Diesel Engine Combustion

1. Characteristics of diesel combustion
2. Different diesel combustion systems
3. Phenomenological model of diesel combustion process
4. Movie of combustion in diesel systems
5. Combustion pictures and planar laser sheet imaging

DIESEL COMBUSTION PROCESS

PROCESS

- Liquid fuel injected into compressed charge
- Fuel evaporates and mixes with the hot air
- Auto-ignition with the rapid burning of the fuel-air that is “premixed” during the ignition delay period
  - Premixed burning is fuel rich
- As more fuel is injected, the combustion is controlled by the rate of diffusion of air into the flame

DIESEL COMBUSTION PROCESS

NATURE OF DIESEL COMBUSTION

- Heterogeneous
  - liquid, vapor and air
  - spatially non-uniform
- turbulent
- diffusion flame
  - High temperature and pressure
  - Mixing limited

The Diesel Engine

- Intake air not throttled
  - Load controlled by the amount of fuel injected
    - >A/F ratio: idle ~ 80
    - >Full load ~19 (less than overall stoichiometric)
- No “end-gas”; avoid the knock problem
  - High compression ratio: better efficiency
- Combustion:
  - Turbulent diffusion flame
  - Overall lean

Diesel as the Most Efficient Power Plant

- **Theoretically, for the same CR, SI engine has higher η_f; but diesel is not limited by knock, therefore it can operate at higher CR and achieves higher η_f**
- **Not throttled - small pumping loss**
- **Overall lean - higher value of γ - higher thermodynamic efficiency**
- **Can operate at low rpm - applicable to very large engines**
  - slow speed, plenty of time for combustion
  - small surface to volume ratio: lower percentage of parasitic losses (heat transfer and friction)
- **Opted for turbo-charging: higher energy density**
  - Reduced parasitic losses (friction and heat transfer) relative to output

Large Diesels: η_f~ 55%
~ 98% ideal efficiency !

Diesel Engine Characteristics (compared to SI engines)

- **Better fuel economy**
  - Overall lean, thermodynamically efficient
  - Large displacement, low speed – lower FMEP
  - Higher CR
    - > CR limited by peak pressure, NOx emissions, combustion and heat transfer loss
  - Turbo-charging not limited by knock: higher BMEP over domain of operation, lower relative losses (friction and heat transfer)
- **Lower Power density**
  - Overall lean: would lead to smaller BMEP
  - Turbocharged: would lead to higher BMEP
    - > not knock limited, but NOx limited
    - > BMEP higher than naturally aspirated SI engine
  - Lower speed: overall power density (P/V_D) not as high as SI engines
- **Emissions: more problematic than SI engine**
  - NOx: needs development of efficient catalyst
  - PM: regenerative and continuous traps

Typical SI and Diesel operating value comparisons

	SI	Diesel
BMEP		
– Naturally aspirated:	10-15 bar	10 bar
– Turbo:	15-25 bar	15-25 bar
Power density		
– Naturally aspirated:	50-70 KW/L	20 KW/L
– Turbo:	70-120 KW/L	40-70 KW/L
Fuel		
– H to C ratio	$CH_{1.87}$	$CH_{1.80}$
– Stoichiometric A/F	14.6	14.5
– Density	0.75 g/cc	0.81 g/cc
– LHV (mass basis)	44 MJ/kg	43 MJ/kg
– LHV (volume basis)	3.30 MJ/L	3.48 MJ/L **(5.5% higher)**
– LHV (CO_2 basis)	13.9 MJ/kgCO_2	13.6 MJ/kgCO_2 **(2.2% lower)**

Disadvantages of Diesel Engines

- Cold start difficulty
- Noisy - sharp pressure rise: cracking noise
- Inherently slower combustion
- Lower power to weight ratio
- Expensive components
- NO_x and particulate matters emissions

