Aalto University
School of Engineering

EEN-E2002 Combustion Technology

Internal Combustion Analysis

January 2019, Martti Larmi

Crank gear and movements

$$\lambda = \frac{r}{l}$$

$$s = l + r - (r\cos\varphi + l\cos\psi)$$

$$\psi = \frac{\lambda \sin\varphi}{\sqrt{1-\lambda^2 \sin^2\varphi}}$$

$$s = r \cdot \left[1 - \cos\varphi + \frac{1}{\lambda}(1 - \sqrt{1-\lambda^2 \sin^2\varphi})\right]$$

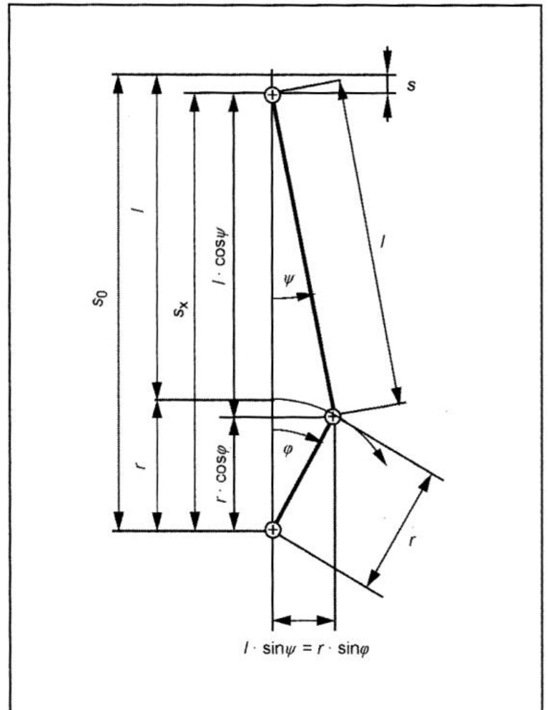
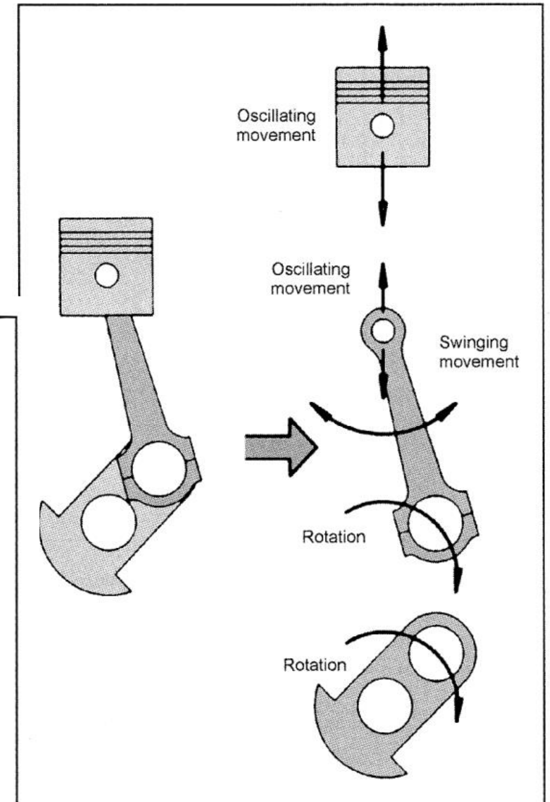


Fig. 6-3 Geometric relationships in the crankshaft drive.



g. **6-2** Movements of the crank gear parts.

Piston travel Fourier series used in balancing and vibration analysis

Fourier series

$$\sqrt{1+x} = 1 + \frac{1}{2}x - \frac{1}{8}x^2 + \frac{1}{16}x^3 - \dots$$

Simplified piston travel equation

$$s = r \cdot \left[1 - \cos\varphi + \frac{\lambda}{2}\sin^2\varphi\right]$$

Piston speed by including time

$$v = r\omega\left(\sin\varphi + \frac{1}{2}\lambda\sin 2\varphi\right)$$

Piston acceleration by squaring the time

$$a = r\omega^2(\cos\varphi + \lambda\cos 2\varphi)$$

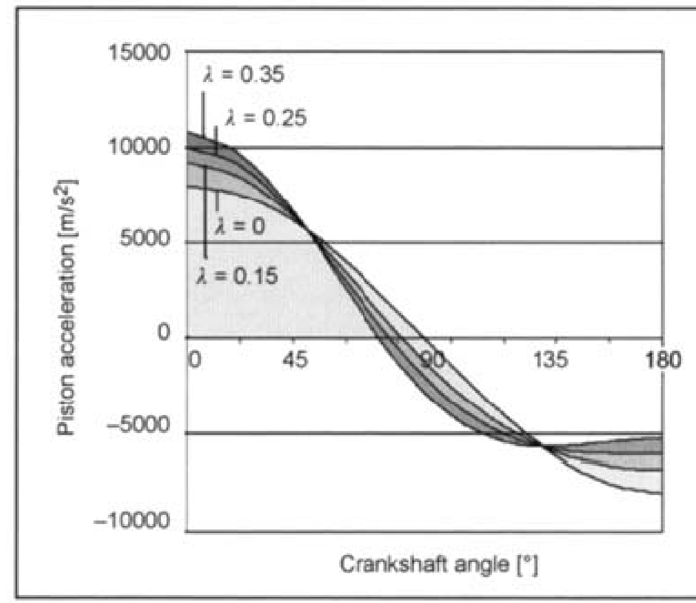


Fig. 6-6 Piston acceleration as a function of crankshaft angle for different conrod ratios.

4-stroke principle

- During the intake stroke piston is going down and the intake valves are open. Piston is drawing air (or air-fuel mixture) into the cylinder.
- During the compression stroke valves are closed and piston is compressing air (or air-fuel mixture). The temperature and pressure of the mixture rise and burning usually begins already at the end of the compression stroke
- During the expansion stroke gases work against the piston while expanding. Major part of the combustion happens when the piston is still close to TDC.
- During the exhaust stroke exhaust valves are open and the piston pushes the burned mixture (exhaust gases) out of the cylinder.
- Working cycle is two revolutions, 720 degrees of crank angle
- Intake and exhaust strokes together are called the gas exchange

Heywood: Figure 1-2

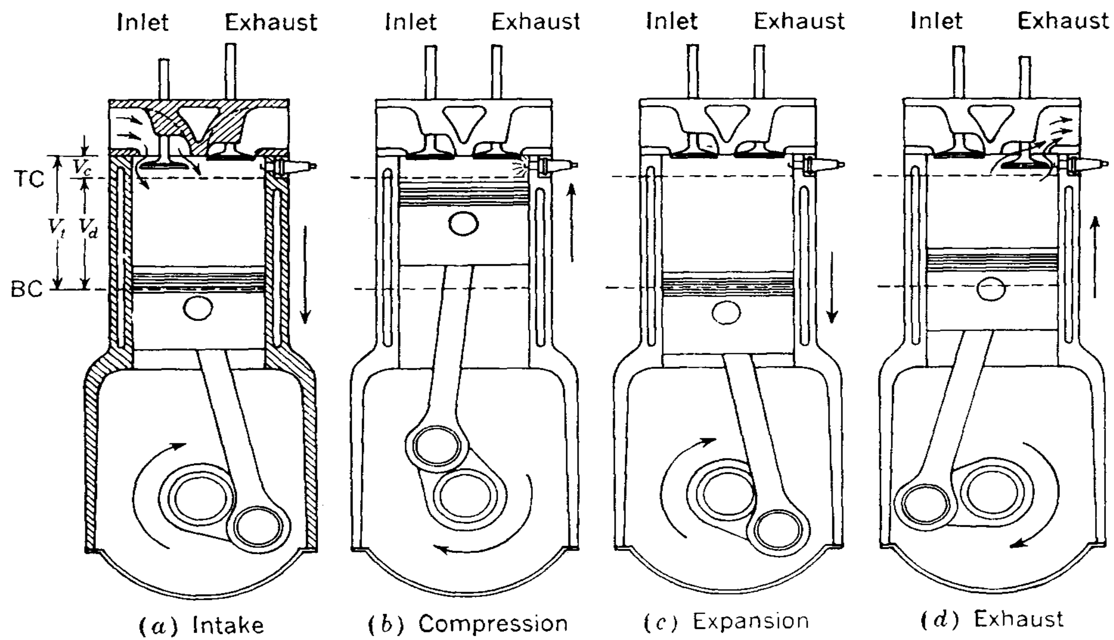


FIGURE 1-2
The four-stroke operating cycle.[10]

2-stroke principle

- During the compression stroke valves are closed and piston is compressing air (or air-fuel mixture). The temperature and pressure of the mixture rise and combustion usually begins already at the end of the compression stroke.
- During the expansion stroke gases work against the piston while expanding. Major part of the combustion happens when the piston is still close to TDC.
- Gas exchange takes place when the piston is close to BDC.
- Gas exchange begins when the exhaust ports open and the exhaust gases discharge to the exhaust duct (Blow down).
- While the piston is still moving down the wash ports (intake ports) open and fresh charge of air (or air-fuel mixture) enters the cylinder (scavenging process). Scavenging is succeeded if the pressure in the intake ports is higher than in the cylinder.

