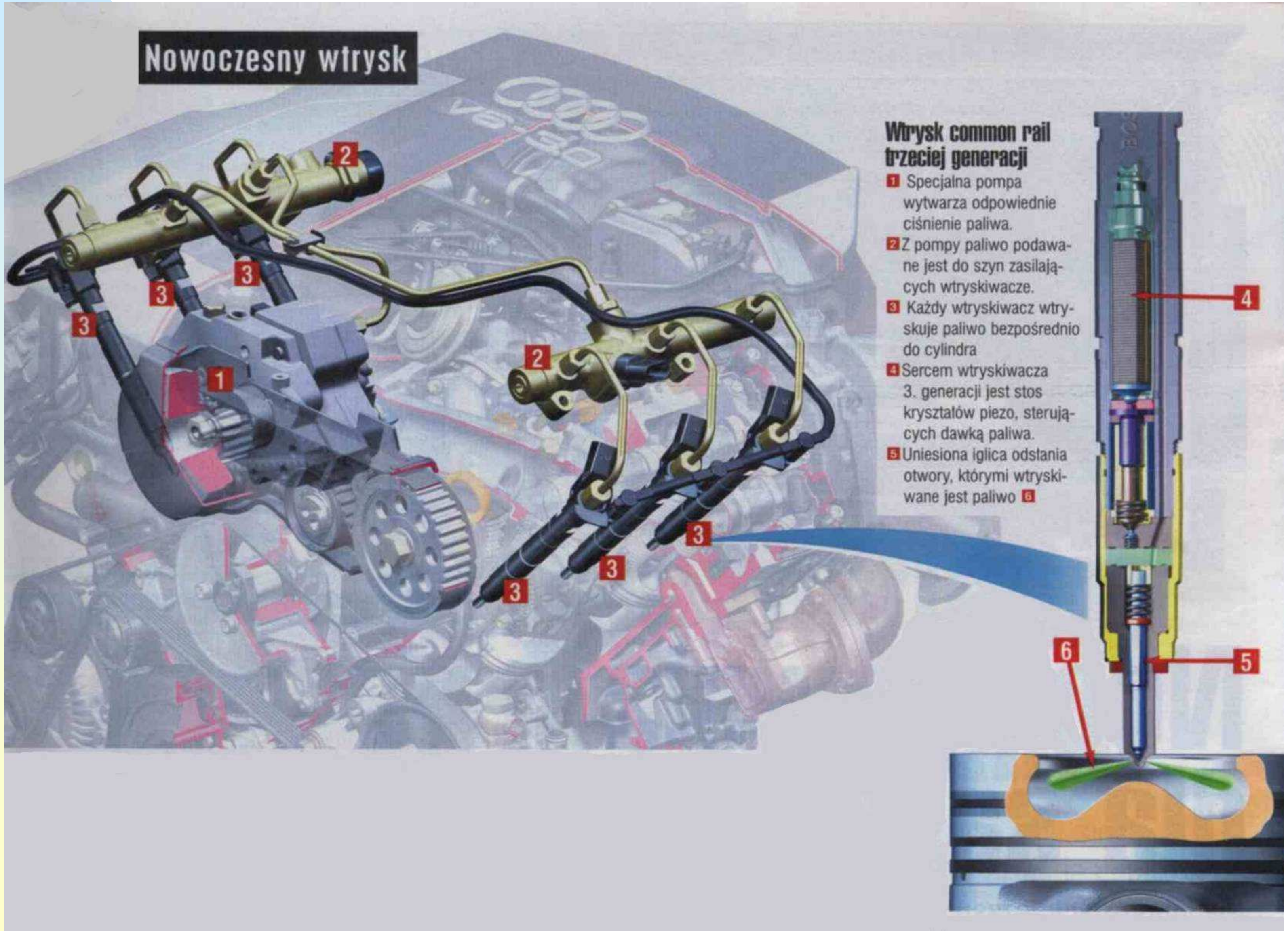
1. Common rail system.