Market penetration

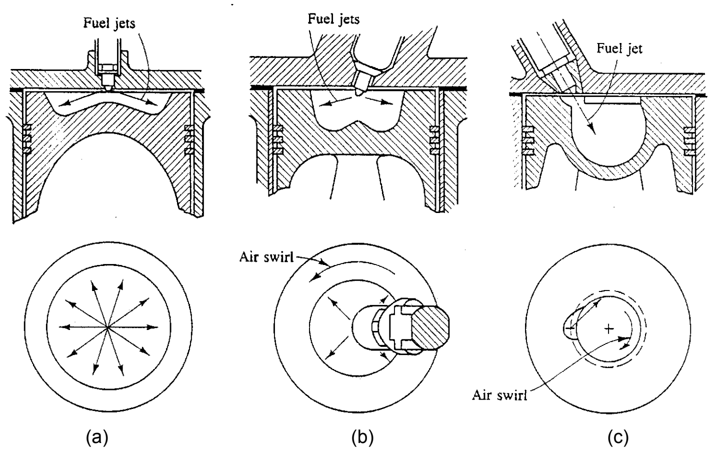
- **Diesel driving fuel economy ~ 30% better than SI**
  - 5% from fuel energy/volume
  - 15% from eliminating throttle loss
  - 10% from thermodynamics
    - 2nd law losses (friction and heat transfer)
    - Higher compression ratio
    - Higher specific heat ratio

- **Dominant world wide heavy duty applications**
- **Dominant military applications**
- **Significant market share in Europe**
  - Tax structure for fuel and vehicle
- **Small passenger car market fraction in US and Japan**
  - Fuel cost
  - Customer preference
  - Emissions requirement

Applications

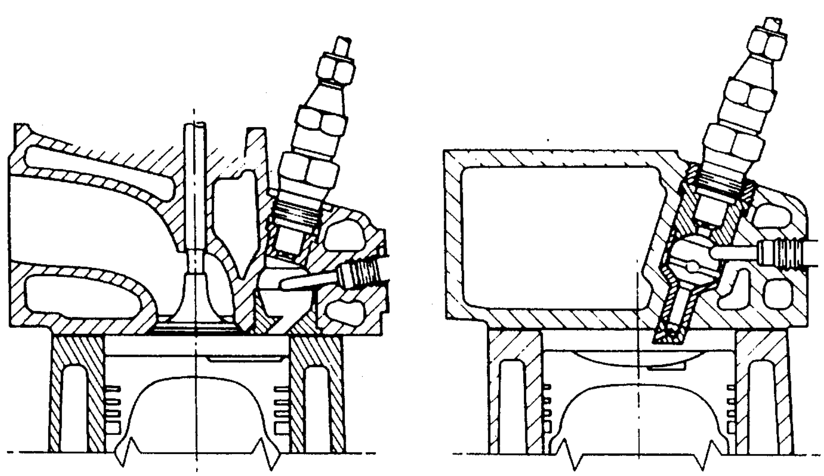
- Small (7.5 to 10 cm bore; previously mainly IDI; new ones are high speed DI)
  - passenger cars
- Medium (10 to 20 cm bore; DI)
  - trucks, trains
- Large (30 to 50 cm bore; DI)
  - trains, ships
- Very Large (100 cm bore)
  - stationary power plants, ships

Common Direct-Injection Compression-Ignition Engines
(Fig. 10.1 of text)



(a) Quiescent chamber with multihole nozzle typical of larger engines
(b) Bowl-in-piston chamber with swirl and multihole nozzle; medium to small size engines
(c) Bowl-in-piston chamber with swirl and single-hole nozzle; medium to small size engines

Common types of small Indirect-injection diesel engines
(Fig. 10.2 of text)

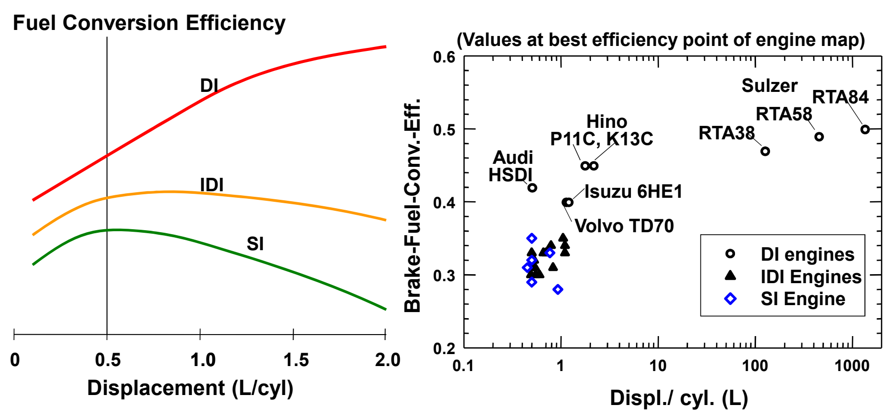


(a) Swirl prechamber **(b) Turbulent prechamber**

Common Diesel Combustion Systems (Table 10.1)

