Internal Combustion Engines – MAK 493E

COMBUSTION in SI ENGINES

Prof.Dr. Cem Soruşbay
Istanbul Technical University

Internal Combustion Engines – MAK 493E

Combustion in SI Engines

- Introduction
- Classification of the combustion process
- Normal combustion : flame speed, turbulence
- Parameters influencing combustion process
- Ignition system
- Abnormal combustion : knock, surface ignition
- Parameters influencing knock
- Cyclic variations in combustion

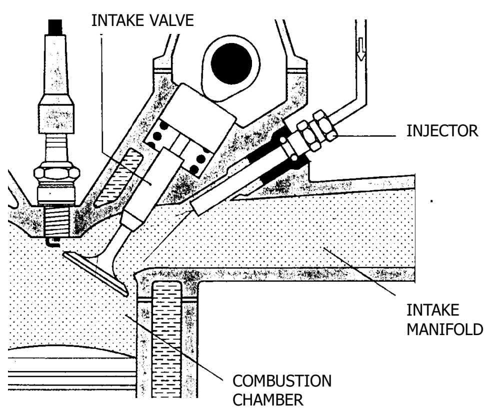
Introduction

In a conventional SI engine, **fuel and air** are mixed together in the intake system, inducted through the intake valve into the cylinder where mixing with residual gas takes place, and then compressed during the compression stroke.

Under normal operating conditions, combustion is initiated towards the end of compression stroke at the spark plug by an electric discharge.

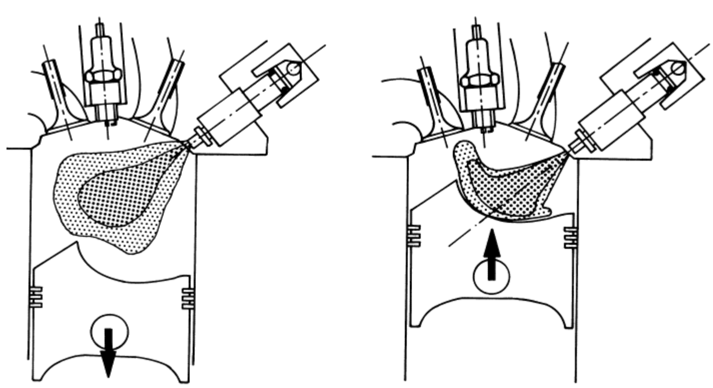
Following inflammation, a turbulent flame develops, propagates through the **premixed air-fuel mixture** (and burned gas mixture from the previous cycle) until it reaches combustion chamber walls, then it extinguishes.

Gasoline Manifold Injection (Conventional Sysytem)



Gasoline Direct Injection

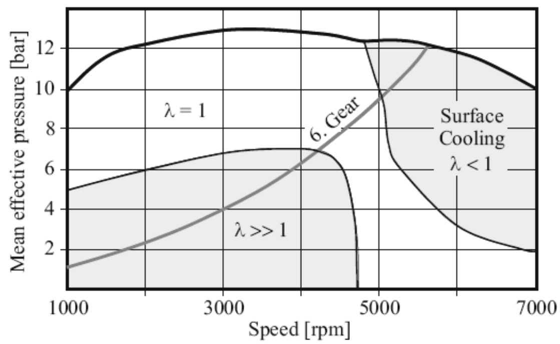
Gasoline Direct Injection



Early injection
homogeneous operation

Late injection
stratified charge

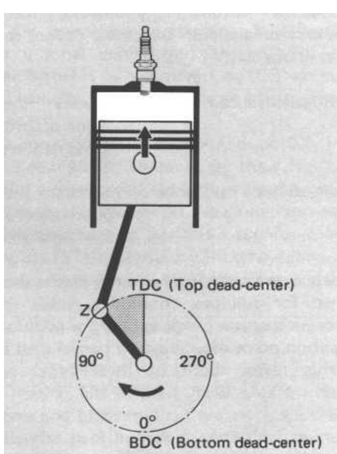
Modes of Opertaion

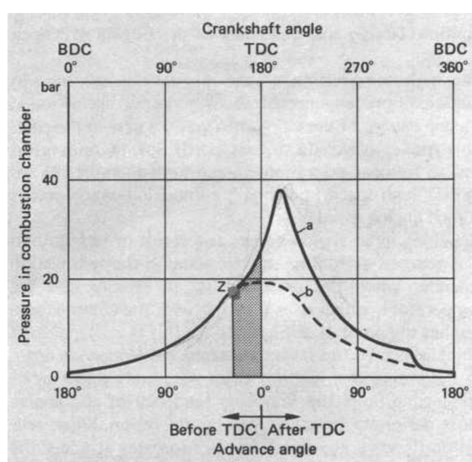


Modes of operation in the characteristic map of a DISI engine acc. to Fröhlich et al. (2003)