2. Pump-injectors.

Scheme of common rail system

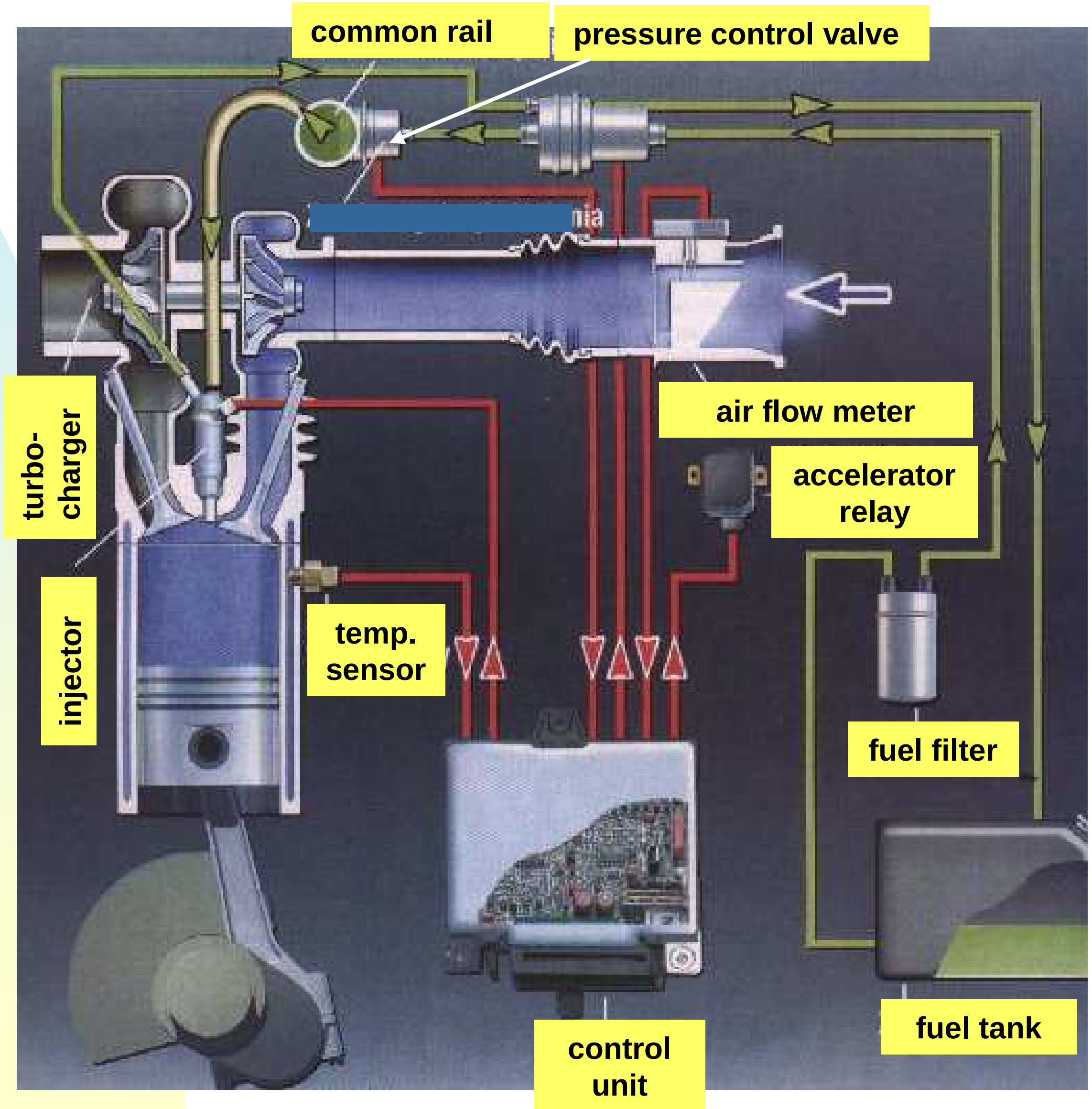


COMMON-RAIL

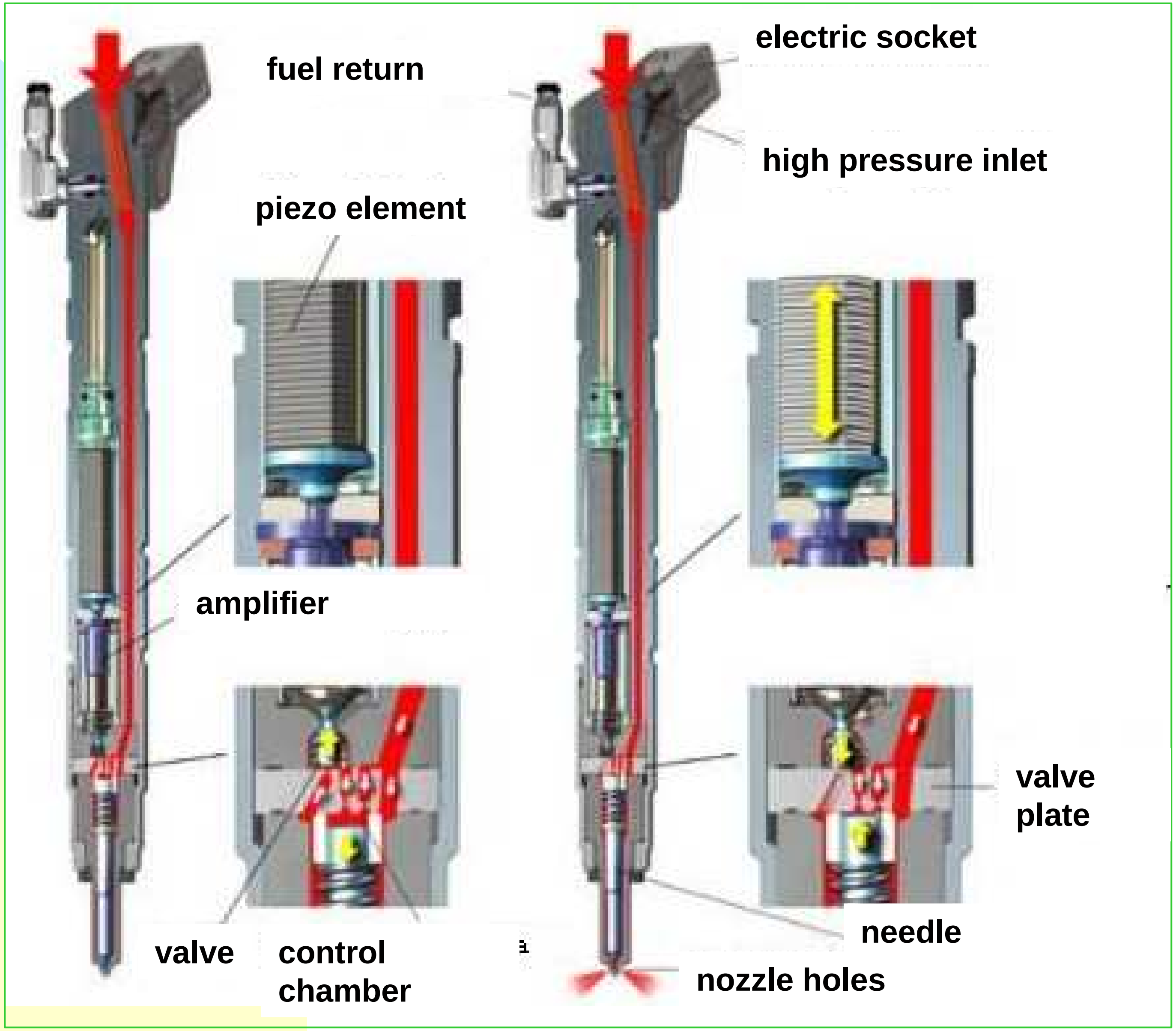


Nowoczesny wtrysk
Wtrysk common rail trzeciej generacji
1 Specjalna pompa wytwarza odpowiednie ciśnienie paliwa.
2 Z pompy paliwo podawane jest do szyn zasilających wtryskiwacze.
3 Każdy wtryskiwacz wtryskuje paliwo bezpośrednio do cylindra
4 Sercem wtryskiwacza 3. generacji jest stos kryształów piezo, sterujących dawką paliwa.
5 Uniesiona iglica odsłania otwory, którymi wtryskiwane jest paliwo 6
1
2
2
3
3
3
3
3
3
3
4
5
6