	Direct injection				Indirect injection	
System	Quiescent	Medium swirl	High swirl "M"	High swirl multispray	Swirl chamber	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

Effect of Engine Size

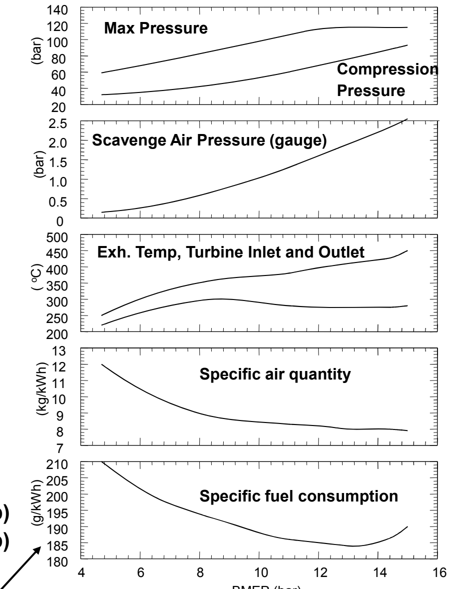


Typical Large Diesel Engine Performance Diagram

Sulzer RLB 90 - MCR 1
Turbo-charged 2-stroke Diesel
- 1.9 m stroke; 0.9 m bore

Rating:
- **Speed: 102 Rev/ min**
  - Piston speed 6.46 m/s
- **BMEP: 14.3 bar**

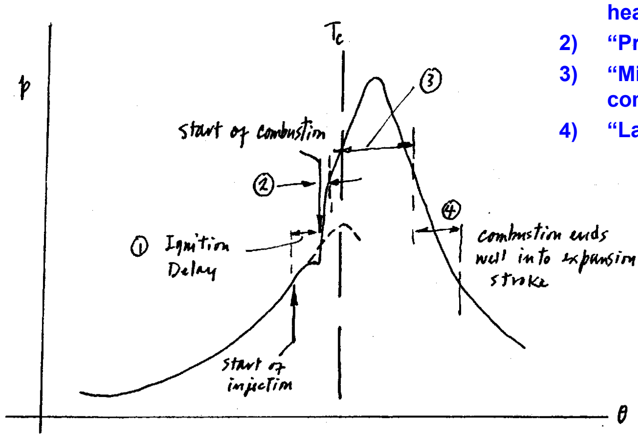
Configurations
- 4 cyl: 11.8 MW (16000 bhp)
- 5 cyl: 14.7 MW (20000 bhp)
- 6 cyl: 17.7 MW (24000 bhp)
- 7 cyl: 20.6 MW (28000 bhp)
- 8 cyl: 23.5 MW (32000 bhp)
- 9 cyl: 26.5 MW (36000 bhp)
- 10 cyl: 29.4 MW (40000 bhp)
- 12 cyl: 35.3 MW (48000 bhp)



$\eta_{f,b}$=0.45 @ 185 g/kW-hr

Sulzer RTA96 engine

Diesel combustion process — direct injection



1) **Ignition delay — no significant heat release**
2) **"Premixed" rapid combustion**
3) **"Mixing controlled" phase of combustion**
4) **"Late" combustion phase**

Note:
(2) is too fast;
(4) is too slow

Rate of Heat Release in Diesel Combustion

(Fig. 10.8 of Text)