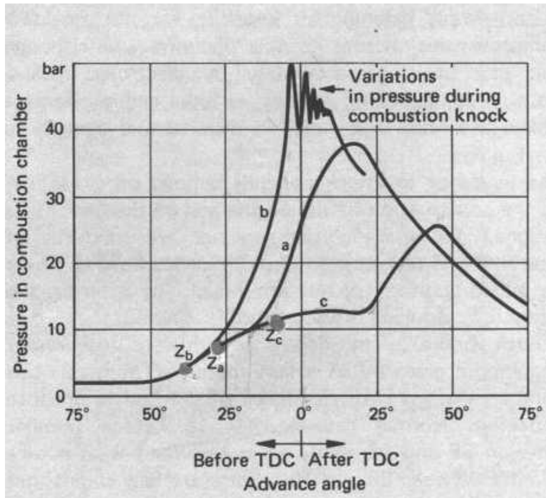
Stratified-charge engine

Cylinder Pressure





Cylinder Pressure



Combustion

Combustion event must be properly located relative to the TDC to obtain max power or torque.

Combined duration of the flame development and propagation process is typically between 30 and 90 CA degrees.

If the start of combustion process is progressively advanced before TDC, compression stroke work transfer (from piston to cylinder gases) increases.

If the end of combustion process is progressively delayed by retarding the spark timing, peak cylinder pressure occurs later in the expansion stroke and is reduced in magnitude.

These changes reduce the expansion stroke work transfer from cylinder gases to the piston.

The optimum timing which gives maximum brake torque (called maximum brake torque or **MBT** timing) occurs when magnitude of these two opposing trends just offset each other.

Combustion

Timing which is advanced or retarded from this optimum MBT timing gives lower torque.

Optimum spark setting will depend on the rate of flame development and propagation, length of flame travel path across the combustion chamber, and details of the flame termination process after it reaches the wall - these depend on engine design, operating conditions and properties of the fuel-air and burned gas mixture.

With optimum spark setting, max pressure occurs at about 15 degrees CA after TDC (10 - 15), half the charge is burned at about 10 degrees CA after TDC.

In practice spark is retarded to give a 1 or 2 % reduction in brake torque from max value, to permit a more precise definition of the timing relative to the optimum.

Combustion

Normal combustion

spark-ignited flame moves steadily across the combustion chamber until the charge is fully consumed.

Abnormal combustion

fuel composition, engine design and operating parameters, combustion chamber deposits may prevent occuring of the normal combustion process.

There are two types of abnormal combustion :

- Knock
- Surface ignition

Knock

Knock is the autoignition of the portion of fuel, air and residual gas mixture ahead of the advancing flame, that produces a noise.

As the flame propagates across combustion chamber, **end gas** is compressed causing pressure, temperature and density to increase. Some of the end gas fuel-air mixture may undergo chemical reactions before normal combustion causing autoignition - end gases then burn very rapidly releasing energy at a rate 5 to 25 times in comparison to normal combustion. This causes high frequency pressure oscillations inside the cylinder that produce sharp metallic noise called **knock**.

Knock will not occur when the flame front consumes the end gas before these reactions have time to cause fuel-air mixture to autoignite. Knock will occur if the precombustion reactions produce autoignition before the flame front arrives.

Piston Damage by Knock

(Foto: Mahle)

Piston Damage by Knock

This photo of a badly damaged piston indicates the effects of long-term engine knock.

Surface Ignition

Surface ignition is ignition of the fuel-air charge by overheated valves or spark plugs, by glowing combustion chamber deposits or by any other hot spot in the engine combustion chamber - it is ignition by any source other than the spark plug.

It may occur before the spark plug ignites the charge (preignition) or after normal ignition (postignition).

It may produce a single flame or many flames.

Surface ignition may result in knock.

Normal Combustion

When piston approaches the end of compression stroke, a spark is discharged between the spark plug electrodes – spark produces a small nucleus of flame that propagates into unburnt gas.

There is a delay of approx constant duration until a noticable increase in the cylinder pressure as a result of chemical reactions is recorded in "p ~ α diagram" - called the delay period.

This is approx 0.5 ms (for example corresponds to 7.5 ^{O}CA at 2500 rpm) and only approx 1 % of the charge is burned during that period.

Delay period depends on temperature, pressure and composition of fuel-air mixture, the energy applied at the spark plug, the duration of the spark, volume of the charge which is ignited initially and the gas flow in the cylinder (turbulence level).