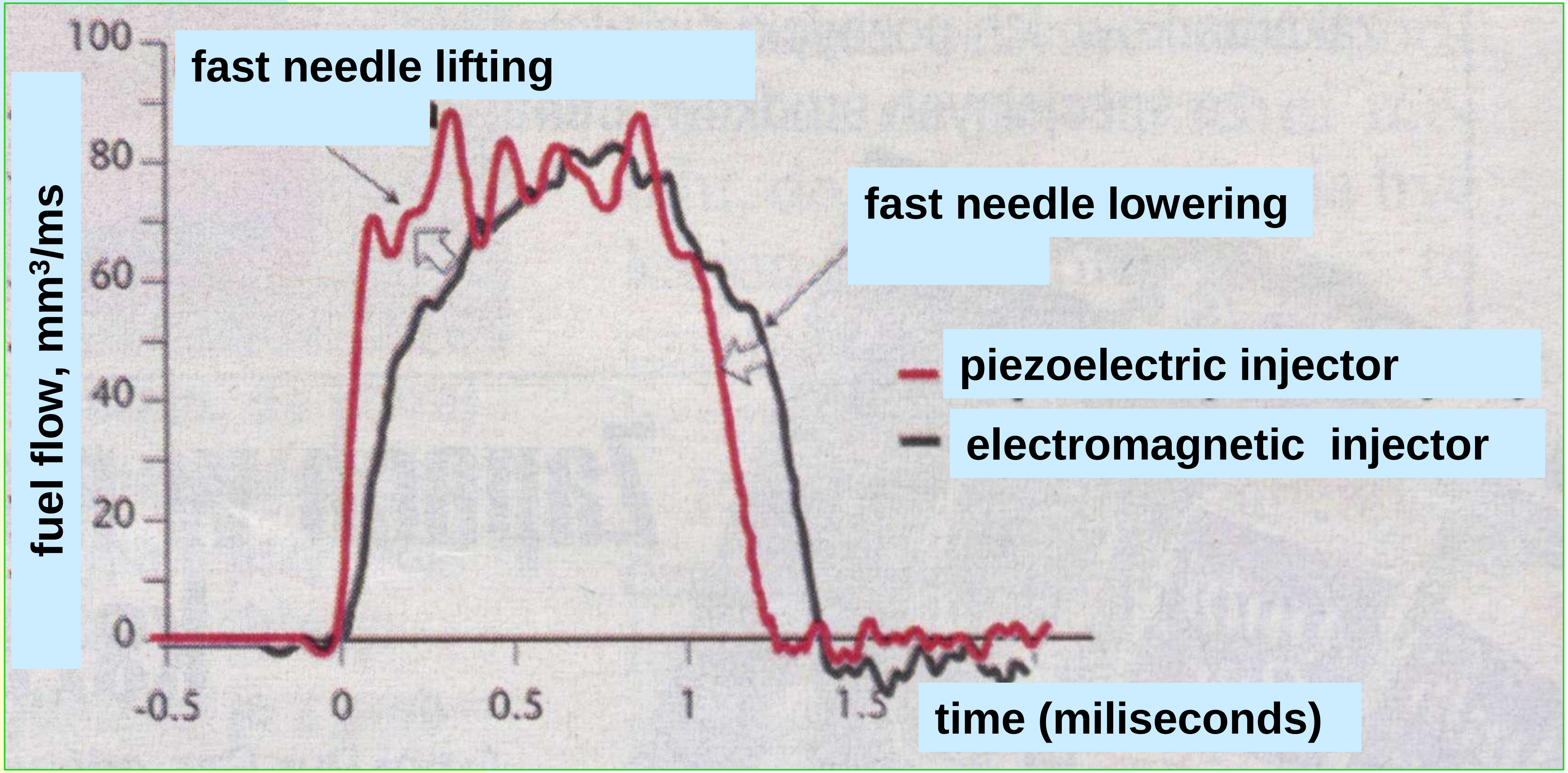
Scheme of CI engine with common-rail



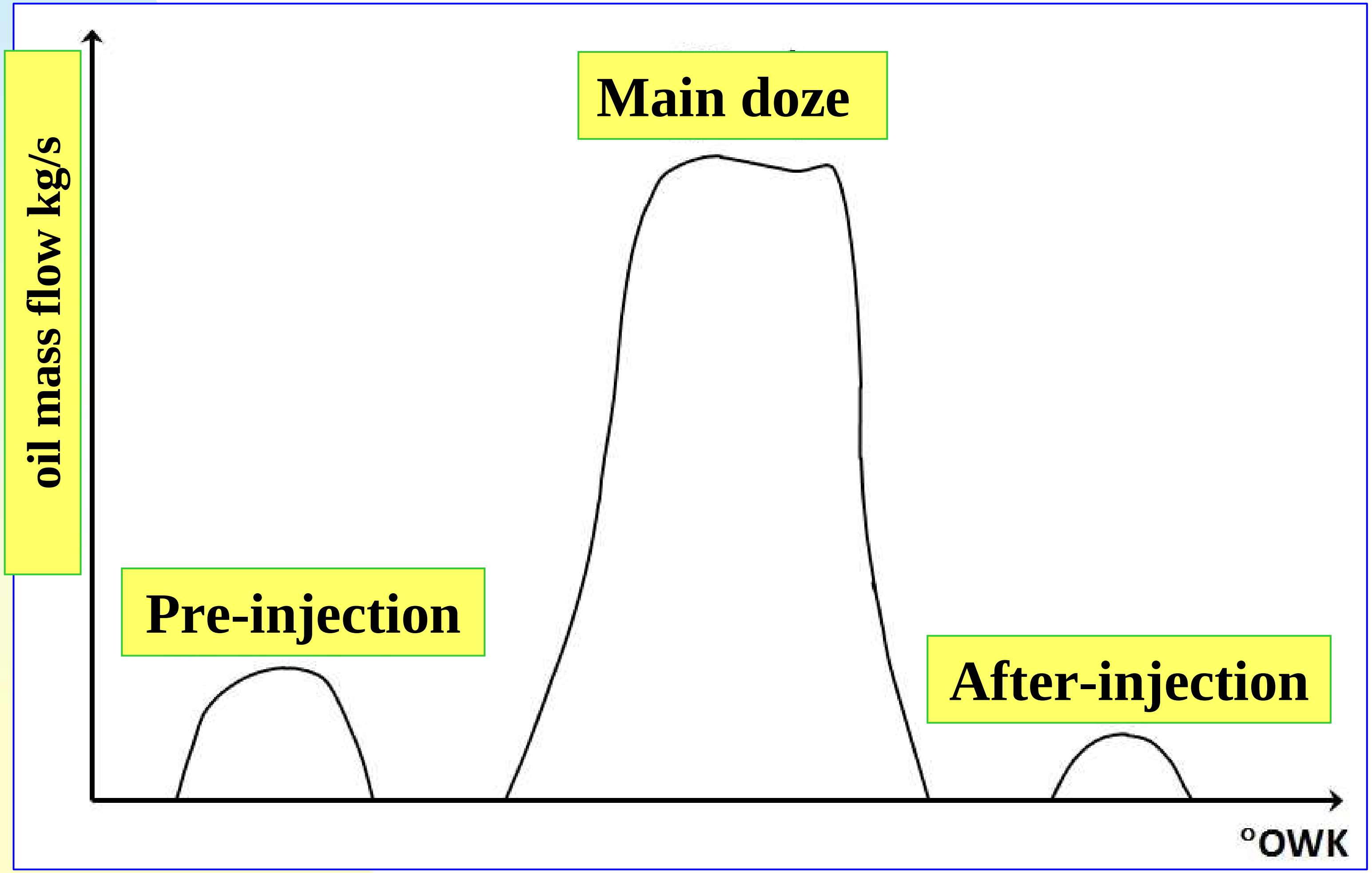
Piezoelectric Diesel oil injector



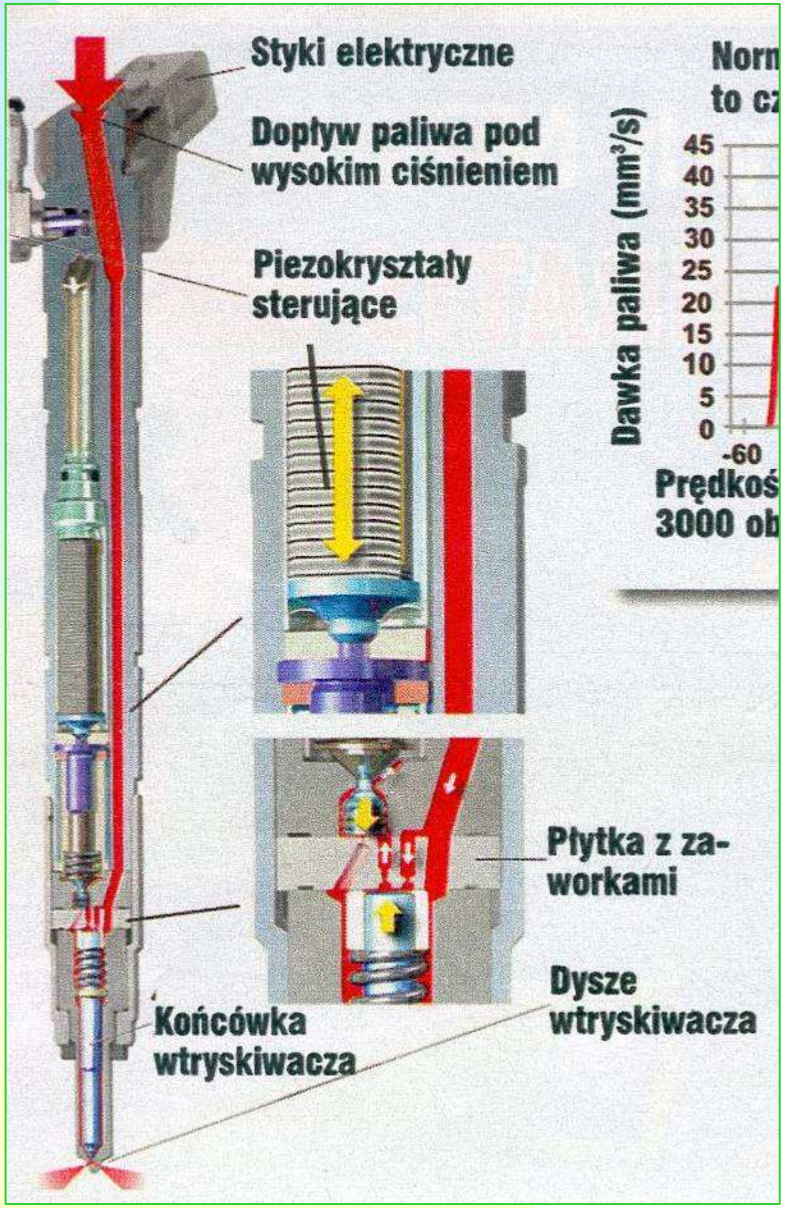
Comparison of piezoelectric and electromagnetic Diesel oil injectors



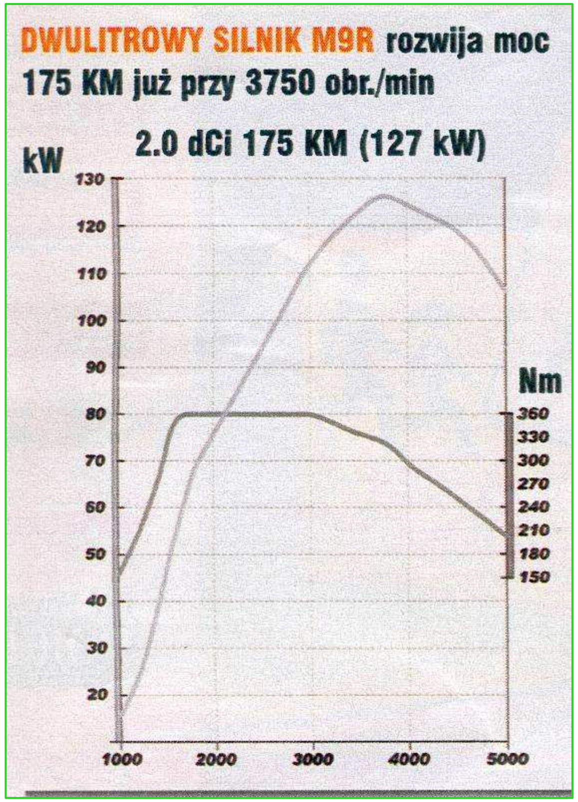
Divided Diesel oil injection



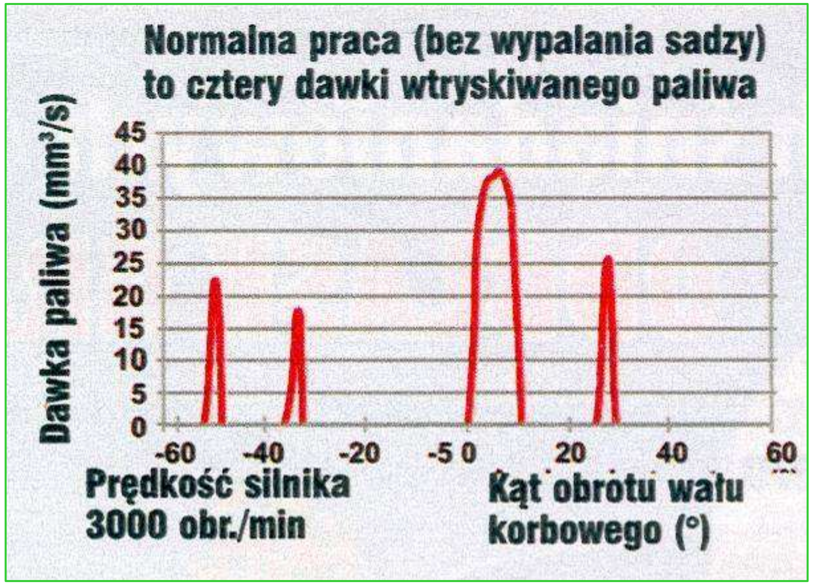
Common rail



Styki elektryczne
Dopływ paliwa pod wysokim ciśnieniem
Piezokryształy sterujące
Płytka z zaworkami
Końcówka wtryskiwacza
Dysze wtryskiwacza



DWULITROWY SILNIK M9R rozwija moc 175 KM już przy 3750 obr./min
2.0 dCi 175 KM (127 kW)
kW
Nm
130
120
110
100
90
80
70
60
50
40
30
20
360
330
300
270
240
210
180
150
1000
2000
3000
4000
5000

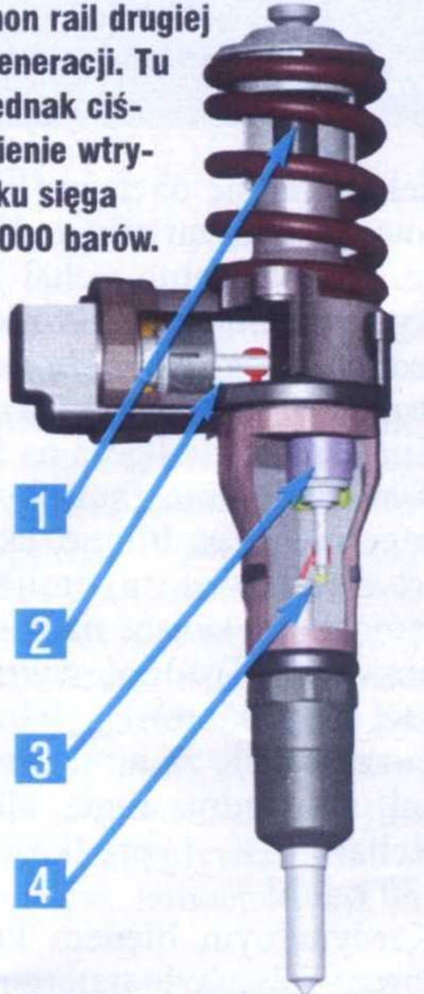


Normalna praca (bez wypalania sadzy) to cztery dawki wtryskiwanego paliwa
Dawka paliwa (mm³/s)
45
40
35
30
25
20
15
10
5
0
-60
-40
-20
-5 0
20
40
60
Prędkość silnika 3000 obr./min
Kąt obrotu wału korbowego (°)

Piezoelectric pump injector

Pompowtryski 3. generacji

Dwa zawory magnetyczne pozwalają na szybkie podzielenie cyklu nawet na pięć wtrysków, podobnie jak w układach common rail drugiej generacji. Tu jednak ciśnienie wtrysku sięga 2000 barów.