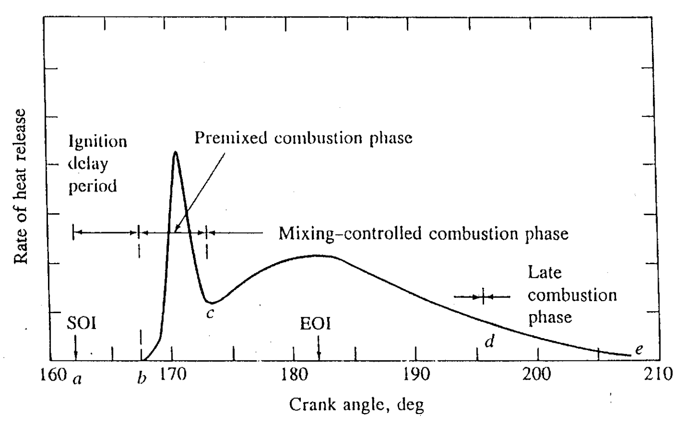
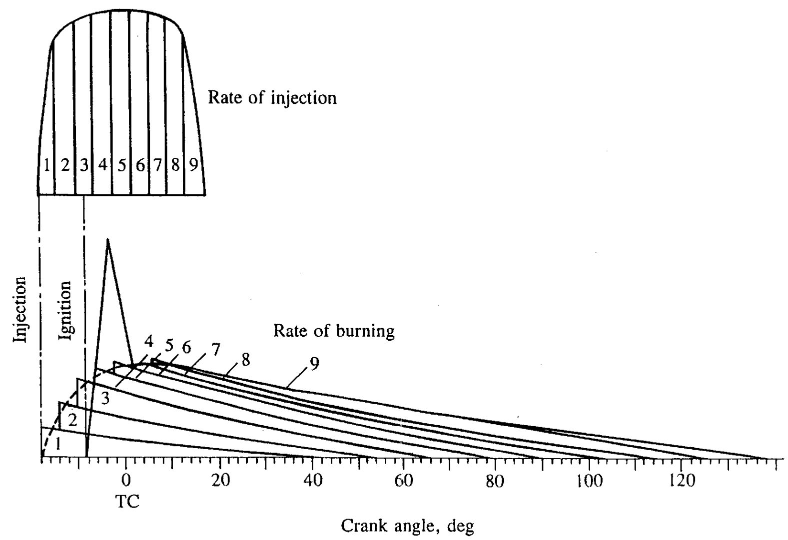
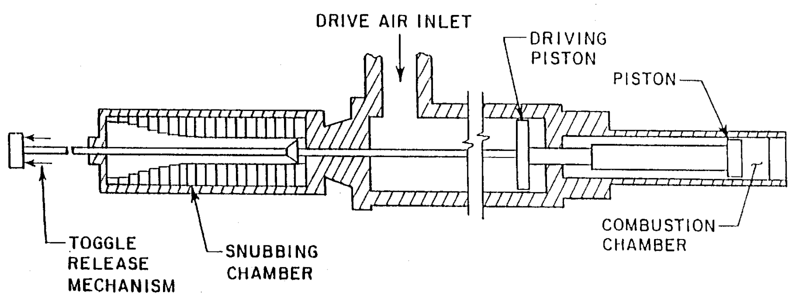


Fig. 10-9

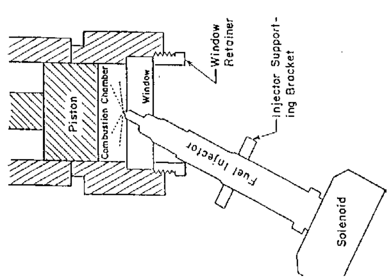
A Simple Diesel Combustion Concept (Fig. 10-8)



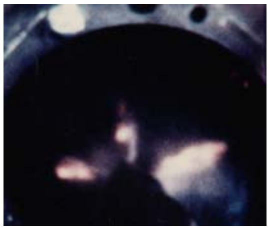
Visualization of Diesel Combustion



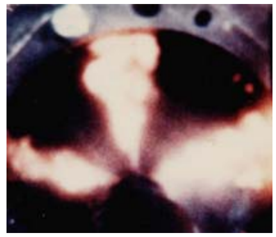
Bore	**10.2 cm**
Stroke	**44.7 cm**
Compression ratio	**15.4**



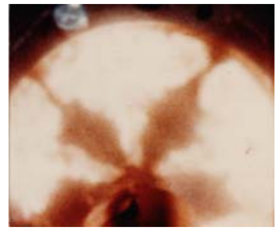
Images From Diesel Combustion



First occurrence of luminous flame
(1.0 ms after start of injection)

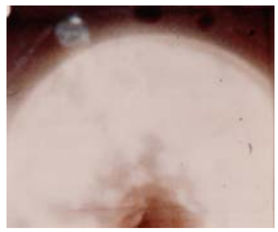


(0.13 ms after ignition)

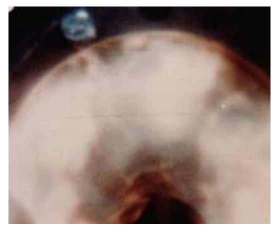


(0.93 ms after ignition)