Heywood: Figure 1-3

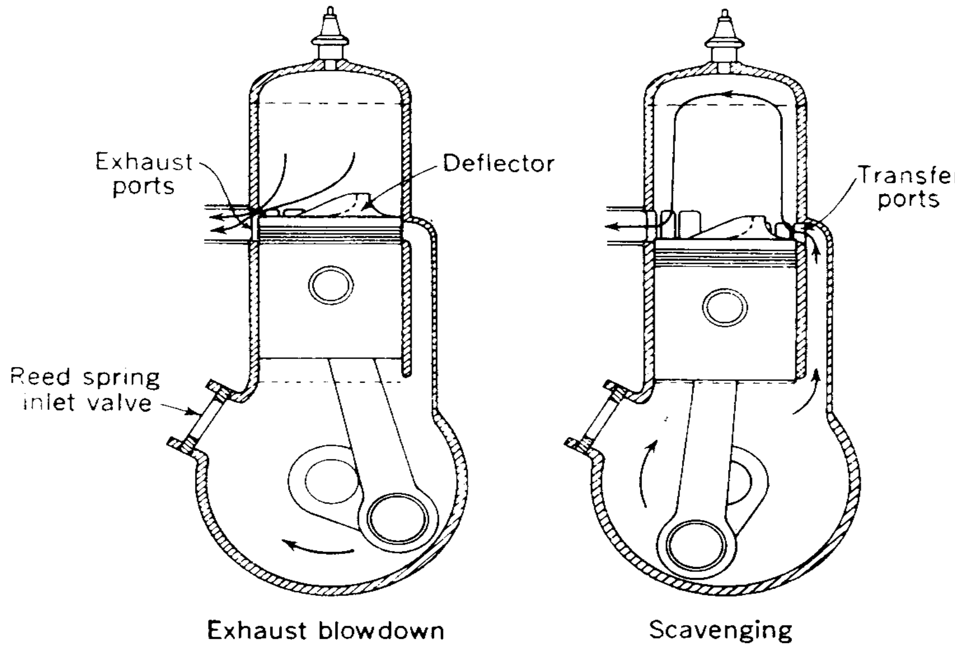
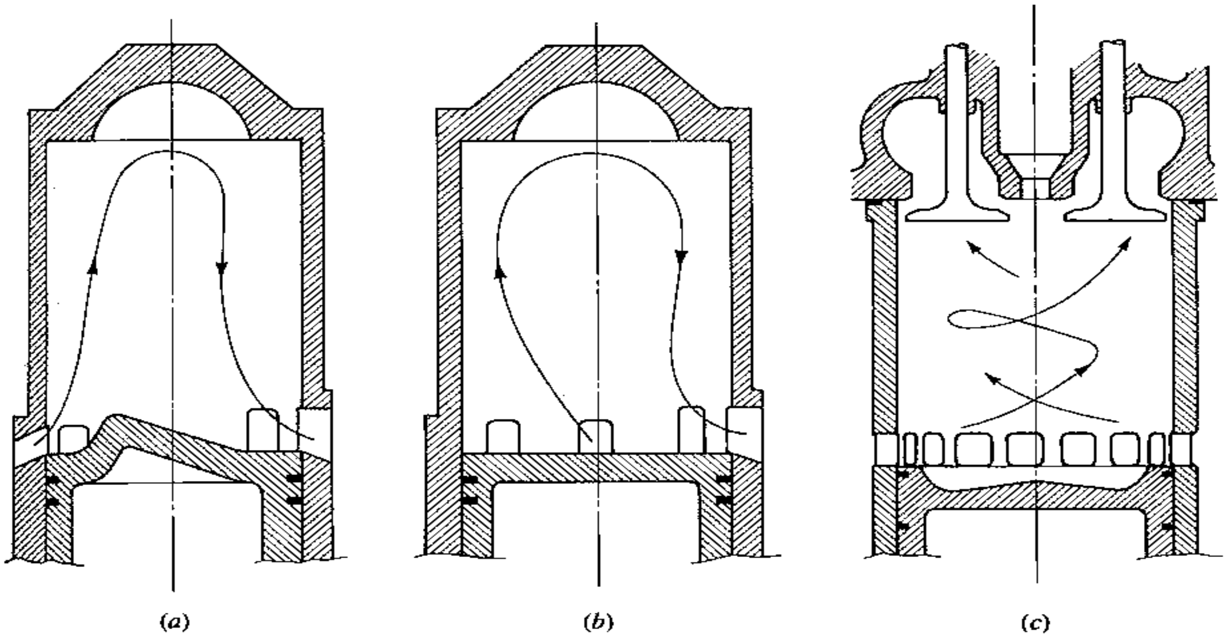


FIGURE 1-3
The two-stroke operating cycle. A crankcase-scavenged engine is shown.[10]

Two-stroke scavenging

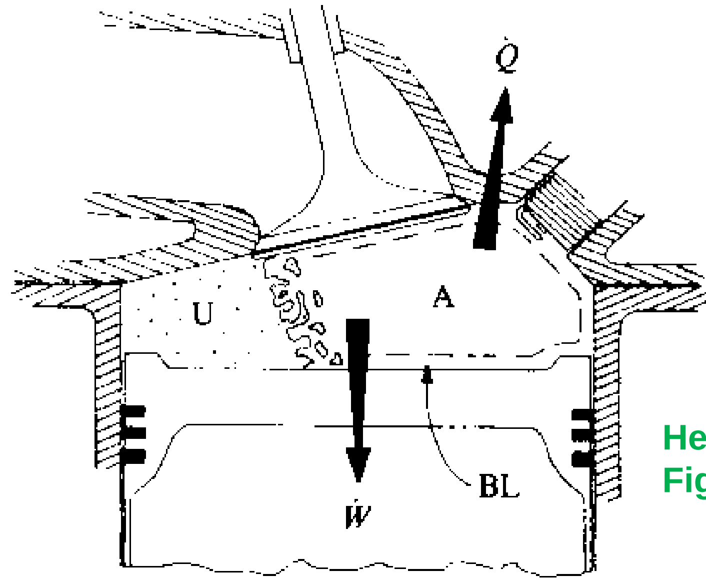


(a) Cross, (b) Loop and (c) Uniflow scavenging

SI engines, turbulent premixed combustion

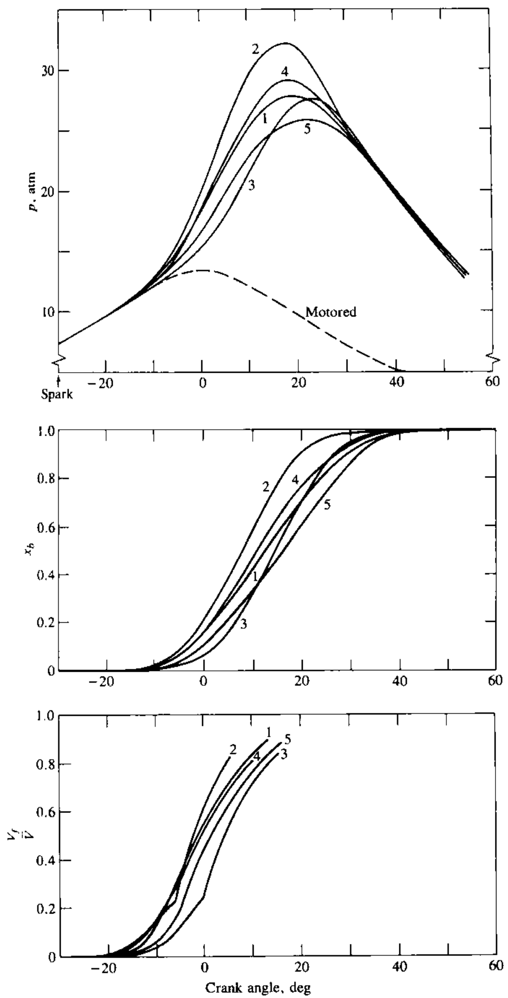
Turbulence driven flame propagation controls combustion

Physics in main role in combustion and in the charge preparation

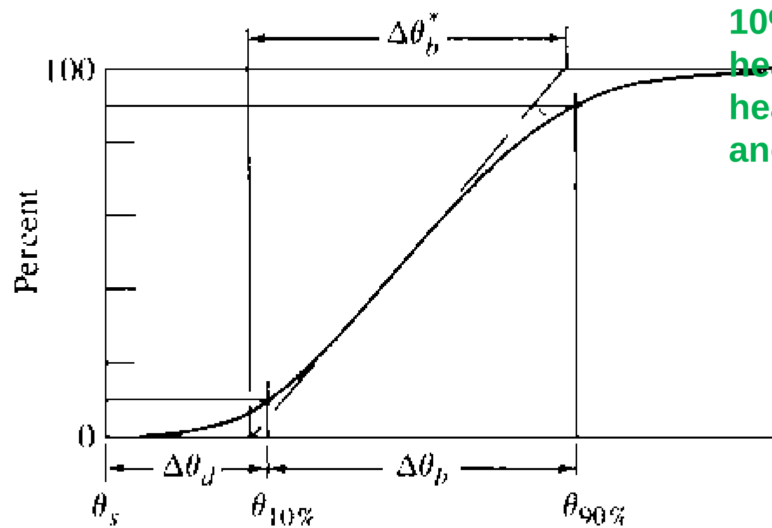


Heywood Figure 9-4

http://www.sandia.gov/ecn/tutorials/visualization/siGasoline.php

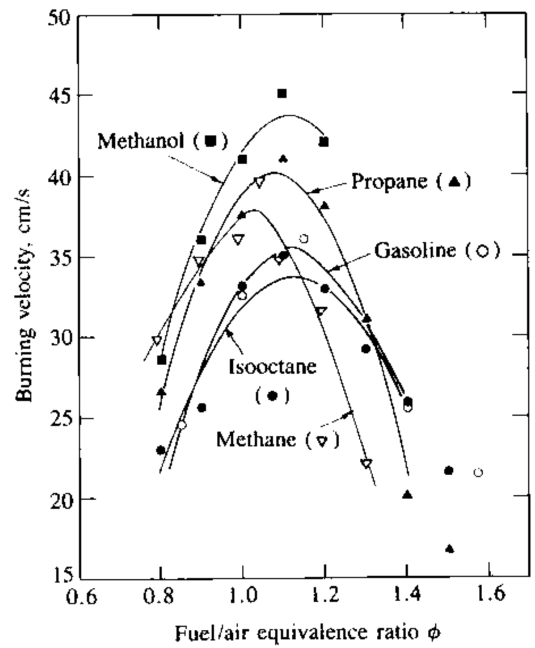


Consecutive cycles, cylinder pressure and fuel burnt, Heywood Figure 9-2. There is variation of combustion start and the combustion "speed". This can be explained by mixture inhomogenity and turbulence.