1 Tradycyjnie, wytworzenie ciśnienia możliwe jest dzięki napędowi odbieranemu od krzywki wałka rozrządu.

2 Ten zawór magnetyczny steruje wzrostem i spadkiem ciśnienia.

3 Drugi zawór magnetyczny steruje otwieraniem i zamykaniem rozpylacza.

4 Element sterujący, tak jak w układzie common rail.

AIR SUPPLY

Air inflow systems of CI engine

1. In CI engines only air flows through the inlet system.
2. There is no throtle in the CI inlet system
3. The engine speed is controlled by the oil injection system.

Stoichiometry of combustion of CI engines

The stoichiometric ration in CI engines is greater than in SI engines because the charge is produced directly in the combustion chamber:

a) atmospheric charged engines: λ **= 1.3-1.4**

b) supercharged engines: λ **> 2**

Supercharged CI engines

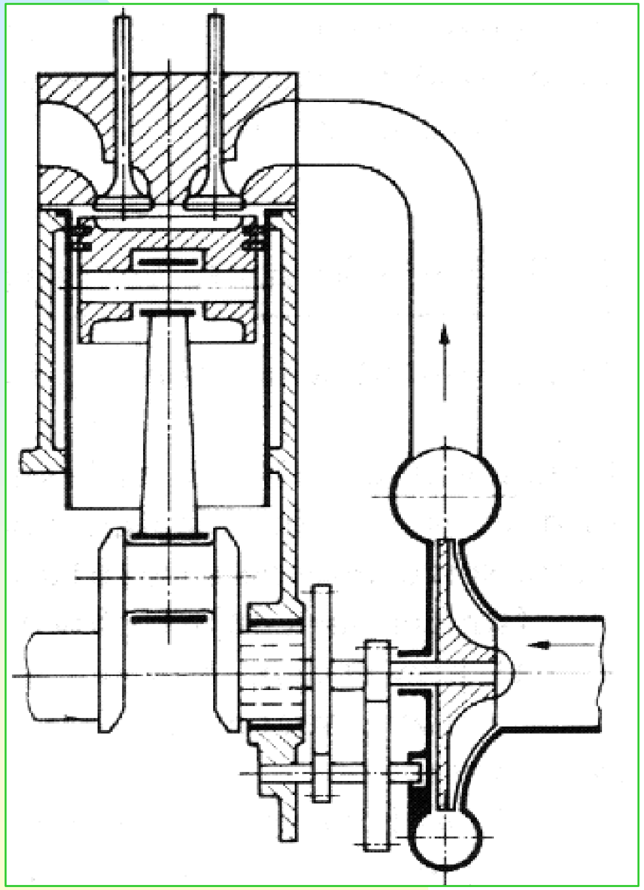
- Supercharge means to supply the cylinder with the charge of greater density (compressed air).

- Supercharge allow to increase of engine’s power without increase it its capacity.

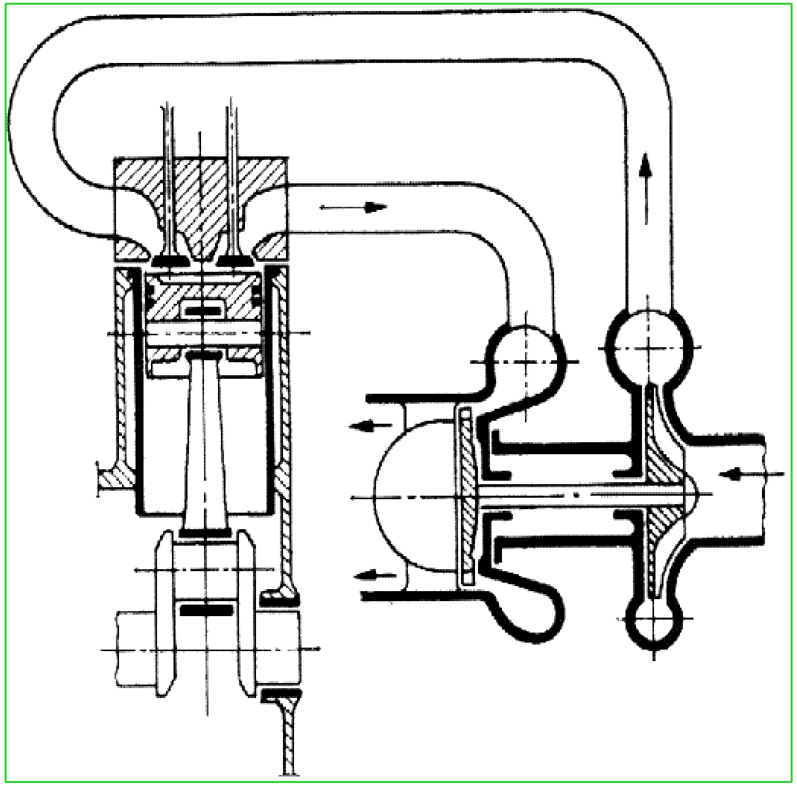
- Types of supercharge:
  - mechanical air compression,
  - gas turbine air compression.

- Compression pressure
  - low-pressure compression: < 0.15 MPa,
  - high pressure compression: from 0.3 to 0.5 MPa.

Types of air compression systems



a) mechanical

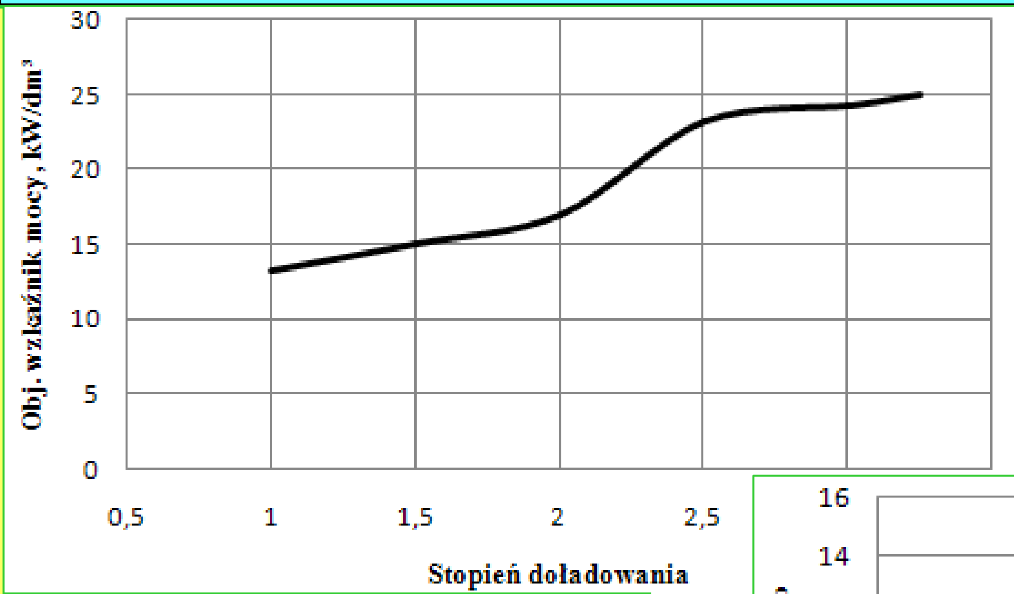


a) gas turbine

Mat. z pracy dypl. S. Dąbrowy

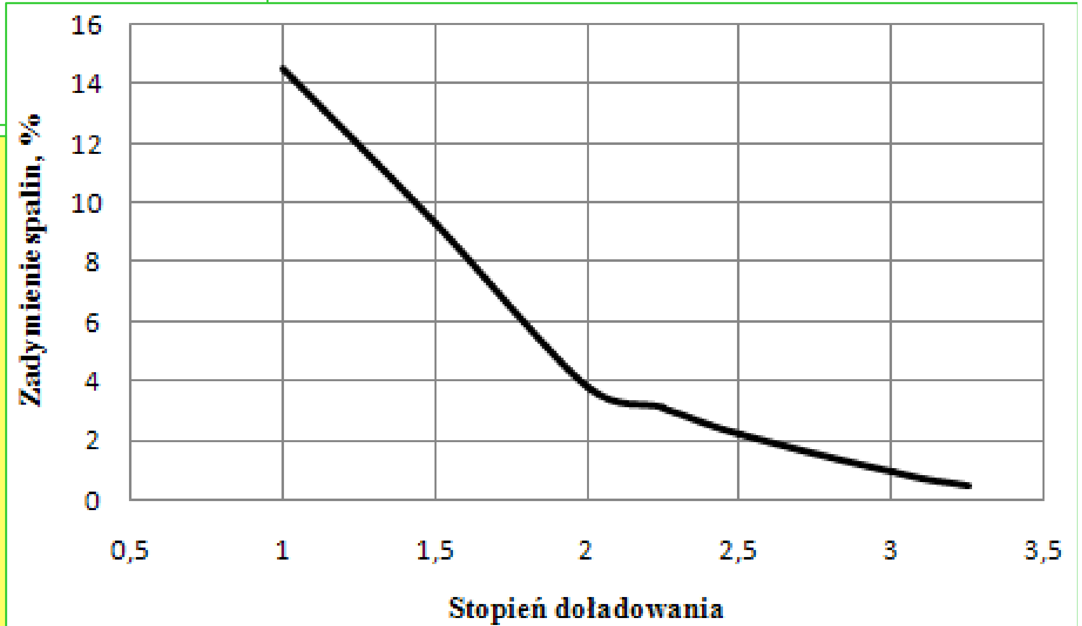
Effect of supercharge on power and soot emission CI engines