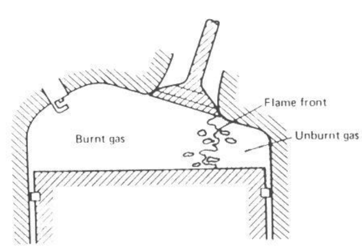
Normal Combustion

Second stage of combustion

after the ignition, cylinder pressure continues to rise while the flame front travels at a certain flame speed and peak pressure is obtained at 5 – 20 ^{O}CA ATDC. This is essential for max thermal efficiency.

Since combustion takes a finite time, mixture is ignited before TDC, at the end of compression stroke – spark advance

The second stage continues until maximum pressure is obtained and lasts about 25 – 30 ^{O}CA.



Normal Combustion

Combustion process takes place in a turbulent flow field.

The structure of the flame and the speed at which it propagates across the combustion chamber depends on charge motion, charge composition and combustion chamber geometry – engine design, operating conditions and mixture properties are important.

The volume enflamed behind the flame front continues to grow in roughly spherical manner, except where intersected by the chamber walls.

At any flame radius and engine geometry, flame front surface area influences combustion – larger this surface area, the greater the mass of fresh charge that cross this surface and enter the flame zone.

Flame Speed

Laminar flame speed is the velocity at which the flame propagates into quiescent premixed unburnt mixture ahead of the flame.

Flame is the result of a self sustaining chemical reaction occuring within a region of space called the flame front where unburnt mixture is heated and converted into products. Flame front consists of two regions; a preheat zone (temperature of the unburnt mixture is raised mainly by heat conduction from the reaction zone, no significant reaction takes place) and a reaction zone (upon reaching a critical temperature exothermic chemical reaction begins - the temperature where exothermic reaction begins to the hot boundary at downstream equilibrium burned gas temperature).

Turbulent Flame Speed

Turbulent flames are characterized by the root mean square velocity fluctuations, the turbulence intensity u'_{rms} and various length scales of turbulent flow ahead of the flame.

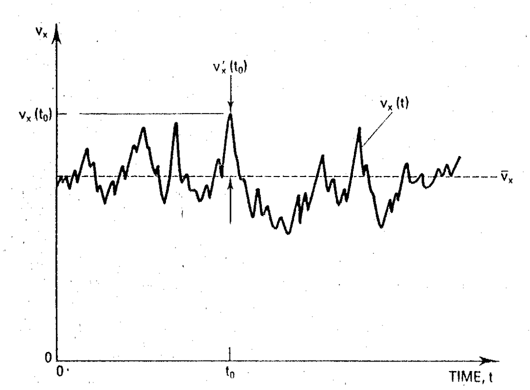
Integral length scale , l_I is a measure of the size of large energy-containing structures of the flow.

Kolmogorov scale , l_K defines the smallest structures of the flow where small-scale kinetic energy is dissipated by molecular viscosity.

Laminar flame thickness, is given as the molecular diffusivity over the laminar flame speed

$$\delta_L = \frac{D_L}{S_L}$$

Turbulent Flame Speed



$$\bar{\phi} \equiv \frac{1}{\Delta t}\int_{t_1}^{t_2} \phi(t)\, dt \qquad \phi(t) = \bar{\phi} + \phi' \qquad \phi'_{rms} \equiv \sqrt{\overline{\phi'^2}}$$

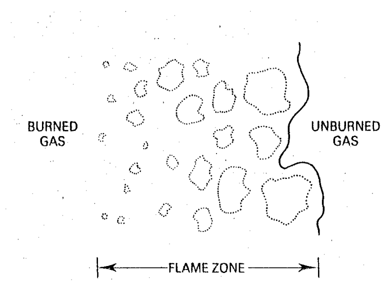
Turbulent Flame Speed

laminar flame speed - depends only on thermal and chemical properties of the mixture

turbulent flame speed - depends on flow conditions as well as mixture properties

$$S_T = f\left(T, p, \lambda, k\right)$$

$$S_T = f\ S_L$$



where f is the flame factor

depending on the intensity of turbulence

Turbulent flame speed is in the range of 50 – 60 m/s

Laminar Flame Speed

Metghalchi and Keck

$$S_L = S_{L,ref}\left(\frac{T_u}{T_{u,ref}}\right)^{\gamma}\left(\frac{P}{P_{ref}}\right)^{\beta}\left(1-2.1\ Y_{dil}\right)$$