Cumulative heat release as function of crank angle Heywood Figure 9-13. The beginning or the end of heat release is difficult to "measure" exactly. Quantitative measures of the location of cumulative heat release could be 10% heat release, 50% heat release or 90% heat release in crank angles

Combustion speeds up with increased mean piston speed due to increased turbulence. This is beneficial for the wide speed range of SI-engines. Heywood Figure 9-17



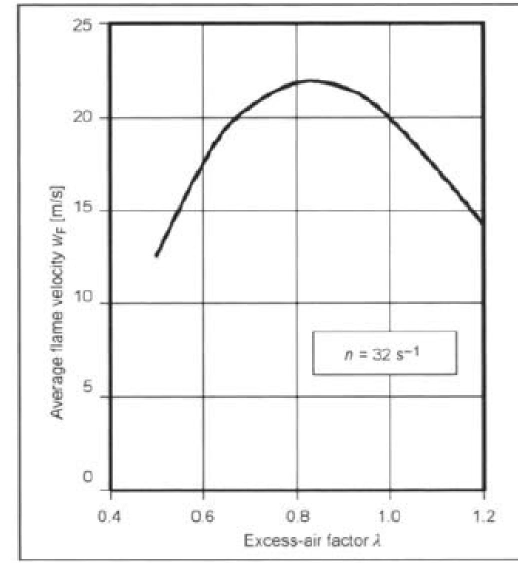
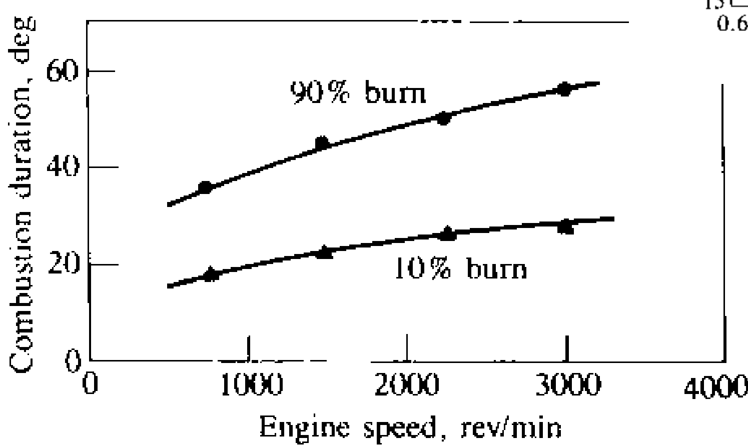
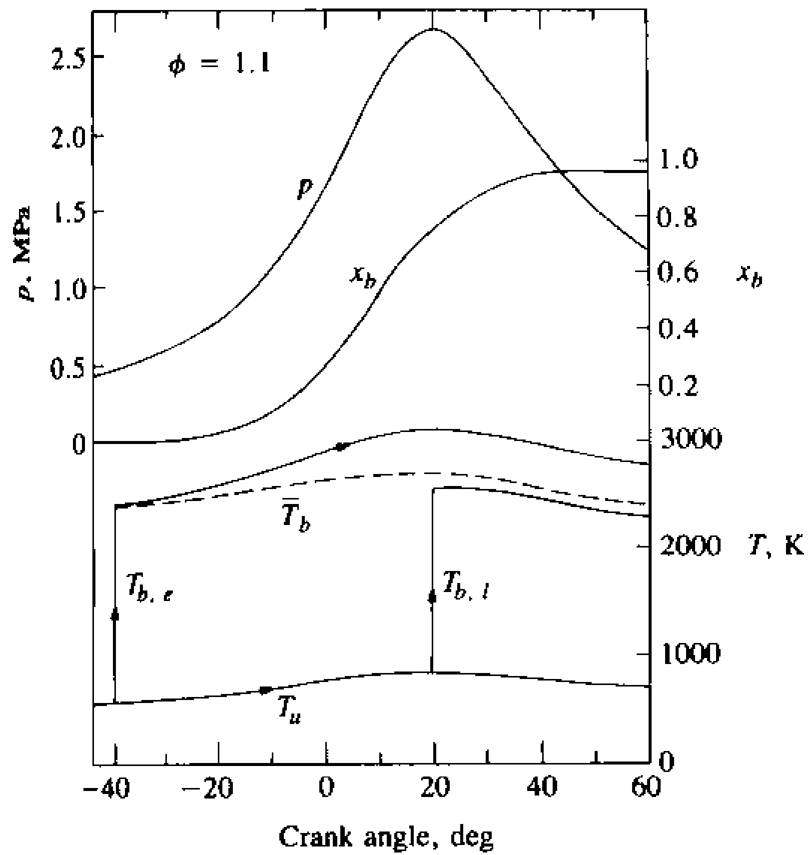


Fig. 15-29 Average flame speed in relation to the excess air factor.



Charge temperatures



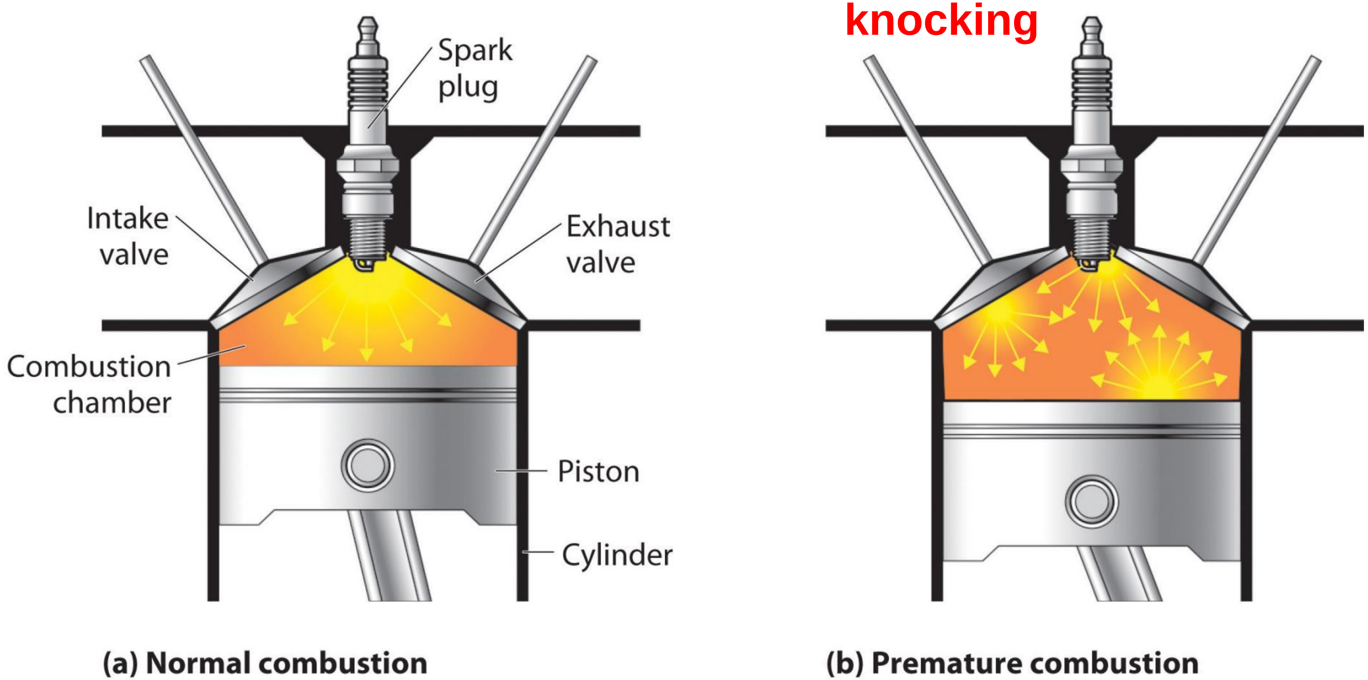
Heywood Figure 9-5 Cylinder pressure and fuel burnt, burnt and unburnt temperatures.

Pay attention to the unburn temperature. The maximum in this case is at 20 deg after top dead center.

The temperature increase after TDC is due to increased pressure caused by the combustion.

This is not knocking

This is pre-ignition, not knocking



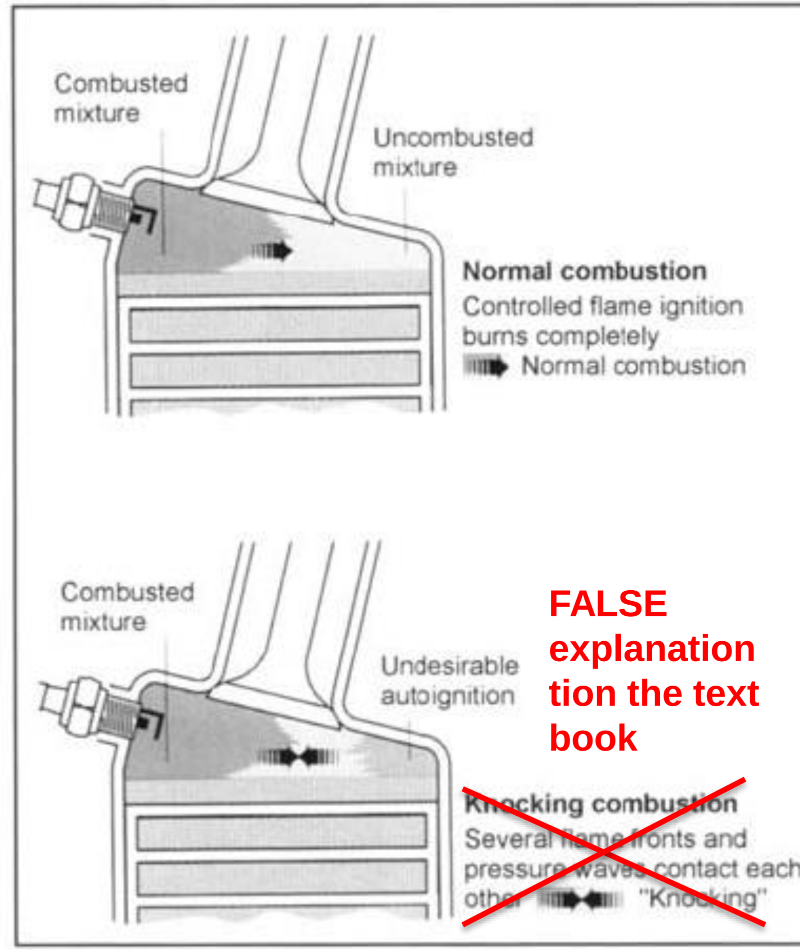
http://chemwiki.ucdavis.edu/

What is knocking?