Pover per volume kW/dm^3



Compression ratio

Fumes opacity, %



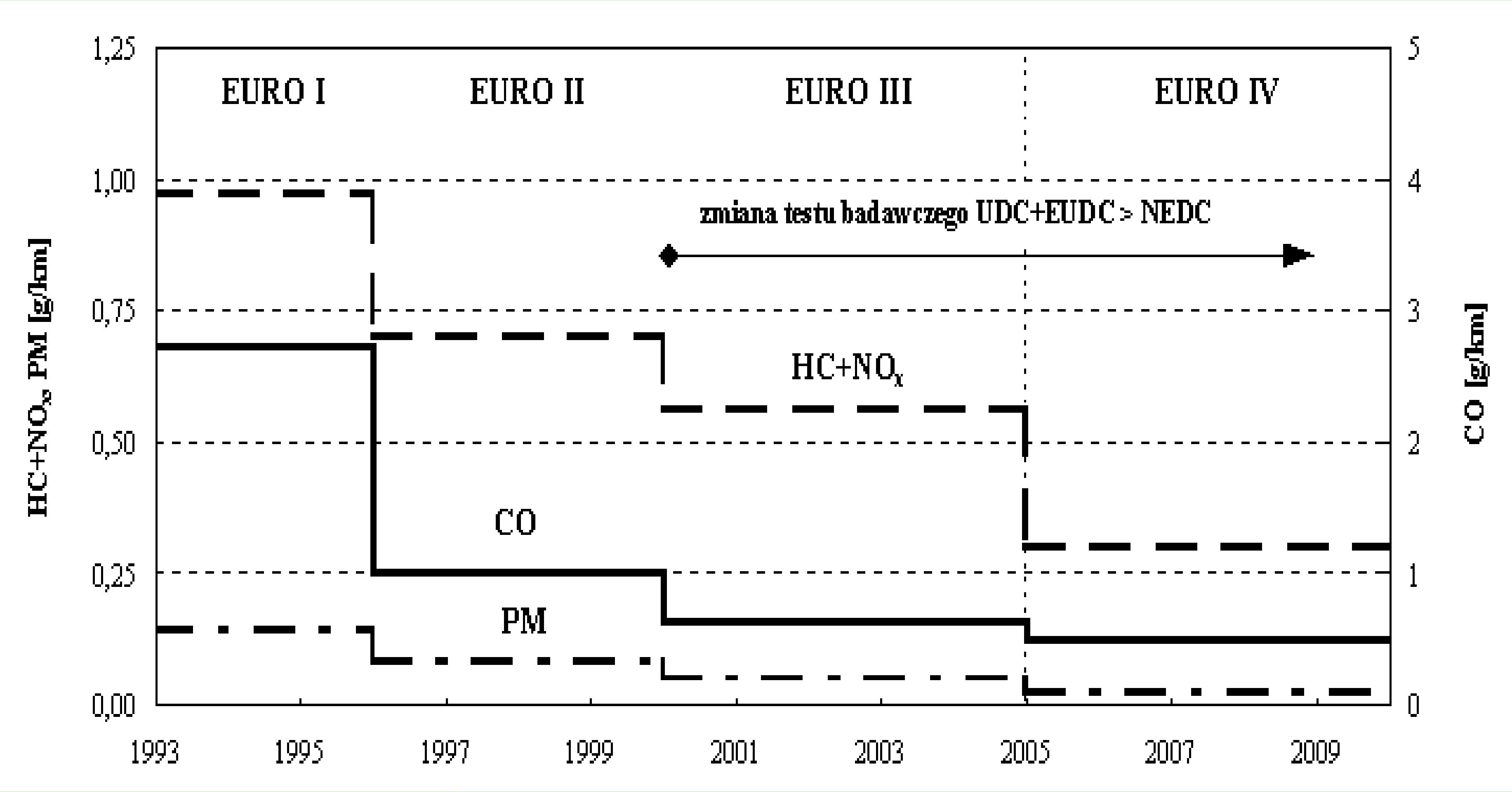
Compression ratio

EMISSIONS OF POLLUTANT FROM CI ENGINES

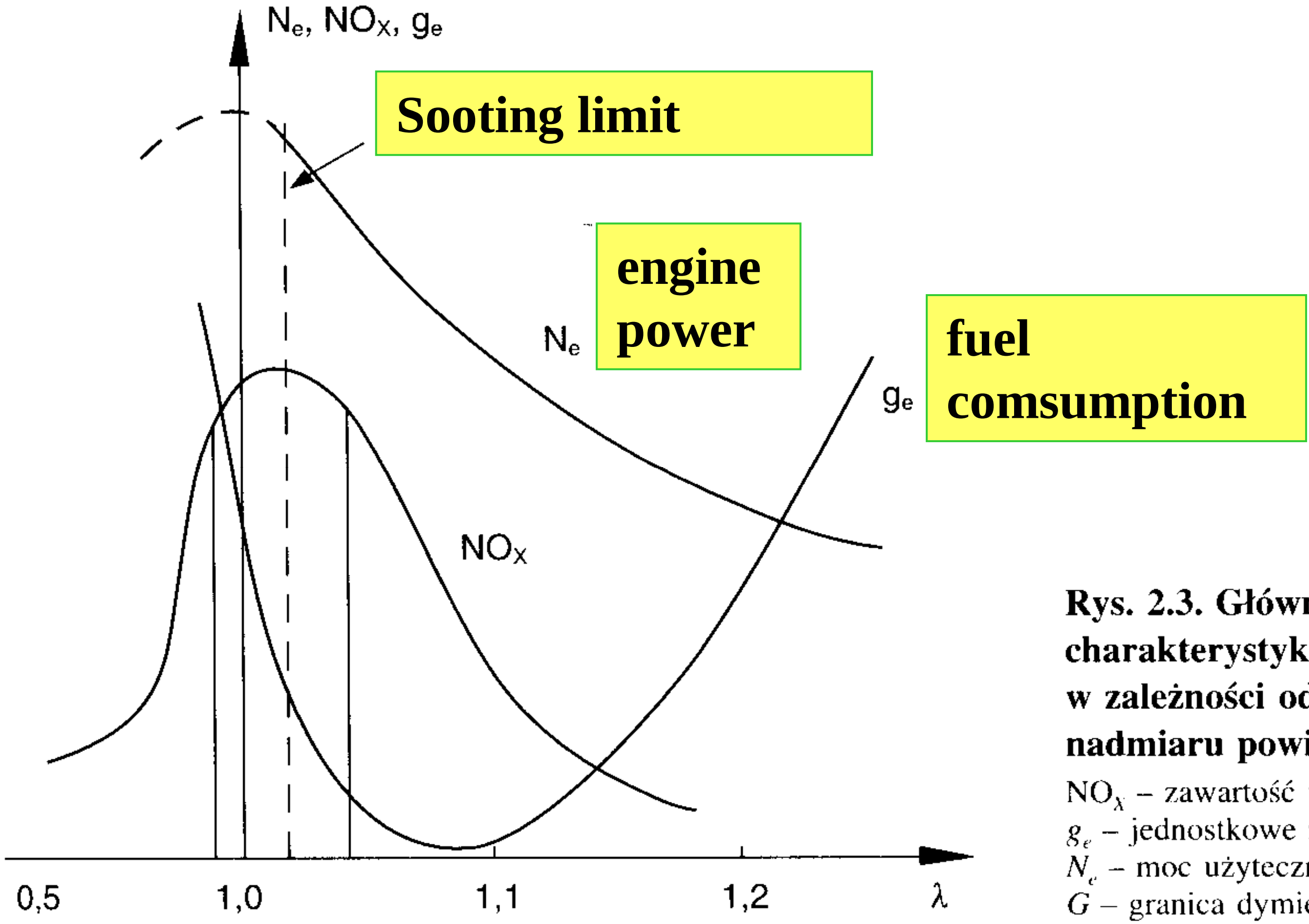
Content of combustion gases from Diesel engines

FLUE GAS			
Non-toxic components		Toxic components	
Water	H_2O	Carbon monoxide	CO
Carbon dioxide	CO_2	Hydrocarbons	HC
Nitrogen	N_2	Nitrogen oxides	NO_x
Hydrogen	H_2	Aldehydes	CHO
Oxygen	O_2	Solids	PM
Noble gases		Others	SO_x, Pb