$T_{u,ref} = 298$ K

$P_{ref} = 1$ atm

Laminar Flame Speed

$$S_{L,ref} = B_M + B_2 \left(\phi - \phi_M\right)^2$$

$$\gamma = 2.18 - 0.8\left(\phi - 1\right)$$

$$\beta = -0.16 + 0.22\left(\phi - 1\right)$$

iso-octane :

ϕ_M = 1.13 B_M = 26.32 [cm/s] B_2 = -84.72 [cm/s]

RMFD-303 (indolene) :

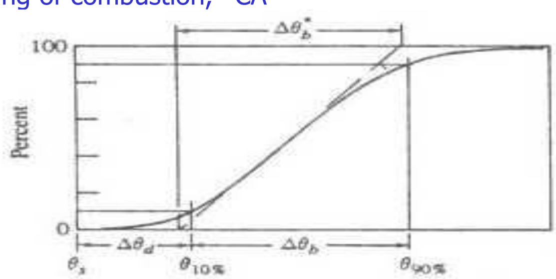
ϕ_M = 1.13 B_M = 27.58 [cm/s] B_2 = -78.34 [cm/s]

Mass Fraction Burned

Wiebe function

$$x_b = \frac{m_b}{m} = 1 - \exp\left[-a\left(\frac{\theta - \theta_o}{\Delta\theta_b}\right)^{m+1}\right]$$

m_b	mass burnt,
m	total mass of mixture.
a and m	are constants
$\Delta\theta_b$	total duration of combustion, ^{O}CA
θ_o	beginning of combustion, ^{O}CA



Pressure Gradiant

Depending on the compression ratio, the pressure gradiant is

$$\frac{dp}{d\alpha} = 0.1 \quad - \quad 0.12 \quad \text{MPa} \ / \ {}^{o}\text{CA}$$

for values of CR 7 : 1 – 8 : 1

$$\frac{dp}{d\alpha} = 0.15 \quad - \quad 0.25 \quad \text{MPa} \ / \ {}^{o}\text{CA}$$

for values of CR 8 : 1 – 10 : 1

Final Stage of Combustion

Final stage covers the period from the max cylinder pressure to the termination of the combustion process.

Maximum temperature value is reached during this stage (after max p)

Usually 70 – 75% of the total energy is released until max p is obtained, and 85 – 90% of the total energy is released until max T is obtained.

For partial load conditions, the flame speed is lower (low T and p), only 50 % of the energy is released until max pressure point.

Factors Influencing Combustion

- Engine speed
- Equivalence ratio
- Residual gas fraction
- Induction pressure
- Compression ratio
- Combustion chamber design
- Spark advance

Engine Speed

Mixture burning rate is strongly influenced by engine speed. The duration of combustion in crank angle degrees only inc slowly with increasing engine speed. Increase of the engine speed, reduces the time available for a complete combustion.

Inc in engine speed also increases the mean piston speed and turbulence intensity – increses flame speed. But this does not effect ignition delay period, thus delay period increases in CA degrees.

To compansate this, ignition timing should be adjusted – spark advance is increased with increasing engine speed.

Mixture Properties

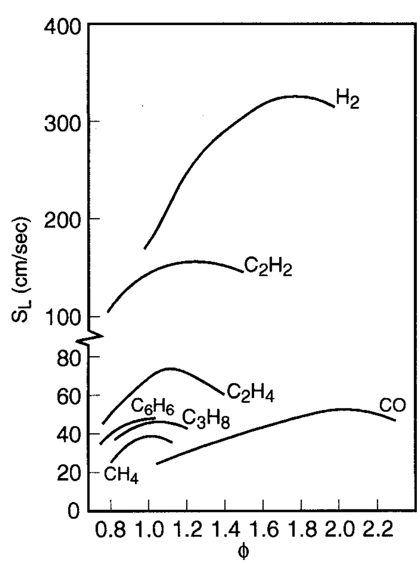
The fuel-air equivalence ratio affects the burning rate. Flame development show a minimum and the burning rate show a maximum for slightly rich mixtures ($\phi \approx 1.2$). Burning rate reduces for richer and leaner mixtures.

The burned gas fraction in the unburned mixture, due to the residual gas fraction and any recycled exhaust gases (EGR), slows down both flame development and propagation.

Residual gas fraction increases at part loads in SI-engines (due to closing the throttle), reducing flame propagation.

Fuel composition changes can be significant. Faster burning engines (high turbulence) are less sensitive to changes in mixture composition, p and T than slower burning engines.

Fuel Properties



Induction Pressure

Increase in the induction pressure reduces flame propagation speed, but also increases the temperatures at the end of compression process which effects the flame speed, and reduces combustion duration.

Induction pressure is effected at part-loads - partially opened throttle.