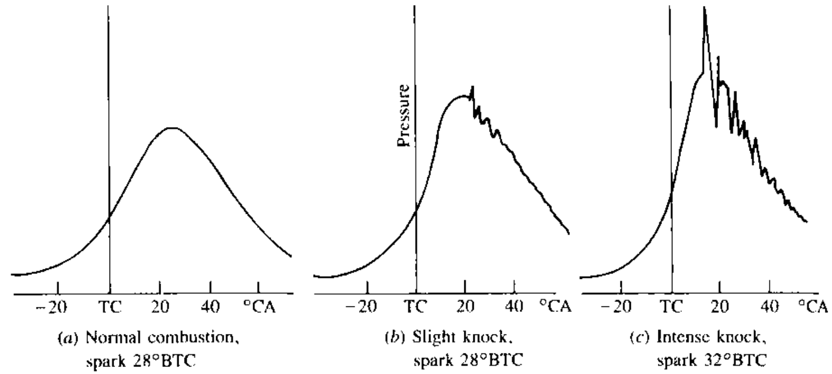
Sudden local heat release is the cause of knocking.

This results in pressure waves oscillationg in the cylinder.

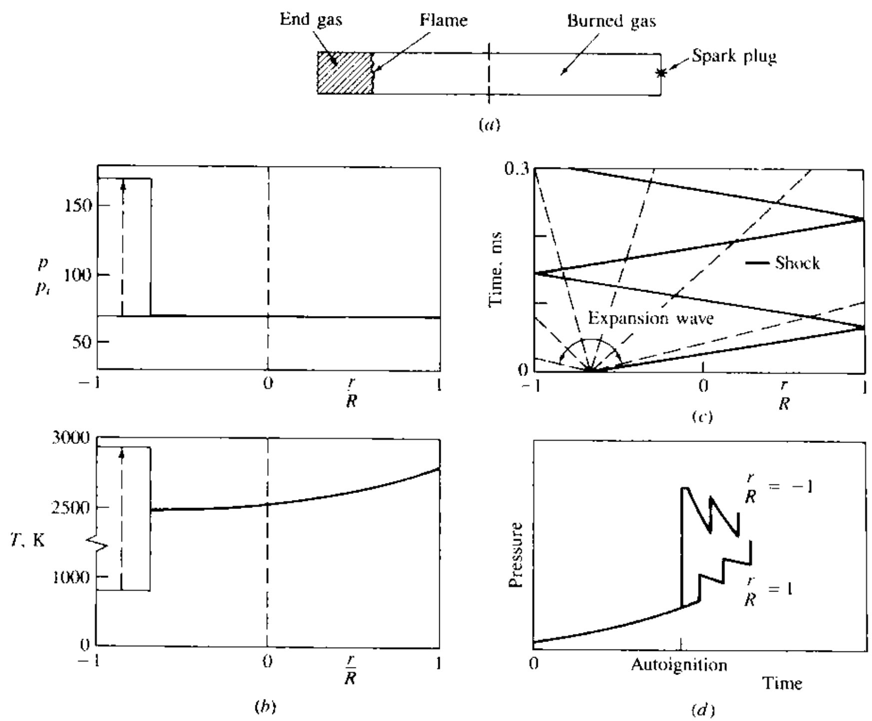
Flame front is proceeding at speed c. 20 m/s, pressure wave is proceeding at the speed of sound (several hundred m/s).



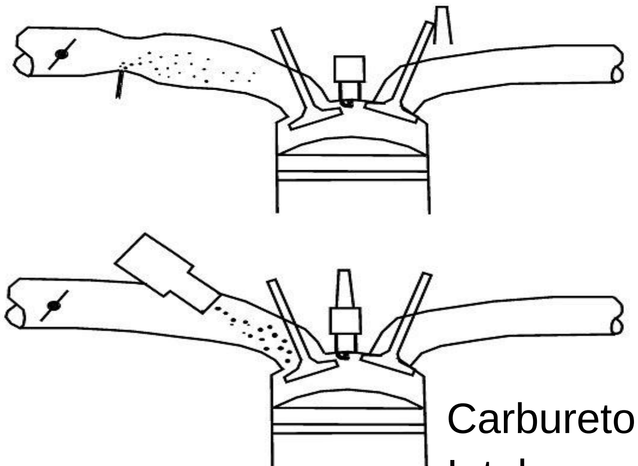
Heywood Figure 9-64. The sudden heat release in the end gas causes pressure wave propagation in the cylinder. The pressure wave can be heard as the knocking sound.

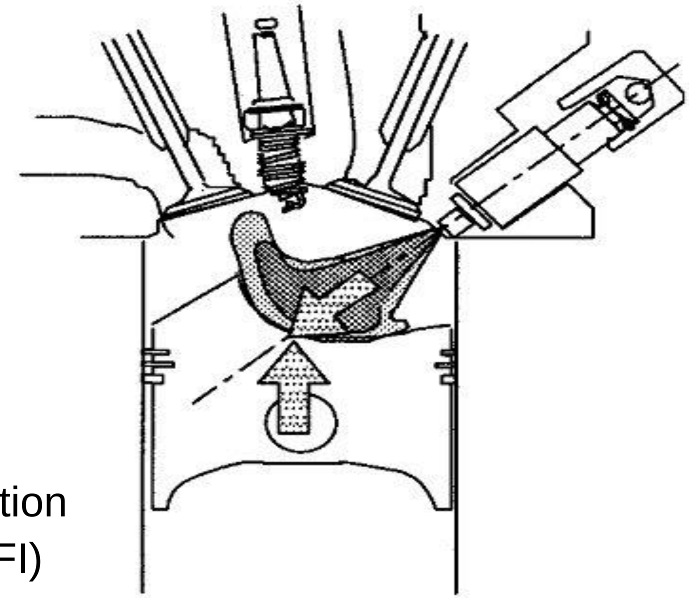


Heywood Figure 9-59. Too early ignition timing (too high ignition advance) can cause knocking.



Mixture formation methods in SI-engine





Carburetor

Intake manifold injection

Port fuel injection (PFI)

Gasoline direct injection (GDI)

- Homogenous mixture
- Stratified mixture: Wall guided, Air guided, Spray guided

Spark Plug

Spark phase	Duration	Energy	Spark erosion
Rise	60 µs		
Breakdown	2 ns	0.5 mJ	$12 \cdot 10^{-12}$ g/mJ
Arc	1 µs	1 mJ	$210 \cdot 10^{-12}$ g/mJ
Glow	2 ms	60 mJ	$3.5 \cdot 10^{-12}$ g/mJ

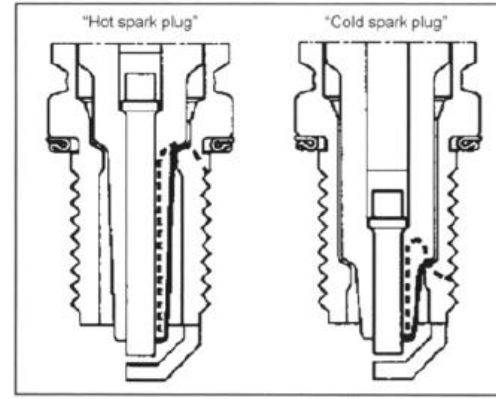
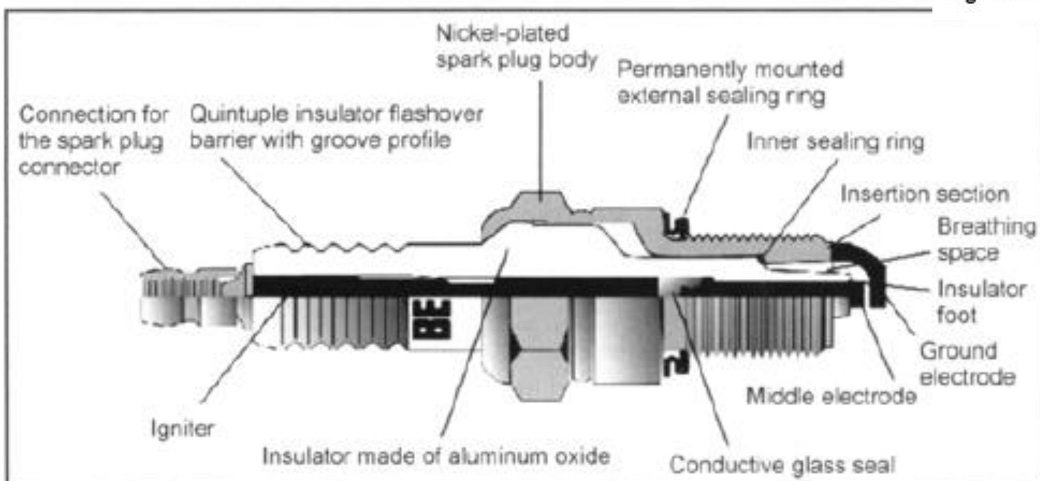


Fig. 13-12 Hot and cold spark plugs.