Limits pollutant emissions from CI engines



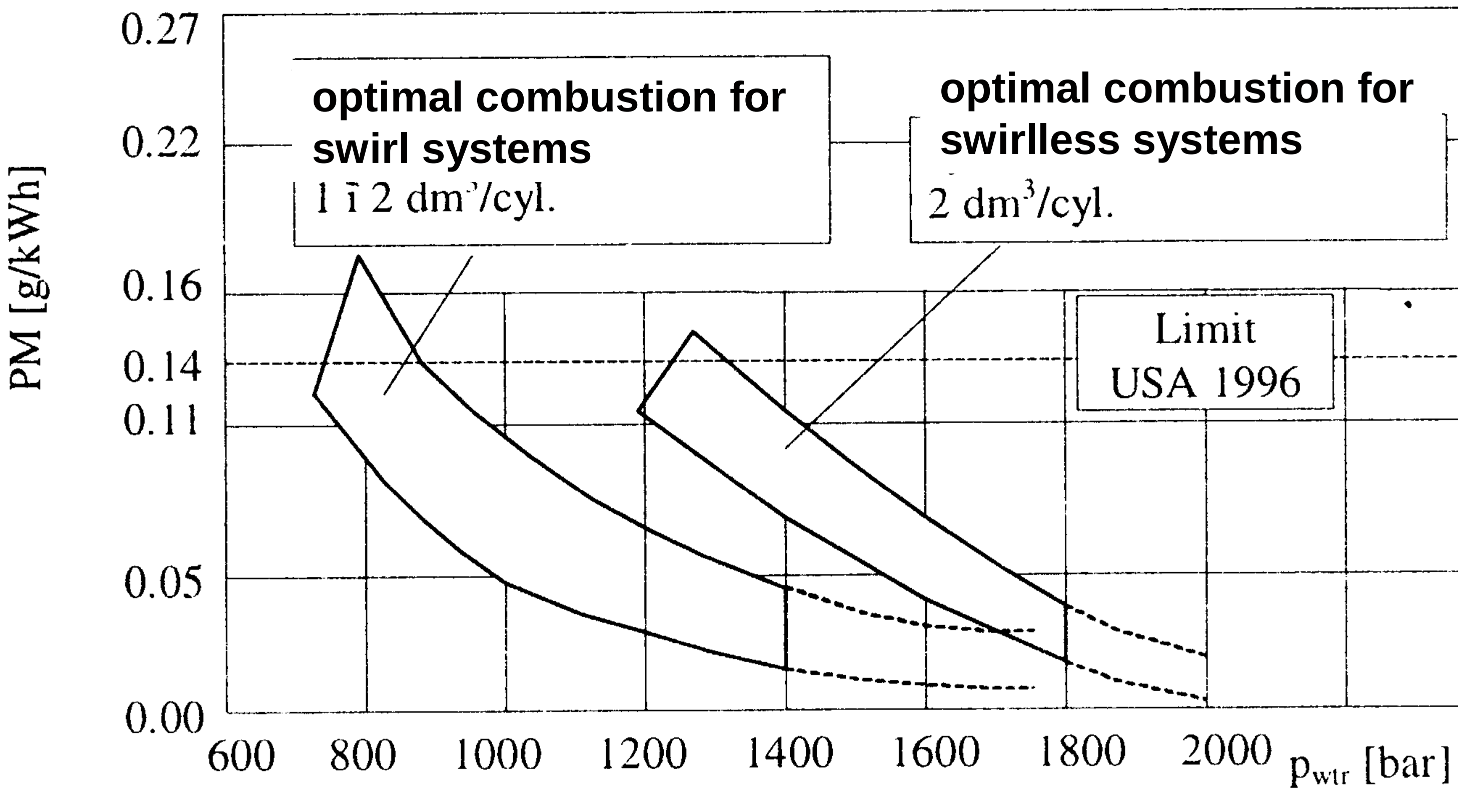
Effect of stoichiometry on pollution emissions from CI engines



Rys. 2.3. Główne charakterystyki silnika ZS w zależności od współczynnika nadmiaru powietrza λ

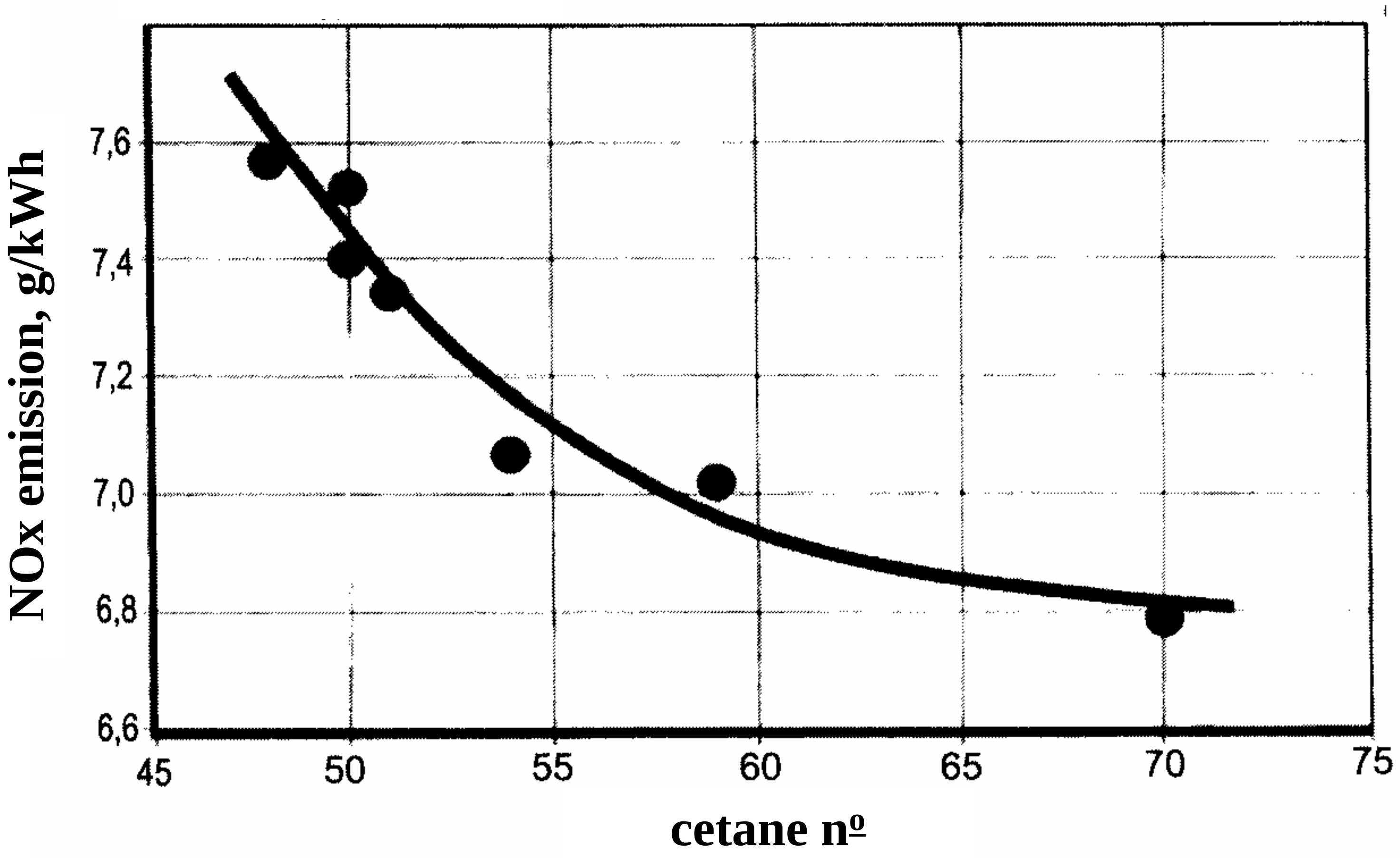
NO_X – zawartość w spalinach,
g_e – jednostkowe zużycie paliwa,
N_e – moc użyteczna silnika,
G – granica dymienia

Effect of injection pressure on soot emission from CI engines



Rys. 39. Redukcja emisji cząstek stałych PM przez zwiększenie ciśnienia wtrysku dla silników HDD [50]

NO_x emission vs. Cetane No.



Soot removal from combustion gases

1. Soot particles are removed from combustion gases in reburning filters.
2. Soot filters are installed in outlet system of an engine.
3. Two types of soot filters are in use:
   - *SMF* (*Sintered Metal Filter*), made of sintered metal with electric heaters inside,
   - *DPF* (*Diesel Particulate Filter*) which is composed of a preliminary catalyst and a main filter made of carbides.

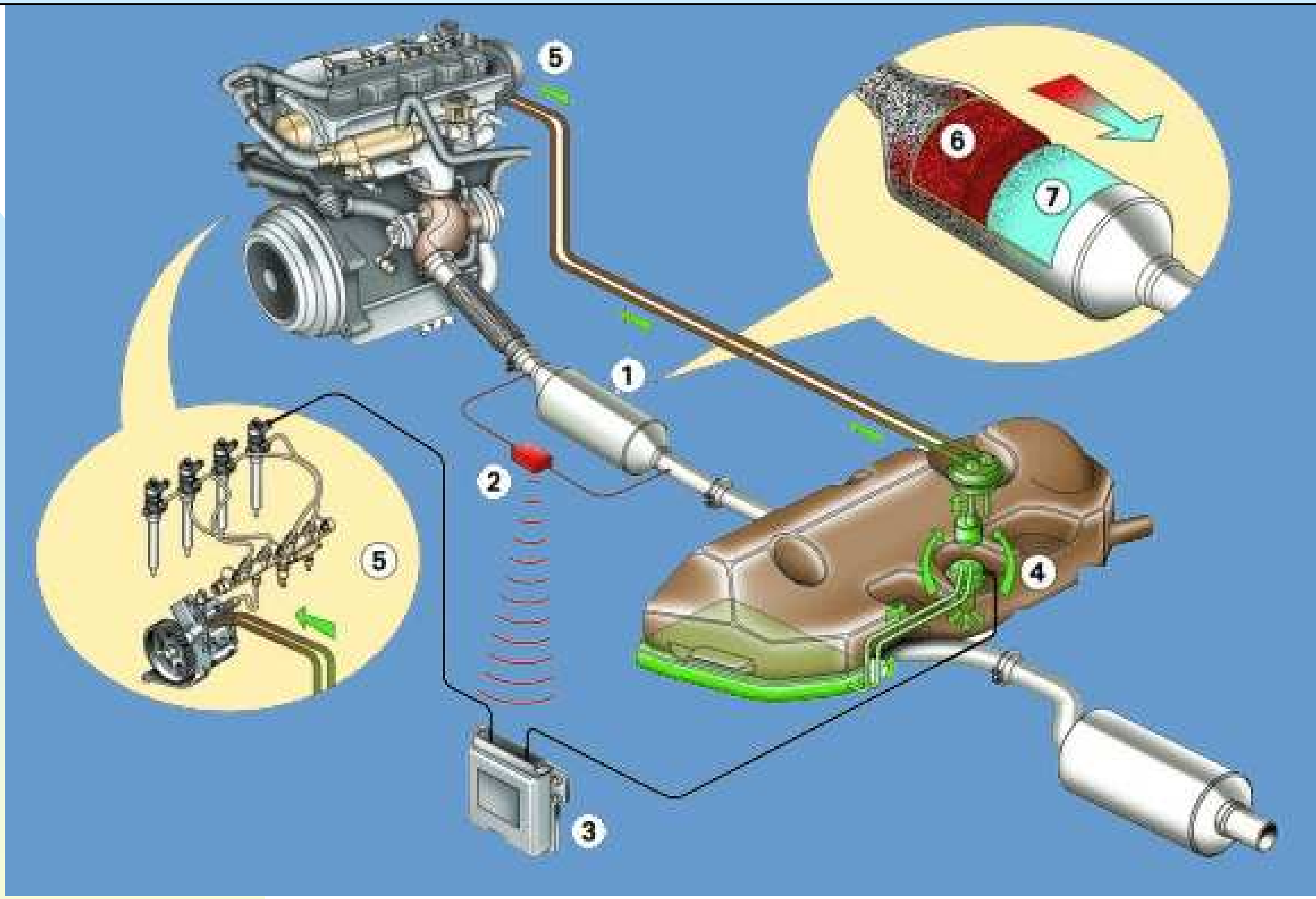
SMF (Sintered Metal Filter)