Flame speed is reduced, to compansate the inc in combustion duration spark advance is increased.

Compression Ratio

Increase in CR increases the p and T of the charge at ignition, reduces the mass fraction of the residual gases - more favorable conditions are developed for ignition which reduces the first stage of combustion, and increases flame propagation rate in the main stage.

Increasing CR, increases Area/Volume ratio of the cylinder, increasing the cooling effects and the quench layers. Final stage of combustion is increased.

Combustion Chamber Design

Intake manifold design and combustion chamber shape effects the gas flow and turbulence intensity. Turbulence strongly effects burning rate of the fuel.

Spark plug location effects distance traveled by the flame and flame front surface area.

Number of spark plugs.

Pressure gradiant should be controlled for optimum conditions in terms of total efficiency.

For best efficiency, $$\frac{dp}{d\alpha} = 0.20 \quad - \quad 0.25 \quad \text{MPa} \ / \ {}^{o}\text{CA}$$

Combustion Chamber Design

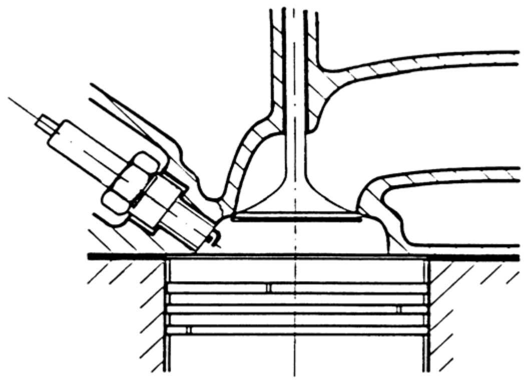
Combustion chambers that provide a minimal tendency to knock must satisfy the following basic requirements:

a) Short flame travel, thus a compact combustion chamber and central position of spark plug

b) **Avoid hot spots at the end of the flame travel**, spark plugs should be located near the hottest spots (exhaust valves)

c) **High flow velocities in combustion chamber** through swirl or tumble movements (turbulence) as well as squish-induced flows at the end of compression, to increase the flame velocity.

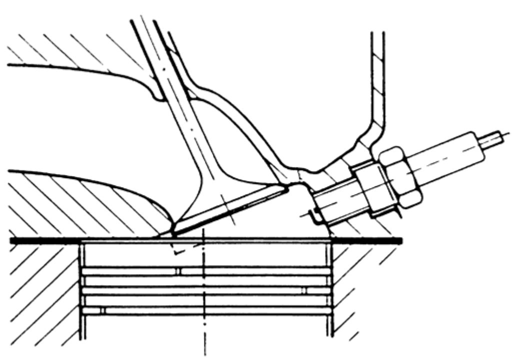
Combustion Chamber Design



Bathtub Combustion Chamber

- satisfies (c)

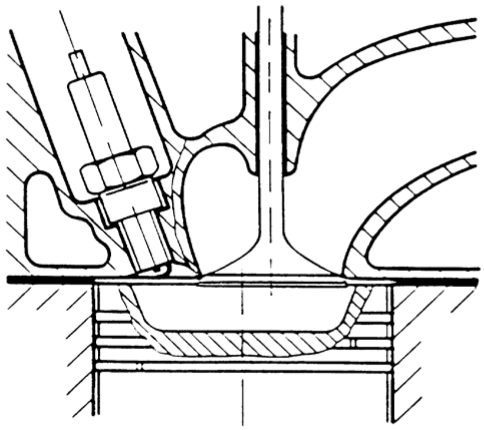
Combustion Chamber Design



Wedge Shaped Combustion Chamber

- satisfies (a), (b) and (c)