Spark and SI combustion ignition

	Breakdown, %	Arc, %	Glow, %
Radiation loss	< 1	5	< 1
Heat conduction at the electrodes	5	45	70
Overall loss	6	50	70
Plasma energy	94	50	30

Fig. 13-2 Energy balance of the three types of discharge.[3]

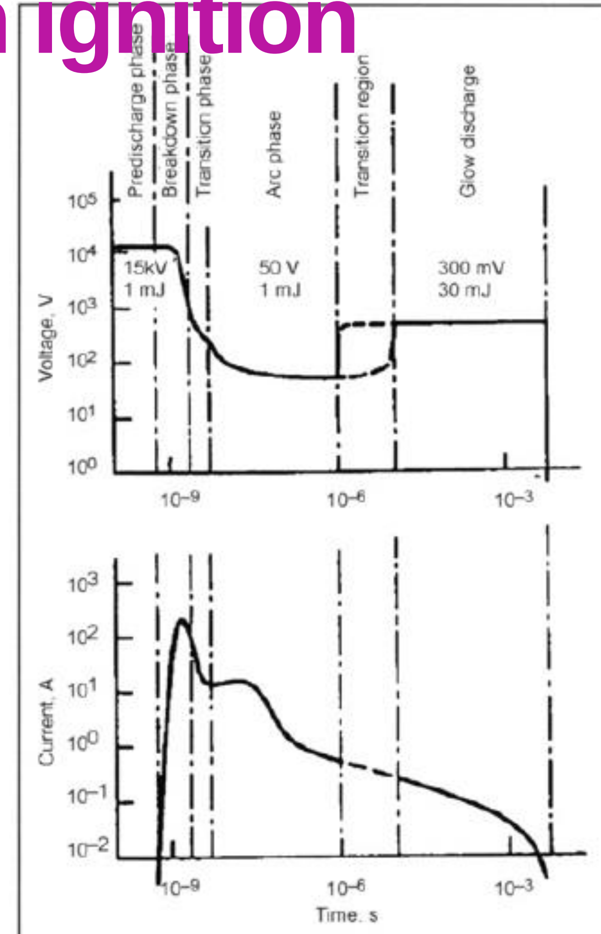
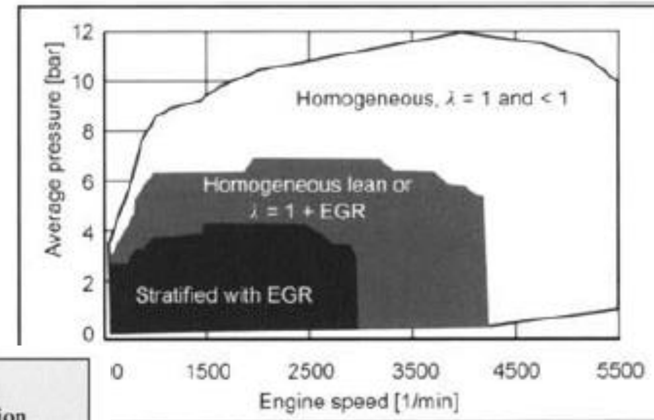


Fig. 13-1 Curve over time of the current and voltage of a transistor coil ignition (TCI).[4] Typical values of occurring voltages and energy transfer in the individual spark phases.

SI operation with stratified charge

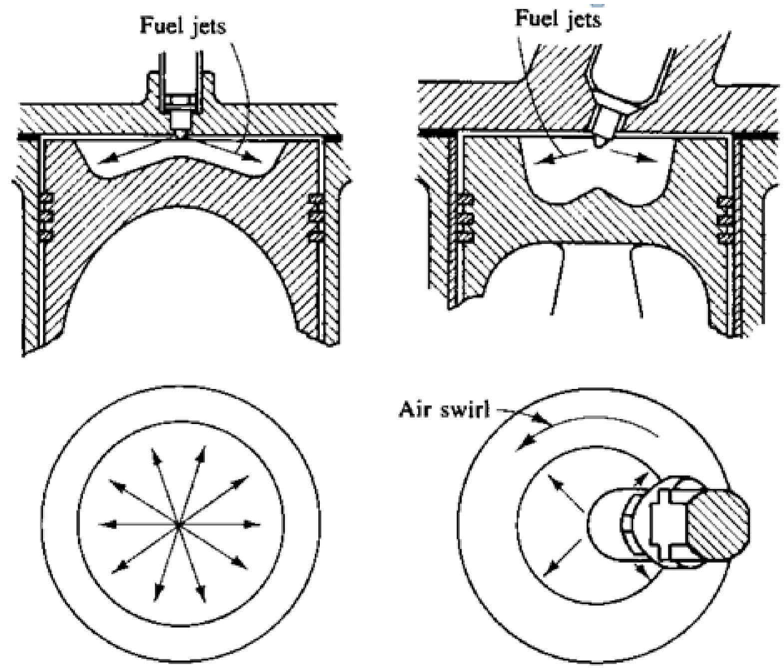


40 Operation strategy.

	Homogeneous operation	Homogeneous lean operation	Stratified operation	Dual injection
Injection timing	Intake stroke	Intake stroke	Compression stroke	Intake, compression, and exhaust cycle
Mixture	Homogeneous	Homogeneous	Stratified	Inhomogeneous
Air-fuel ratio	0.7 to 1.0	1.0 to 1.7	1.7 to 4.0	0.6 to 1.5
Exhaust temperature	High	Medium	Low	Medium–very high
Throttling	High	Medium	Low	Medium

Fig. 15-39 Features of the different types of operation.

CI engines, turbulent mixing controlled combustion

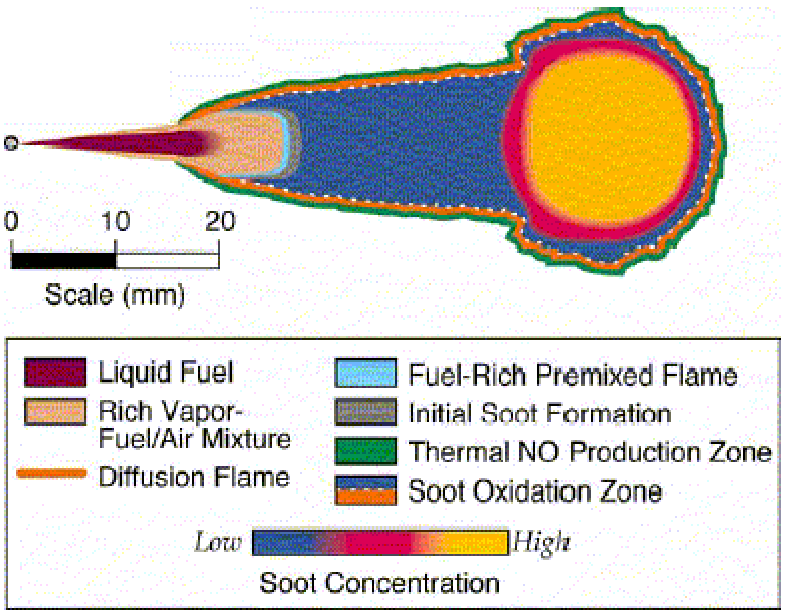


Fuel spray induced mixing controls the combustion.

Spray physics in a big role

http://www.sandia.gov/ecn/tutorials/visualization/ciDiesel.php

John Dec's conseptual model of CI combustion



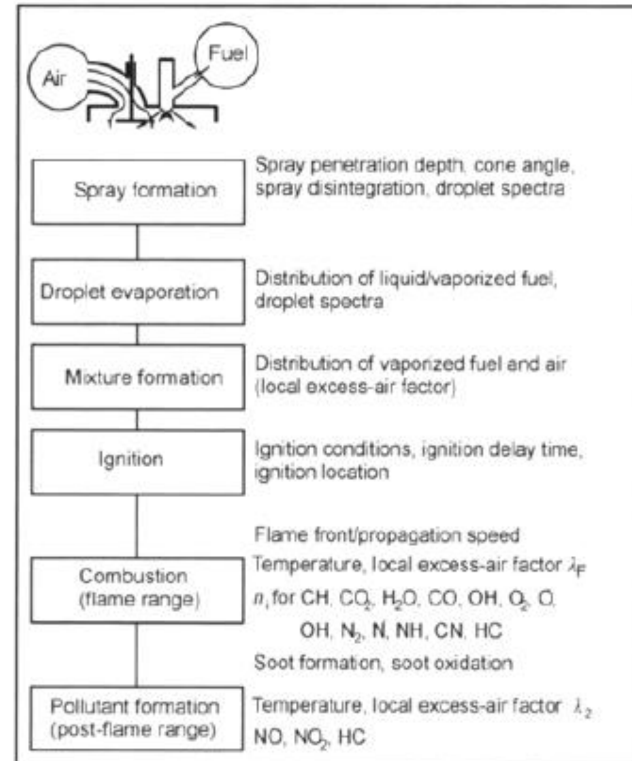


Fig. 14-20 Part processes of mixture formation and combustion in the diesel engine.