(1.87 ms after ignition)



End of injection
(2.67 ms after ignition)

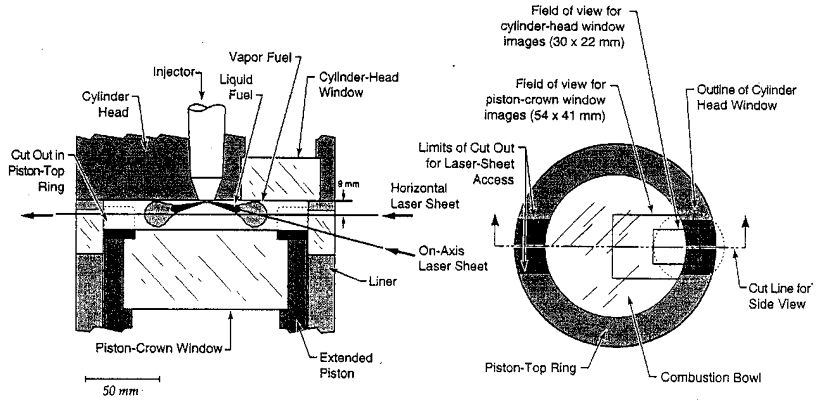


5.33 ms after ignition

FEATURES OF DIESEL COMBUSTION

- **Ignition delay**
  - Auto-ignition in different parts of combustion chamber
- **After ignition, fuel sprays into hot burned gas**
  - Then, evaporation process is fast
- **Major part of combustion controlled by fuel air mixing process**
  - Mixing dominated by flow field formed by fuel jet interacting with combustion chamber walls during injection
- **Highly luminous flame:**
  - Substantial soot formation in the fuel rich zone by pyrolysis, followed by substantial subsequent oxidation

Imaging of Diesel Combustion by Laser Sheet Illumination



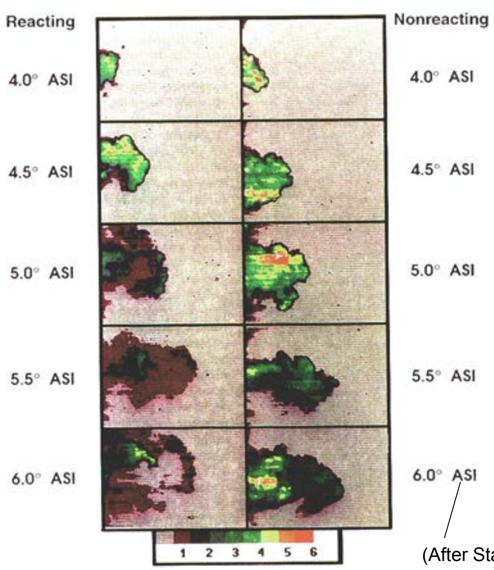
Side View of Combustion Chamber | **Top View of Piston**

Rayleigh scattering
reflection from molecules

Laser Induced Florescence
(pump at) OH @284 nm
PAH @387 nm
NO @ 226 nm

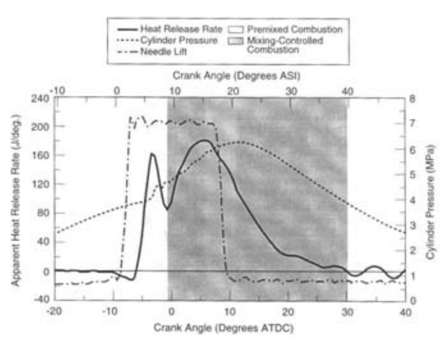
From J.Dec, SAE 970873

Fuel Equivalence Ratio



(After Start of Injection)

- Obtained by Planar Rayleigh scattering
- Substantial reduction of fuel equivalence ratio in the 'premixed' region indicates fuel-rich oxidation