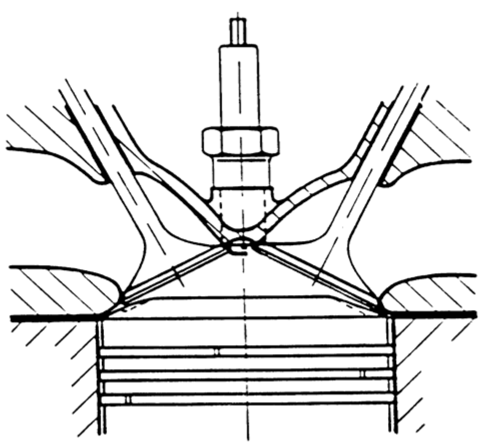
Combustion Chamber Design



Recessed Combustion Chamber in the Piston

- satisfies (a), (b)* and (c) , * superior

Combustion Chamber Design

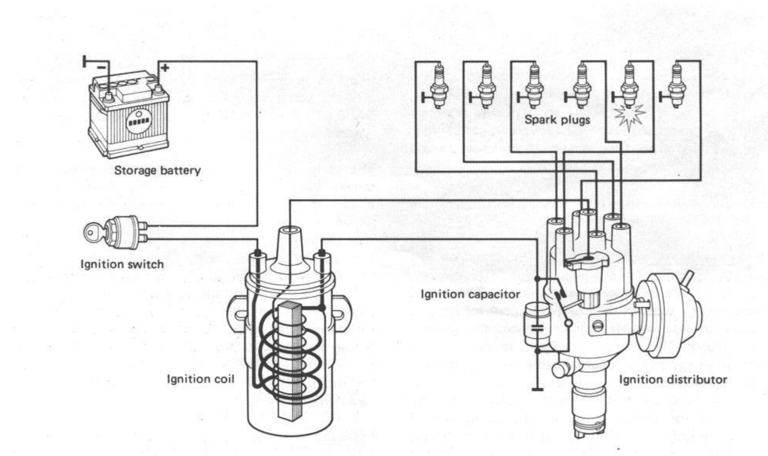


Hemispherical Combustion Chamber

- satisfies (a)*, (b) and (c) , * superior

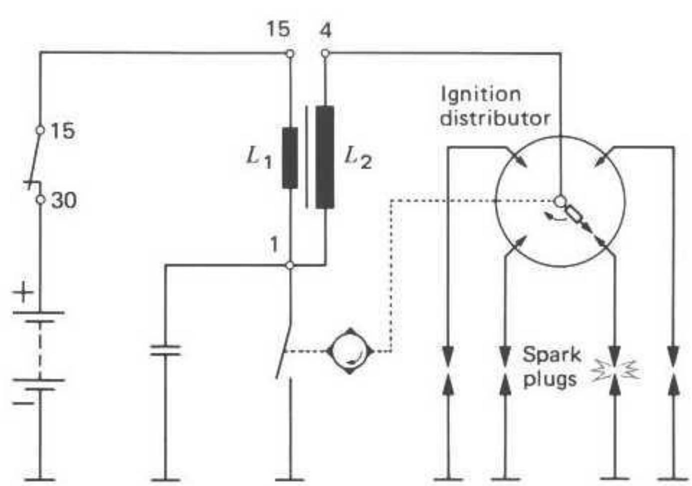
Ignition System

Spark ignition engines

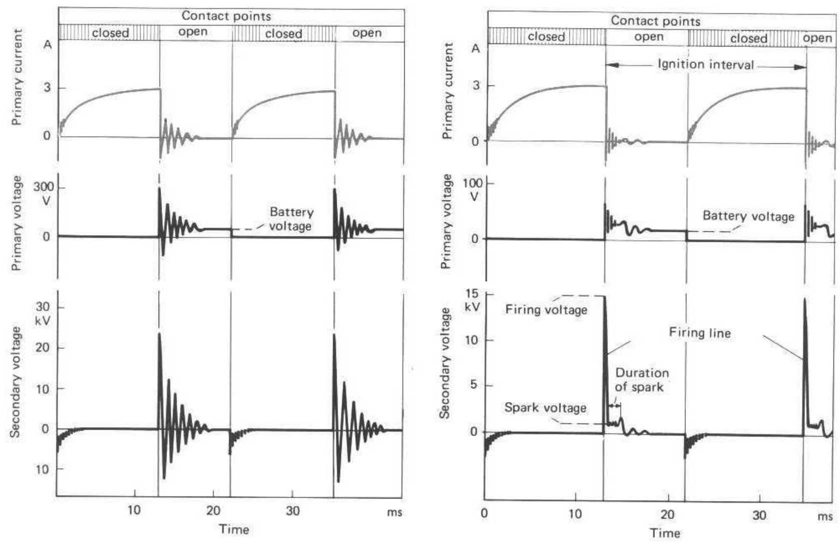


8

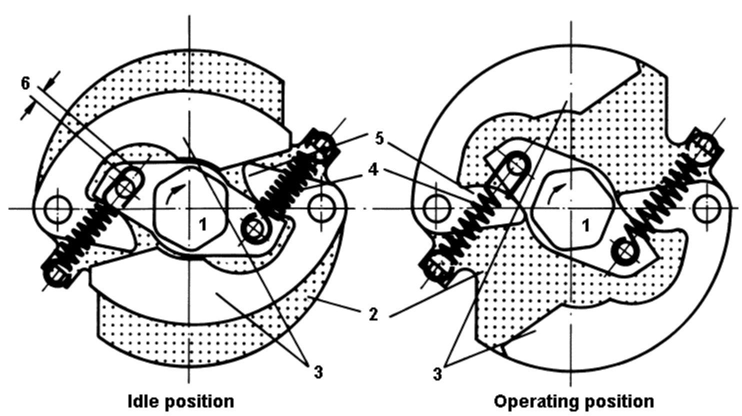
Ignition System



Ignition System

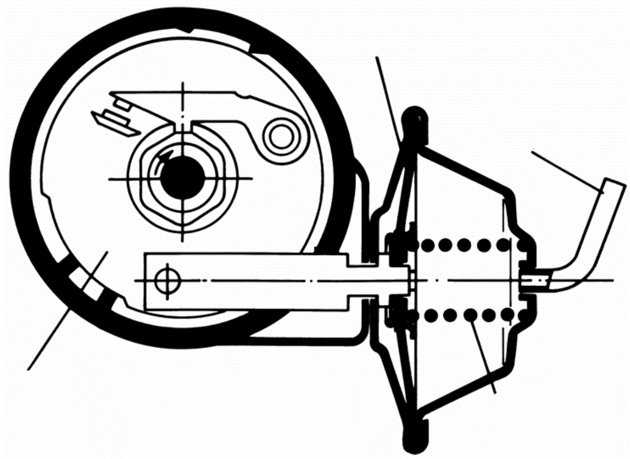


Ignition System



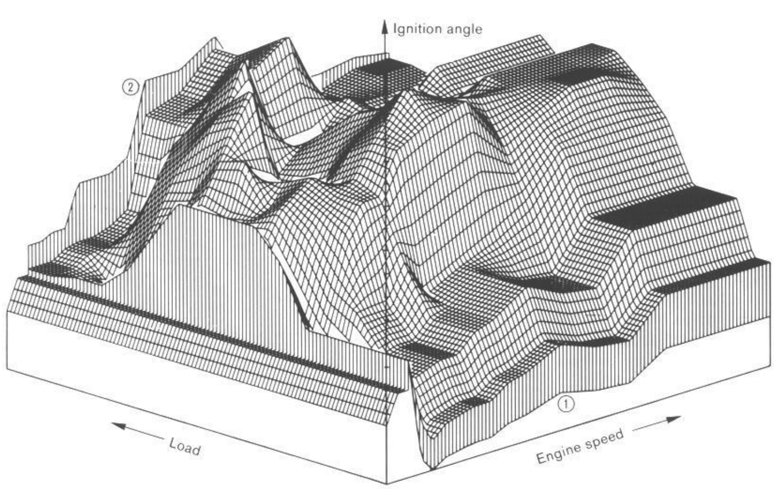
Centrifugal Ignition Advance Device

Ignition System



Vacuum Ignition Advance Device

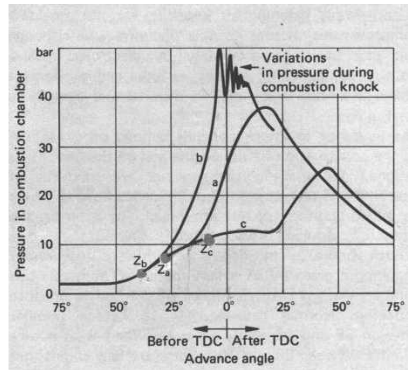
Engine Map



Abnormal Combustion

Knock originates in the extremely rapid release of much of the energy contained in the end-gas ahead of the propagating turbulent flame, resulting in high local pressures.

Nonuniform nature of this pressure distribution causes pressure waves or shock waves to propagate across the chamber, which may cause chamber to resonate at its natural frequency.



Knock Fundamentals

Origin of knock

Autoignition theory holds when fuel-air mixture in the end-gas region is compressed to sufficiently high p and T, the fuel oxidation process - starting with the preflame chemistry and ending with rapid energy release - can occur spontaneously in parts or all of the end-gas region.

Detonation theory postulates that under knocking conditions, advancing flame front accelerates to sonic velocity and consumes the end-gas at a rate much faster than would occur with normal flame speeds.

Knock Fundamentals

Autoignition is the term used for a rapid combustion reaction which is not initiated by any external ignition source.

Autoignition of gaseous fuel-air mixture occurs when the energy released by the reaction as heat is larger than heat lost to surroundings - as a result T of the mixture increases, rapidly accelerating the rates of reactions involved.

In complex reacting systems, large number of reactions take place - simultaneous, interdependent reactions or chain reactions.

There is initiating reaction where highly reactive intermediate species or radicals are produced from stable molecules (fuel and oxygen).