Swirl and CI Combustion

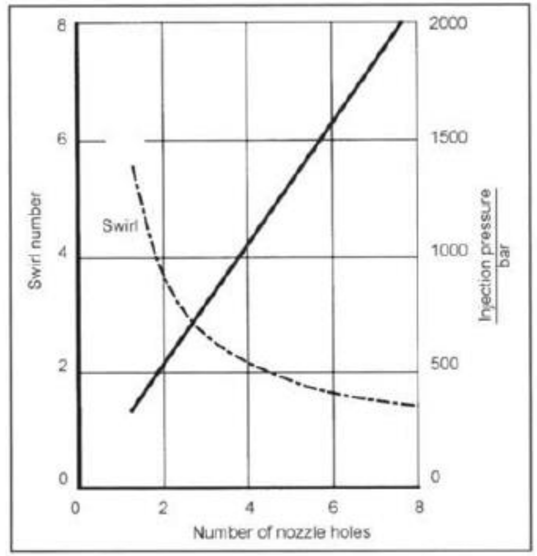


Fig. 15-13 Typical relationship between injection pressure, swirl number, and nozzle hole number.[16]

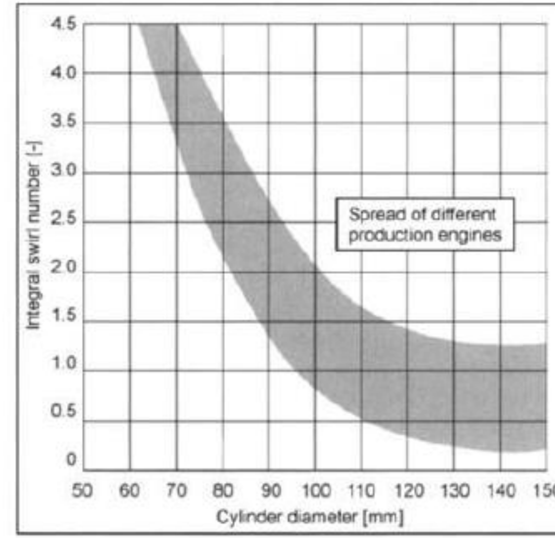
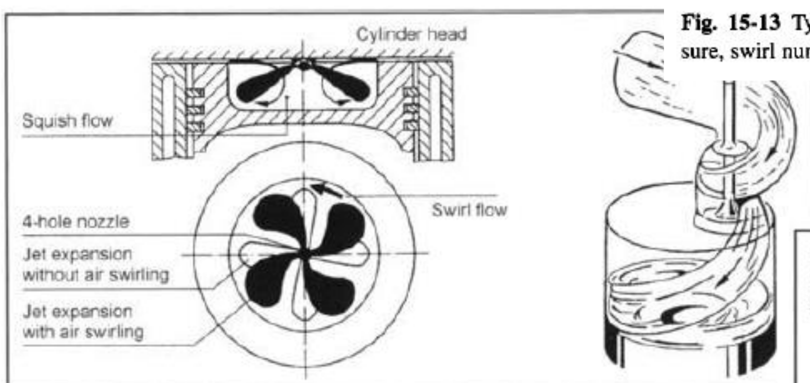


Fig. 15-15 Typical relationship of the required swirl number to cylinder diameter.[17]



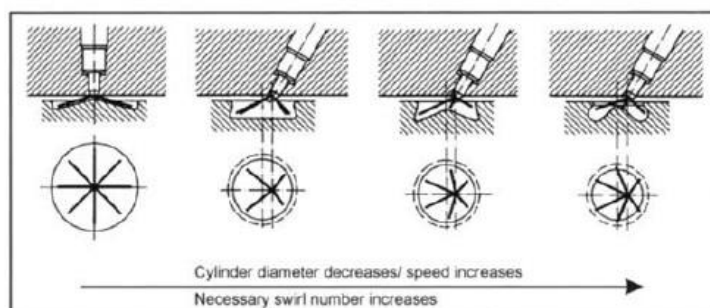
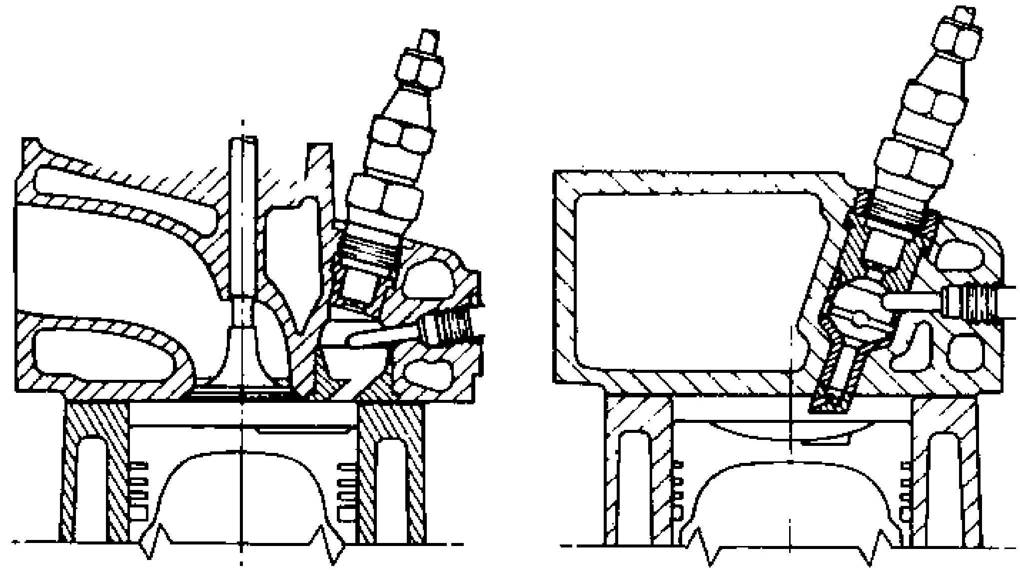


Fig. 15-14 Influence of engine size (speed) on the combustion chamber recess shape and required air movement in diesel engines that use direct injection as described by Ref. [4].

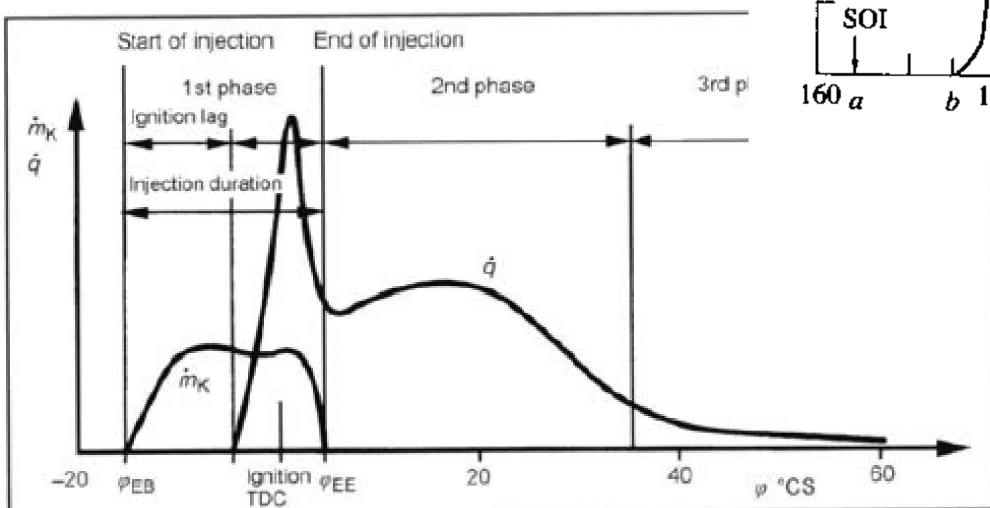
Old prechamber technology

Low efficiency, high heat losses



(a) (b)

Heat release



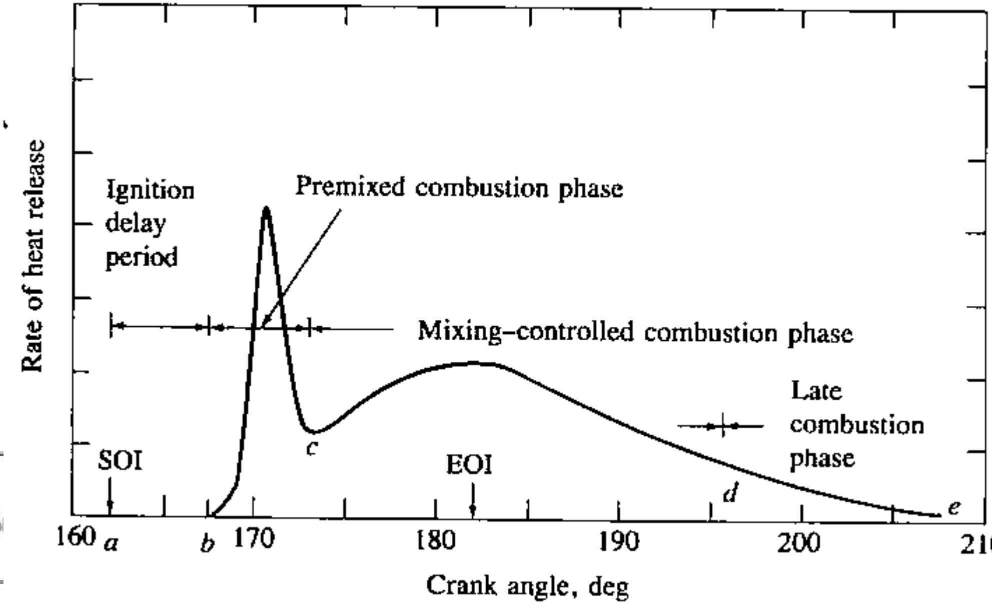


Fig. 15-6 Qualitative characteristic of fuel injection and heat release.[6]