Combustion gases flow through the filter (size of pores - 10 μm), which stops soot particles. Temperature and pressure sensors start up the system of filter regeneration. The electric heaters burn soot collected in the filter with the efficiency better than 95%. Advantage of this type of soot filters is relatively low hydraulic drag for combustion gases.

DPF (Diesel Particulate Filter)

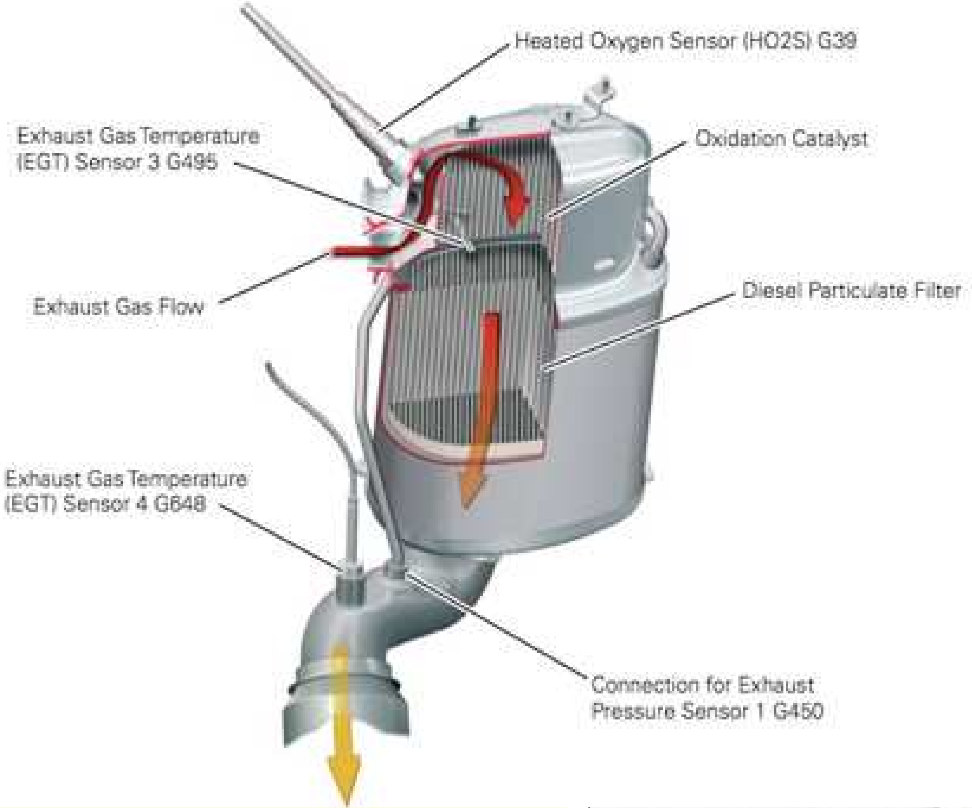
The DPF filter is composed of a preliminary catalyst of combustion gases and main filter of particulate matter made of carbides. Soot particles collected in the filter are ignited by hot combustion gases. Because temperature of combustion gases in the outlet collector is in the range of 150÷200 ºC, and the ignition temperature of soot is approx. 550 ºC, temperature of combustion gases is increased by burning of additional sample of oil during the decompression stage.

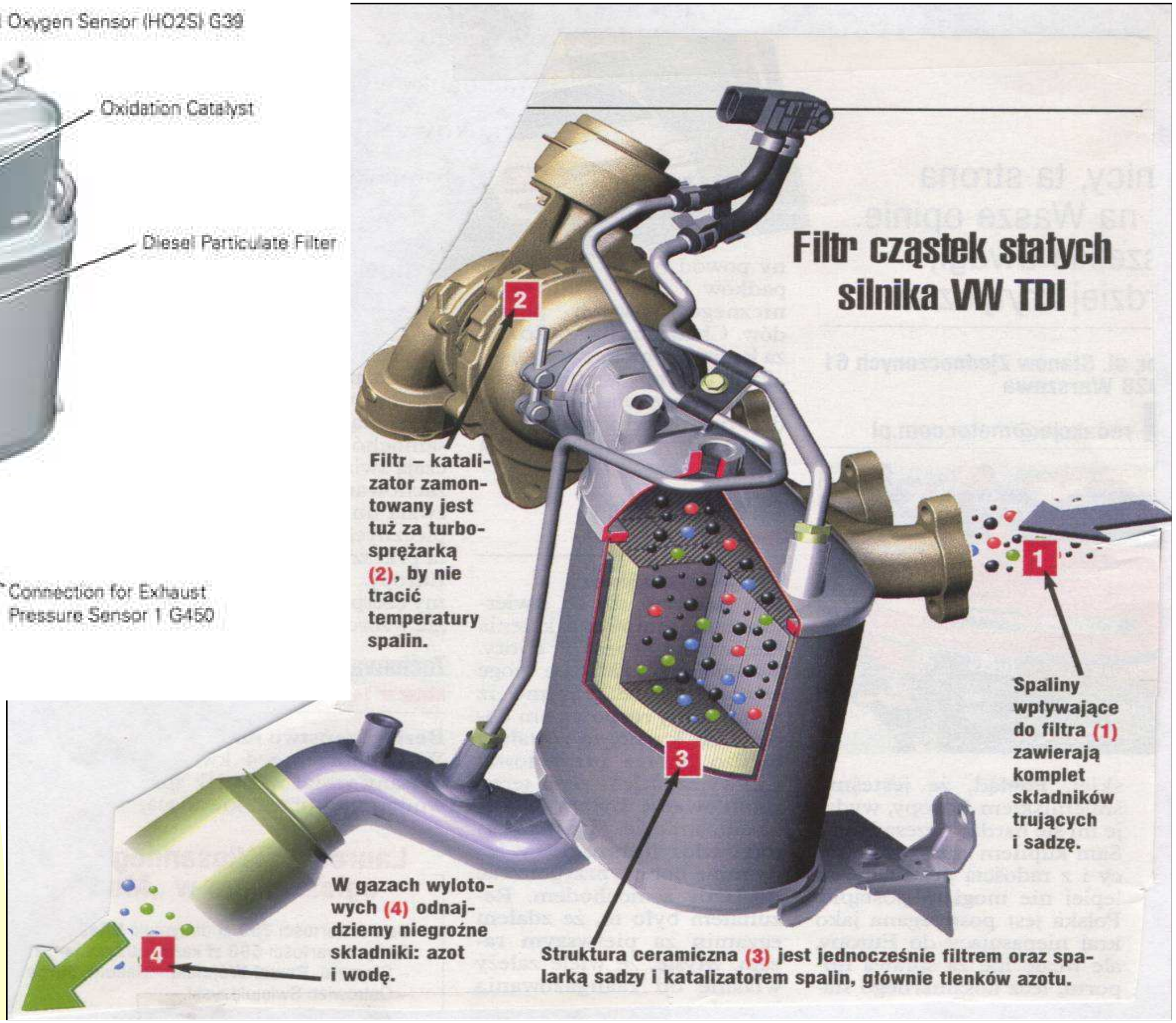
Scheme of soot particles removal



1. Particulate 'Filter and Pre-catalyst' filter assembly
2. Temperature and pressure sensors
3. Engine ECU
4. Injection of additives into the fuel in the main tank if necessary
5. Specific information sent to injector head when post-combustion needed
6. Pre-catalyser
7. Particulate filter

Catalysts in cleaning of combustion gases





DIESEL FUELS

Basic parameters of Diesel fuels

1. Colour and general look
2. Density at the temperature 15 ^{o}C
3. Cetane No.
4. Viscosity at the temperature 40 ^{o}C
5. Low-temperature parameters :
   - temperature of become hazy
   - temperature of cold filter blocking
   - temperature of flow
6. Sulphur content
7. Solid impurities content
8. Water content
9. Lubricating ability
10. Corrosivity

Basic parameters of Diesel fuels

11. Resistance to oxidation
12. Coking ability (Conradson no.)
13. Ashing
14. Content of aromatic hydrocarbons
15. Content of PAH
16. Temperature of ignition
17. Acidity no.
18. Washing properties
19. Content of FAME, ethanol, methanol and microorganisms
20. Content of metals (Zn, Cu, Mn, Ca, Na i in.)