This step is followed by propagation reactions - radicals react with reactant molecules to form products and other radicals to continue the chain. Some propagating reactions produce two reactive radical molecules for each radical consumed - chain branching, extremely fast reaction rates.

The process ends with termination rections - chain propagating radicals are removed.

Fuel Factors

The knocking tendancy is related to molecular size and structure of the fuel.

Paraffins - inc length of carbon chain inc knocking tendancy, compacting carbon atoms by side chains dec tendancy to knock, adding methyl groups (CH3) dec knocking tendancy.

Olefins - introduction of one double bond has little effect on antiknock, two or three bond inc antiknock tendancy

Napthenes and aromatics - N have significantly greater knocking tendancy than corresponding size A, introduction of one double bond has little effect on antiknock, two or three bond reduce knocking tendancy considerably, lengthening side chain attached to basic ring structure inc knocking tendancy, branching of the side chain dec knocking tendancy.

Design Parameters

Compression ratio

increase in CR increases thermal efficiency but also increases the tendancy to knock - limits engine performance.

Combustion chamber size and shape

as combustion chamber volume gets smaller, “surface area-to-volume” ratio increases providing efficient cooling, reduces tendancy to knock.

In SI-engines max piston diameter is limited to 150 mm

Flame propagation distance (chamber shape and spark plug location, number of spark plugs used) also effects knock

Design Parameters

Valve overlap

reduces residual gases, produces cooling effect - reduces knock tendancy

Engine cooling

efficient cooling reduces tendancy to knock - water cooling systems are more effective, in air-cooled engines CR is limited

Operating Parameters

Equivalence ratio

autoignition reactions occur at slightly lean mixtures - flame speed is lower (more time for autoignition to happen), pre-reaction duration is relatively short.

Lean and rich mixtures - tendancy to knock is reduced.

Spark advance

increasing spark advance, p and T increases, flame speed also increases reducing the time for pre-reactions, but tendancy to knock increases with increasing spark advance.

Engine speed

turbulence intensity increases - flame propagation increases, volumetric eff is reduced and induction p is reduced, tendancy to knock decreases with inc in engine speed (rpm)

Operating Parameters

Induction p and T

with decreasing induction p and T, compression p and T is reduced which reduces the tendancy to knock.

In turbocharged engines **boosting pressure** increases and knock tendancy is increased.

Oxygen concentration in combustion chamber

decreasing oxygen concentration reduces the tendancy to knock humidity of intake air also cools the charge and reduces knocking tendancy.

Cooling water temperature

cooling water T effects mean combustion chamber temperatures - tendancy to knock decreases with decrease in T

Cyclic Variations in Combustion

For successive operating cycles, cylinder pressure versus time (or CA) shows substantial variations - due to variations occuring in combustion process.

Each individual cylinder can also have significant differences in the combustion process and pressure development between cylinders in a multicylinder engine.

Cyclic variations are caused by variations in mixture motion within cylinder at the time of spark cycle-by-cycle, variations in the amounts of air and fuel fed to the cylinder each cycle, and variations in the mixing of fresh mixture and residual gases within cylinder (especially in vicinity of spark plug) at each cycle.

Same phenomena applies to cylinder-to-cylinder differences.

Cyclic Variations in Combustion

Cycle-to-cyle variations are important for, optimum spark advance (effects engine power output and efficiency) and extreme cyclic variations limit engine operation.

Fastest burning cycles with over-advanced spark timing have highest tendancy to knock - determine fuel octane requirement and limit compression ratio.

Slowest burning cycles with retarded spark timing are most likely to burn incompletely - set practical lean operating limits, limit EGR which engine will tolerate.

Variations in cylinder p correlate with variations in brake torque which is directly related to vehicle drivability.

Cyclic Variations in Combustion

Measures for cycle-to-cycle variations

pressure related parameters - max cylinder p, the crank angle at which max p occurs, max rate of p rise, crank angle at which $(dp/d\theta)_{max}$ occurs, indicated mean effective pressure.

burn-rate related parameters - max heat transfer rate, max mass burning rate, flame development angle ($\Delta\theta_d$), rapid burning angle ($\Delta\theta_b$)

flame front position parameters - flame radius, flame front area, enflamed or burnt volume, all at given times, flame arrival at given locations.

Cyclic Variations in Combustion

The coefficient of variation (COV) in indicated mean effective pressure

standard deviation in indicated mean effective pressure (p_{ime}) divided by mean p_{ime} expressed in percent (usually),

$$COV_{imep} = \frac{\sigma_{imep}}{p_{ime}}.100$$

vehicle driveability problems usually result when COV_{impe} exceeds about 10 percent.

COV increases by leaning the mixture.