Experimental heat release analysis, Heywood

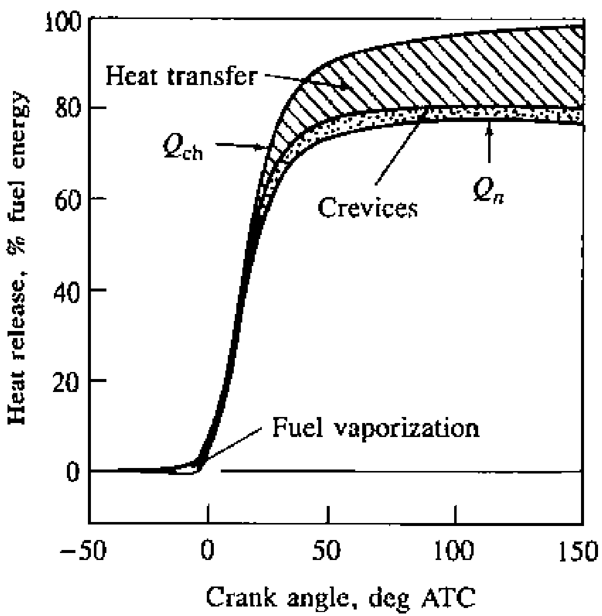
$$\frac{dQ}{dt} - p\frac{dV}{dt} + \sum_i \dot{m}_i h_i = \frac{dU}{dt} \quad (10.1)$$

$$\frac{dQ}{dt} - p\frac{dV}{dt} + \dot{m}_f h_f = \frac{dU}{dt} \quad (10.2)$$

$$\frac{dQ_n}{dt} = \frac{dQ_{ch}}{dt} - \frac{dQ_{ht}}{dt} = p\frac{dV}{dt} + \frac{dU_s}{dt} \quad (10.3)$$

$$\frac{dQ_n}{dt} = p\frac{dV}{dt} + mc_v\frac{dT}{dt} \quad (10.4)$$

Experimental heat release analysis, Heywood



$$\frac{dp}{p} + \frac{dV}{V} = \frac{dT}{T} \tag{10.5}$$

$$\frac{dQ_n}{dt} = \left(1 + \frac{c_v}{R}\right) p \frac{dV}{dt} + \frac{c_v}{R} V \frac{dp}{dt}$$

or (10.6)

$$\frac{dQ_n}{dt} = \frac{\gamma}{\gamma - 1} p \frac{dV}{dt} + \frac{1}{\gamma - 1} V \frac{dp}{dt}$$

$$Q_{ch} = \int_{t_{start}}^{t_{end}} \frac{dQ_{ch}}{dt} dt = m_f Q_{LHV} \tag{10.7}$$

CI cold start

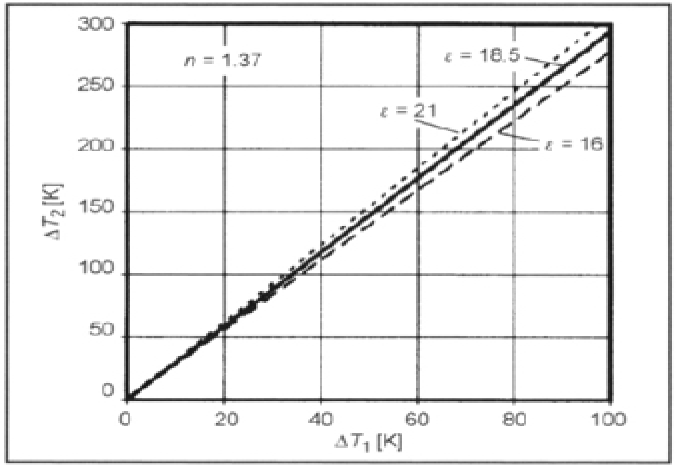


Fig. 13-26 Increase in final compression temperature by preheating intake air.

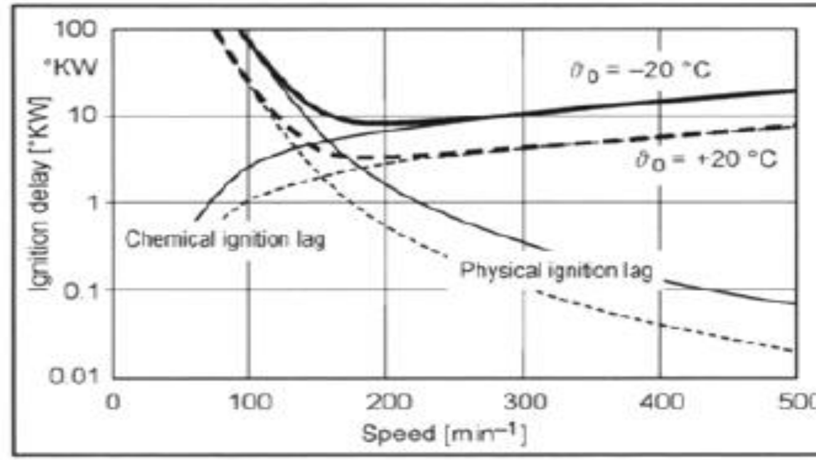


Fig. 13-22 Ignition lag.[3]

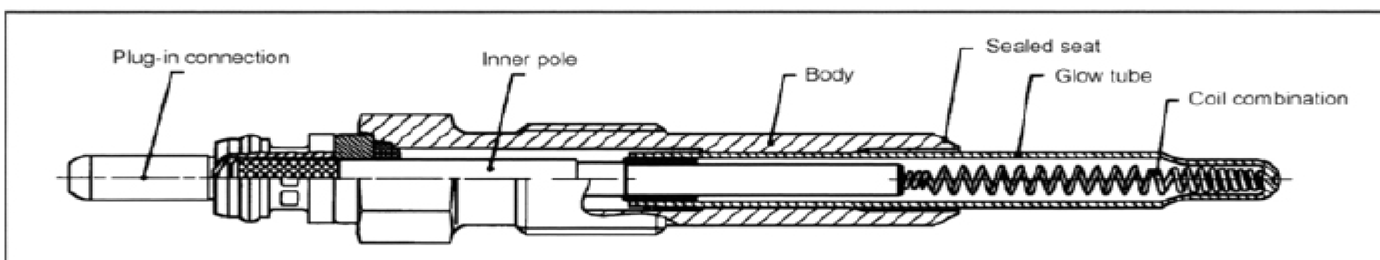


Fig. 13-24 Glow plug design.

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Engine start

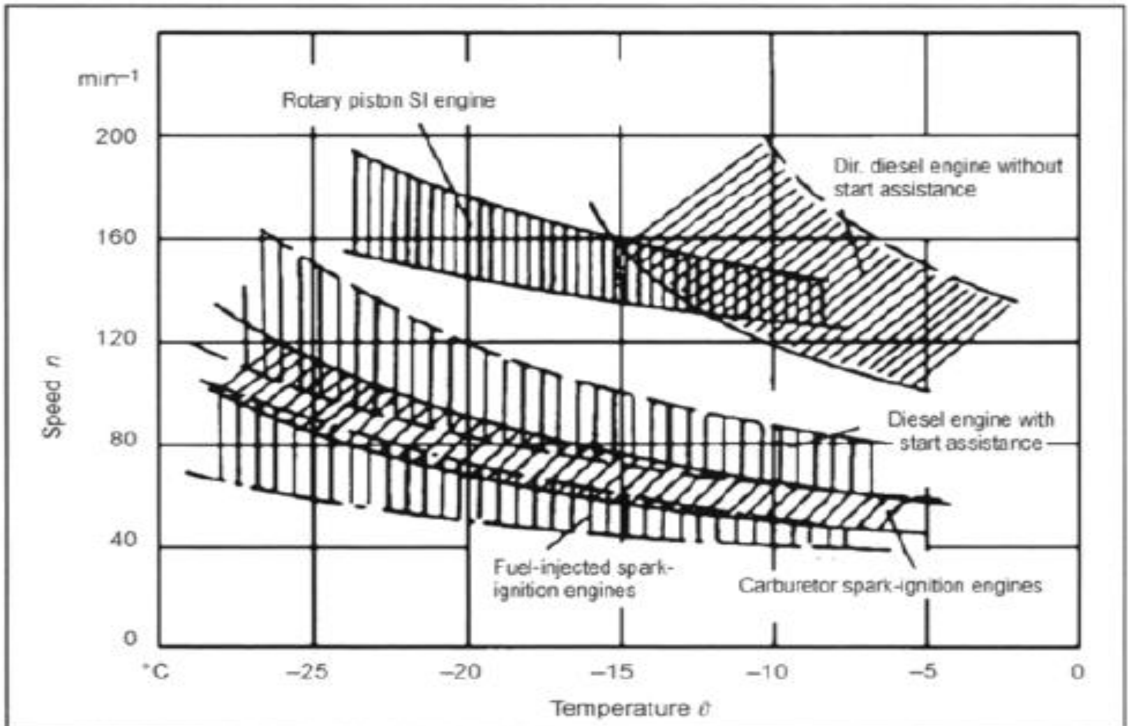


Fig. 13-21 Minimum start speed.[2]

Four Stroke SI Cylinder Pressure, 720 degCA

Heywood: Figure 1-8

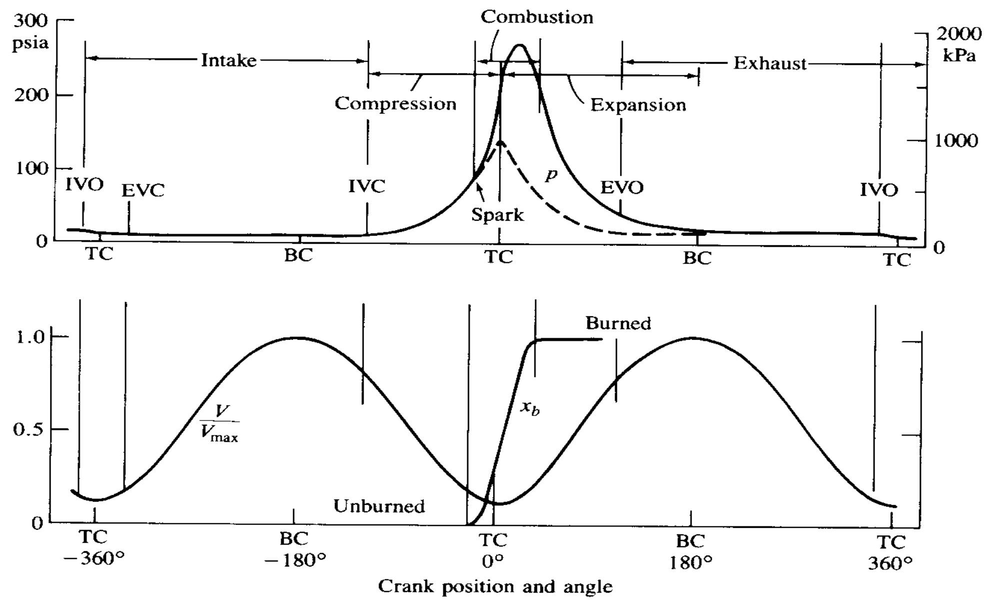


FIGURE 1-8
Sequence of events in four-stroke spark-ignition engine operating cycle. Cylinder pressure p (solid line, firing cycle; dashed line, motored cycle), cylinder volume V/V_{max}, and mass fraction burned x_b are plotted against crank angle.