Properties of Diesel oil

Parameter	Unit	Value	
		Minimum	Maximum
Cetane No.	-	51,0	-
Density at 15 °C	kg/m^3	820	845
Content of PAH	% mass.	-	11
Content of sulphur	mg/kg	-	50
Temperature of selfignition	°C	> 55	-
Content of ash	% mass.	-	0,01
Content of water	mg/kg	-	200
Viscosity at 40 °C	mm^2/s	2,00	4,50
Content of FAME	% vol.	-	5

Wg. PN EN 590

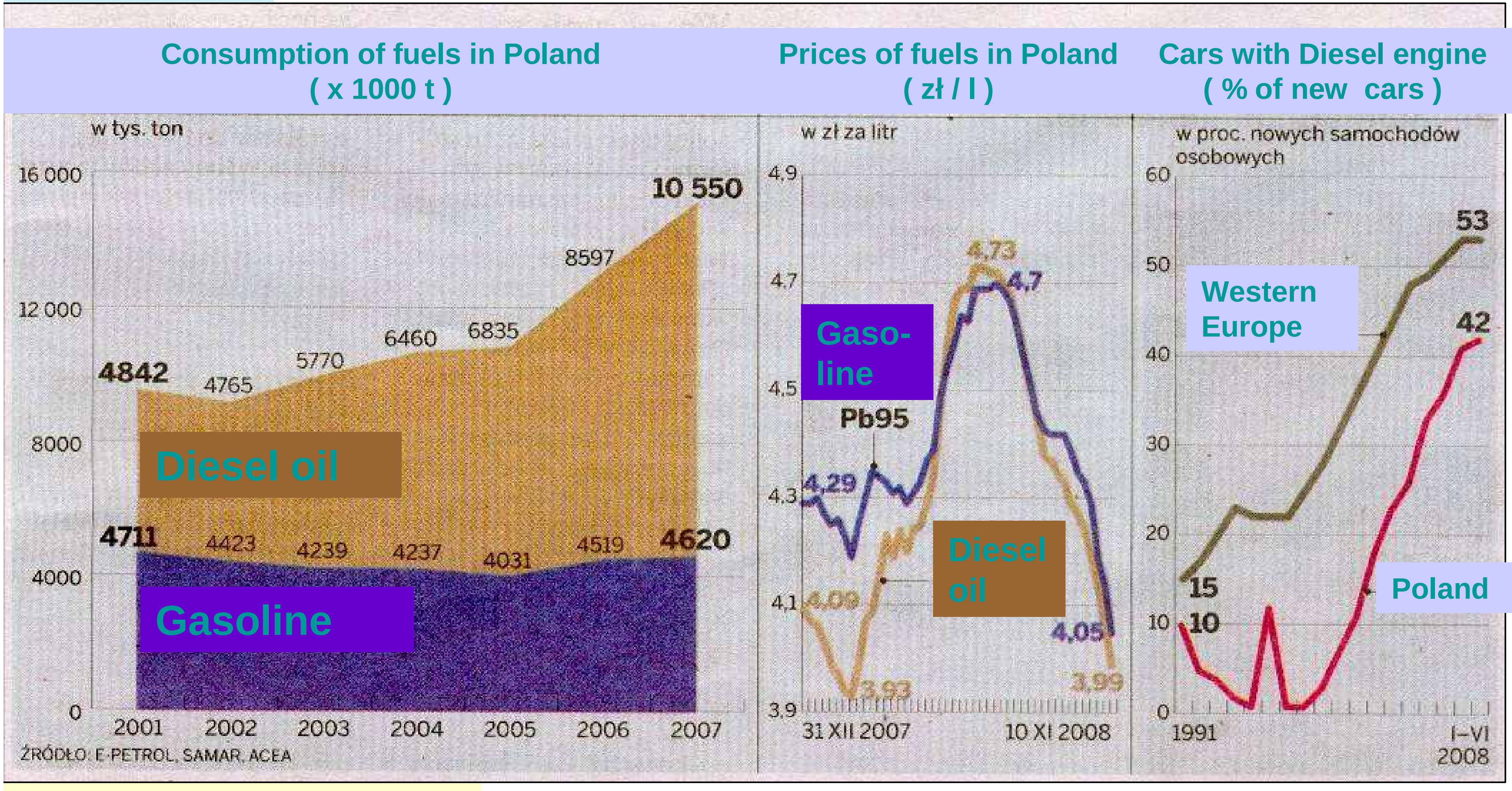
World Chart of Fuels (1998)

I. Categories of Diesel oils: 1 – 4

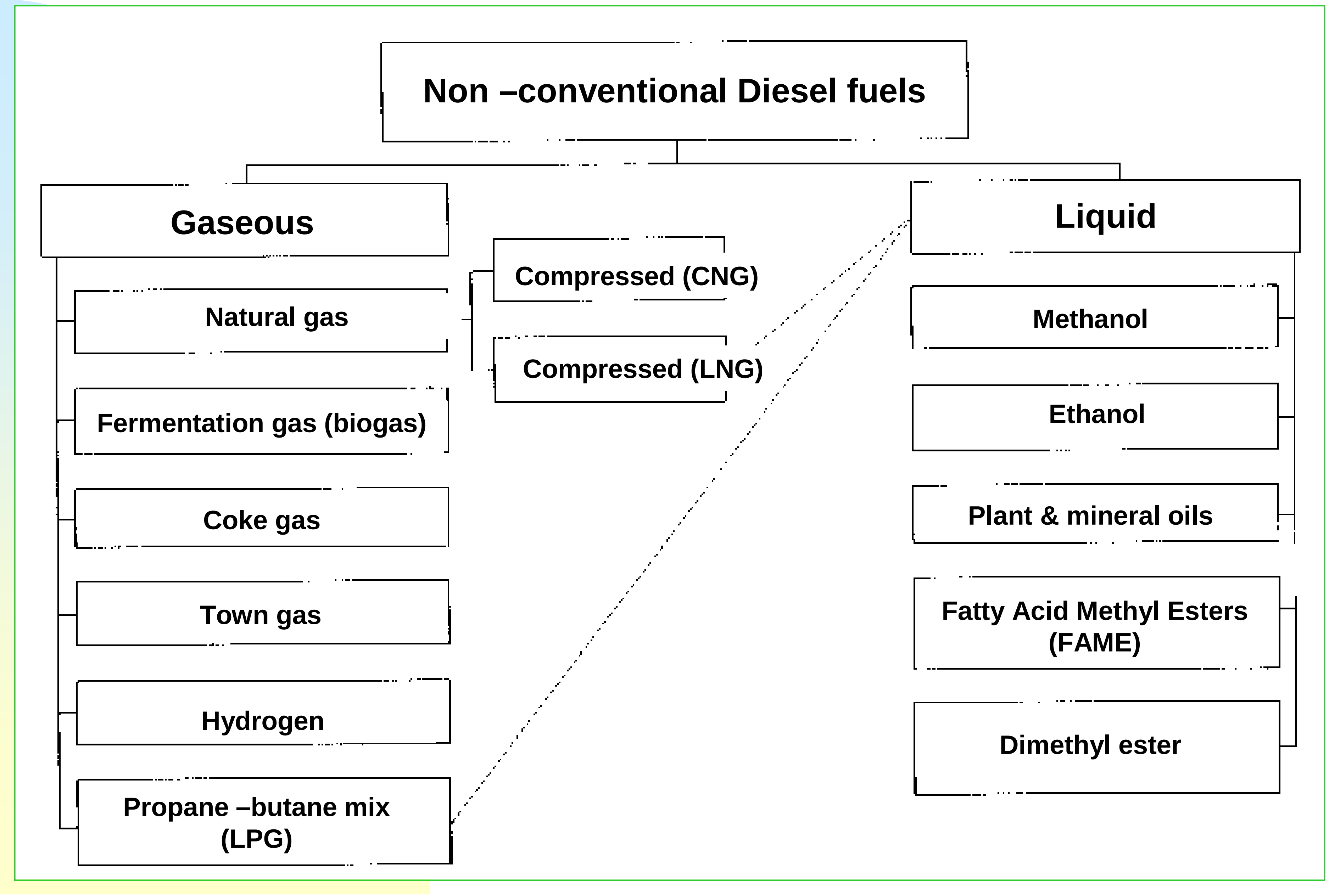
II. Changes with increase of category:

1. Fourth category: sulphur-less
2. Reduction of aromatic hydrocarbons content
3. No ethanol and methanol in Diesel oil
4. Content of FAME limited to 5%

Diesel oil market in Poland



Non-conventional Diesel fuels



Alcohols and esters as CI fuels

Alcohols

- Methyl alcohol CH_3OH LC = 3-5
- Ethyl alcohol C_2H_5OH LC = 5-8

Esters

- Dimethyl ester CH_3OCH_3 LC = 55-60
- Diethyl ester $C_2H_5OC_2H_5$

Gaseous CI engine fuels

Possible gaseous fuels:

a) LPG group:
- Propane
- Butane

b) NG group (stationary CI engines)
- LNG
- CNG

Because of low LC no. Gaseous fuels require for ignition:

a) Outer ignition source (e.g. electric spark)

b) Igniting pilot dose of Diesel oil