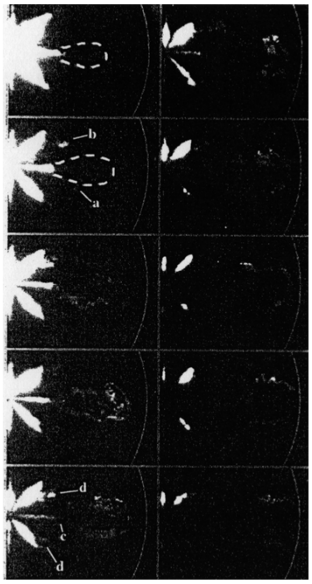


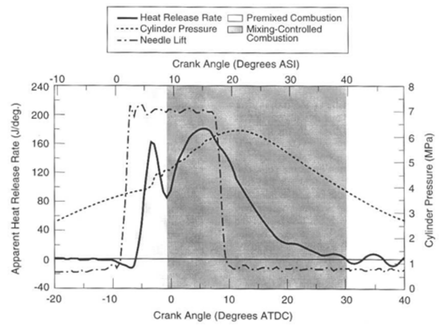
From J.Dec, SAE 970873

OH Image by PLIF

Oxidation occurs at the edge of the air and fuel rich region

5.0° ASI | 7.5° ASI
5.5° ASI | 8.0° ASI
6.0° ASI | 8.5° ASI
6.5° ASI | 9.0° ASI
7.0° ASI | 9.5° ASI





(Dash lines in the first two frames marks the vapor boundary of the fuel jet)

(After Start of Injection)

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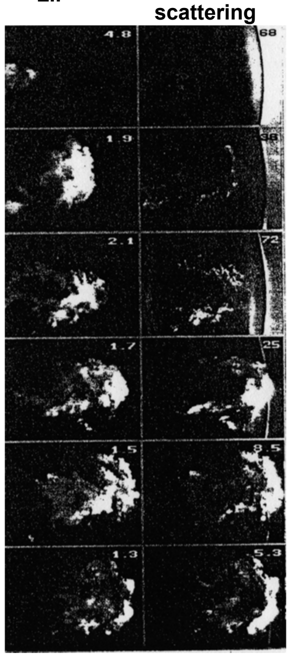
Image of the Particulates

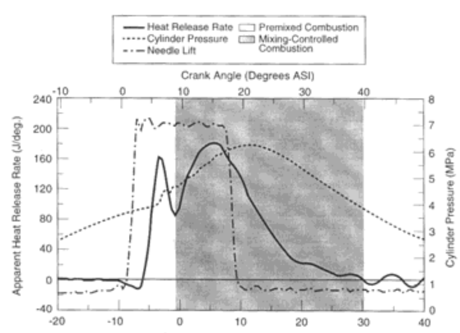
LII | Elastic scattering

6.0° ASI | 6.0° ASI
6.5° ASI | 6.5° ASI
7.0° ASI | 7.0° ASI
7.5° ASI | 7.5° ASI
8.0° ASI | 8.0° ASI
8.5° ASI | 8.5° ASI



Laser Induced Incandescence
(signal ~ d^3; observe small particles)

Elastic scattering
(signal ~ d^6; observe large particles)



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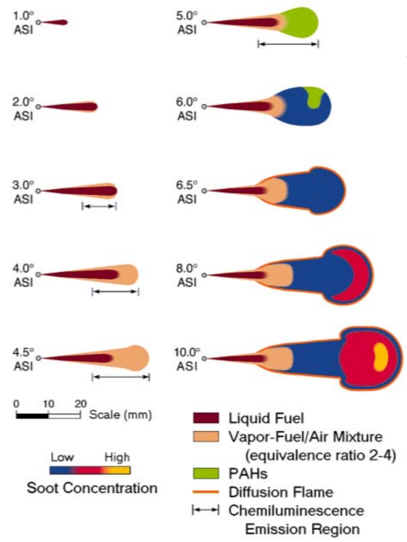
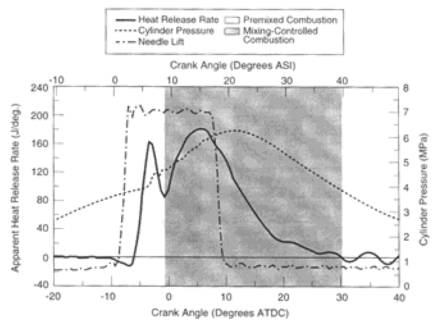
Diesel Ignition, Premixed Burning and Transition into Diffusion Burning

- Premixed burning
  - Release of energy from fuel rich combustion
- Diffusion burning
  - Oxidation of incomplete products of the rich premixed combustion and fuel vapor at the 'jet'/ air interface





Figures from J.Dec, SAE 970873