Four Stroke SI Cylinder Pressure, 360 degCA

Heywood: Figure 1-15

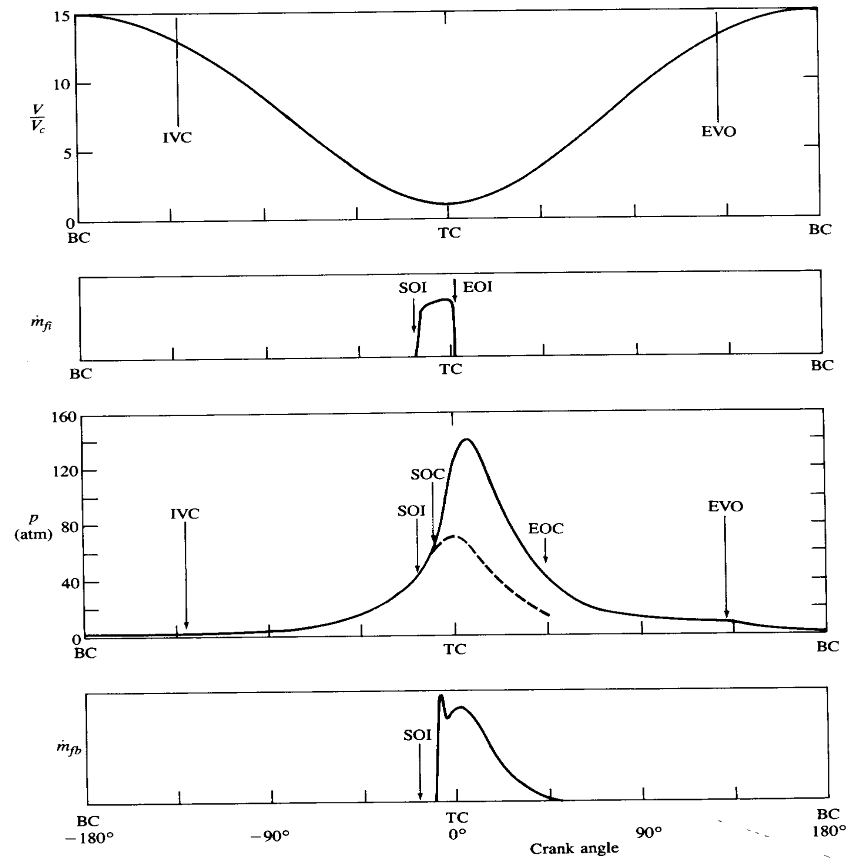


FIGURE 1-15
Sequence of events during compression, combustion, and expansion processes of a naturally aspirated compression-ignition engine operating cycle. Cylinder volume/clearance volume V/V_c, rate of fuel injection $\dot{m}_{fi}$, cylinder pressure p (solid line, firing cycle; dashed line, motored cycle), and rate of fuel burning (or fuel chemical energy release rate) $\dot{m}_{fb}$ are plotted against crank angle.

Two-Stroke Engine Cylinder Pressure, Inlet and Exhaust Ports 360 degCA

Heywood: Figure 1-16

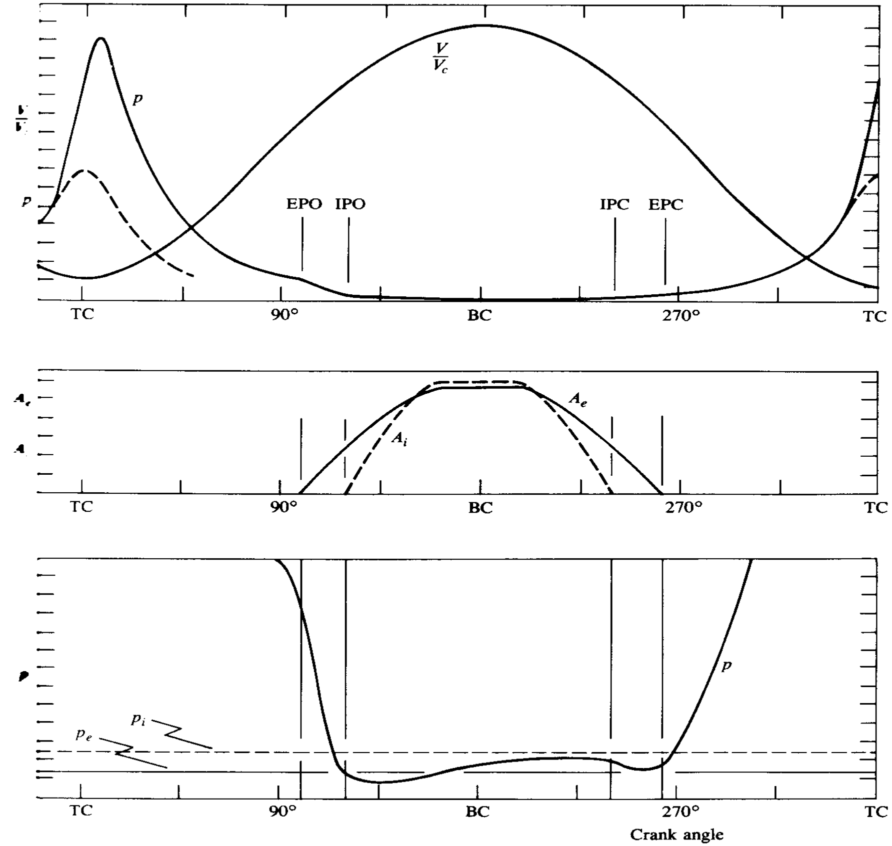
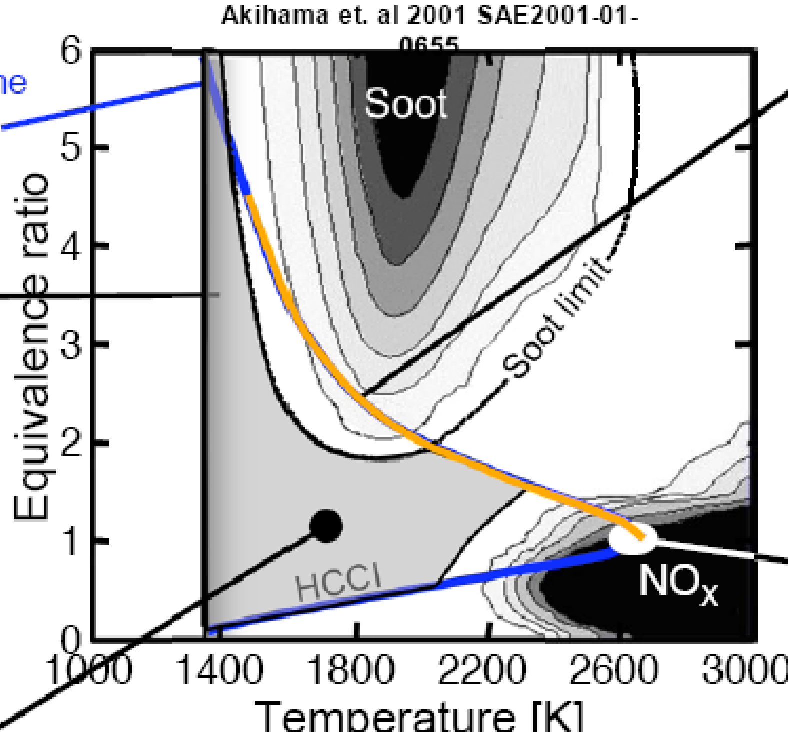
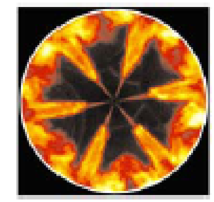


FIGURE 1-16
Sequence of events during expansion, gas exchange, and compression processes in a loop-scavenged two-stroke cycle compression-ignition engine. Cylinder volume/clearance volume V/V_c, cylinder pressure p, exhaust port open area A_e, and intake port open area A_i are plotted against crank angle.



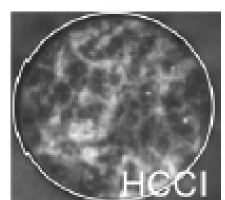
Diesel combustion

- controlled heat release (mixing)
- controlled combustion timing
- wide load range
- high efficiency (relative to SI)
- **NOx and PM emissions**



LTC

- offers diesel-like efficiency (high CR & no throttling)
- low NOx and particulate emissions
- **load range?**
- **combustion timing?**
- **heat release rate?**
- **transient control?**
- **fuel?**



Spark ignition (SI) combustion

- controlled heat release (flame propagation)
- controlled combustion timing
- wide load range
- three-way catalyst
- **low efficiency** (relative to diesel)