Chapter 4

Internal Combustion Engines

CHAPTER HIGHLIGHTS

- *Internal Combustion Engine*
- *Classification of I.C. Engines*
- *Components I.C. Engine*
- *Terminology used in I.C. Engine*
- *C.I. Engine Fuels*
- *Rating of Fuels*
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- *Combustion in S.I. Engine*
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- *Combustion in C.I. Engines*
- *Performance I.C. Engine*
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Internal Combustion (I.C.) Engines

Applications

1. Road vehicles such as trucks, tractors, etc.
2. Rail, aviation and marine.
3. Lawn mowers, motorboats, concrete mixing equipment, etc.

Difference Between Steam Engine and I.C. Engine

Steam Engine	IC Engine
1. Combustion takes place outside the engine, i.e., steam is generated outside the plant	(a) Combustion takes place inside the engine
2. Operates at less temperature, 600°C	(b) Operates at temperature about 2300°C
3. Does not require cooling system	(c) Requires cooling system
4. Exhaust of steam is used as feedwater by feeding into the condenser	(d) Exhaust gases are simple fed into the atmosphere
5. Efficiency is very low–15 to 20%	(e) Efficiency is high–30 to 35%

Classification of I.C. Engines

I.C. Engines are classified based on following parameters:

Number of Stokes Per Cycle

1. 4–Stroke engine–Cycle is completed in four strokes and two revolutions of the crankshaft
2. 2–Stroke engine–Cycle is completed in two strokes and one revolution of the crankshaft

Nature of Thermodynamic Cycle

1. Constant volume combustion (Otto cycle)
2. Constant pressure combustion (diesel cycle)
3. Partly constant volume and pressure combustion (dual or mixed cycle)

Ignition System

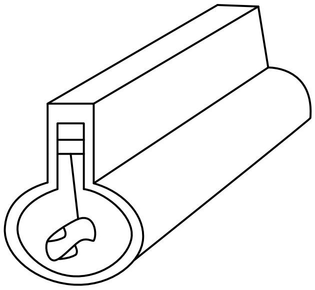
1. Spark Ignition (S.I.) engine: Spark plug is used for combustion (petrol engine)
2. Compression ignition (C.I. engine): Combustion starts automatically due to compression (diesel engine)

Fuel Used

1. Gas engine: Uses gaseous fuels such as methane, etc.
2. Petrol engine: Uses highly volatile liquid level such as petrol.
3. Oil engine: Uses less volatile liquid fuel such as diesel oil, kerosene, heavier residual fuels.
4. Bi-fuel engine: Gas is used as basic fuel. Liquid fuel is used for starting purpose.

Cylinder Arrangement

1. In-line engines: These engines contain on bank of cylinders with their axes parallel.
   - They transmit power to single crankshaft.



2. V-engines: Engines are arranged in the form of V.
   - Engines are connected to same crankshaft and same crankcase.

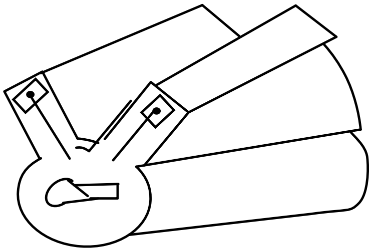


Figure 1 V-engines

3. Opposed cylinder: Engines are mounted on opposite sides of a common crankshaft.

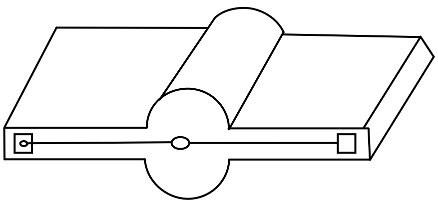


Figure 2 Opposed cylinder

4. X-engine: 4 engines in X shape.

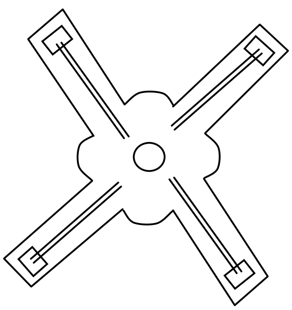


Figure 3 X-engine

5. Opposed piston: Single cylinder house, two pistons each of which drives a separate crankshaft.
6. Radial engine: Cylinders are arranged radically like spokes of a wheel and are connected to single crankshaft.

NOTE

These engines are used in aircraft.

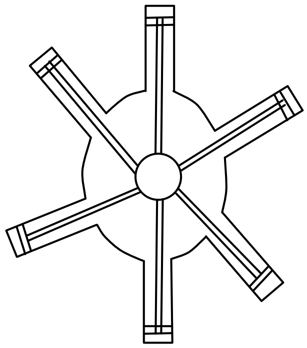


Figure 4 Radial engine

Cooling System

1. Water cooled engine: Cylinder is cooled by water.
2. Air cooled engine: Cylinder is cooled by air.

Field of Application

1. Stationary engine: Used in small or medium capacity electric power plants and to drive pumping units in agriculture.
2. Mobile engine: These engines are used in motor vehicles, aero planes, ships, locomotive, etc.

Fuel Supply System

1. Carburetor engine (petrol engine): The air and fuel is properly mixed in a carburetor before induction to the cylinder.
2. Air injection engine (diesel engine): The fuel is supplied under pressure to the engine cylinder by using compressed air.

Method of Control

1. Quality control engine: The composition of mixture is changed by admitting more or less fuel according to load.
2. Quantity control engine: The composition of mixture remains constant but quantity of mixture is changed.
3. Quality and quantity control engine: Both quality and quantity of the mixture is changed to affect control.

Lubrication System

1. Wet sump lubrication
2. Dry sump lubrication
3. Pressurized lubrication

Components of I.C. Engine

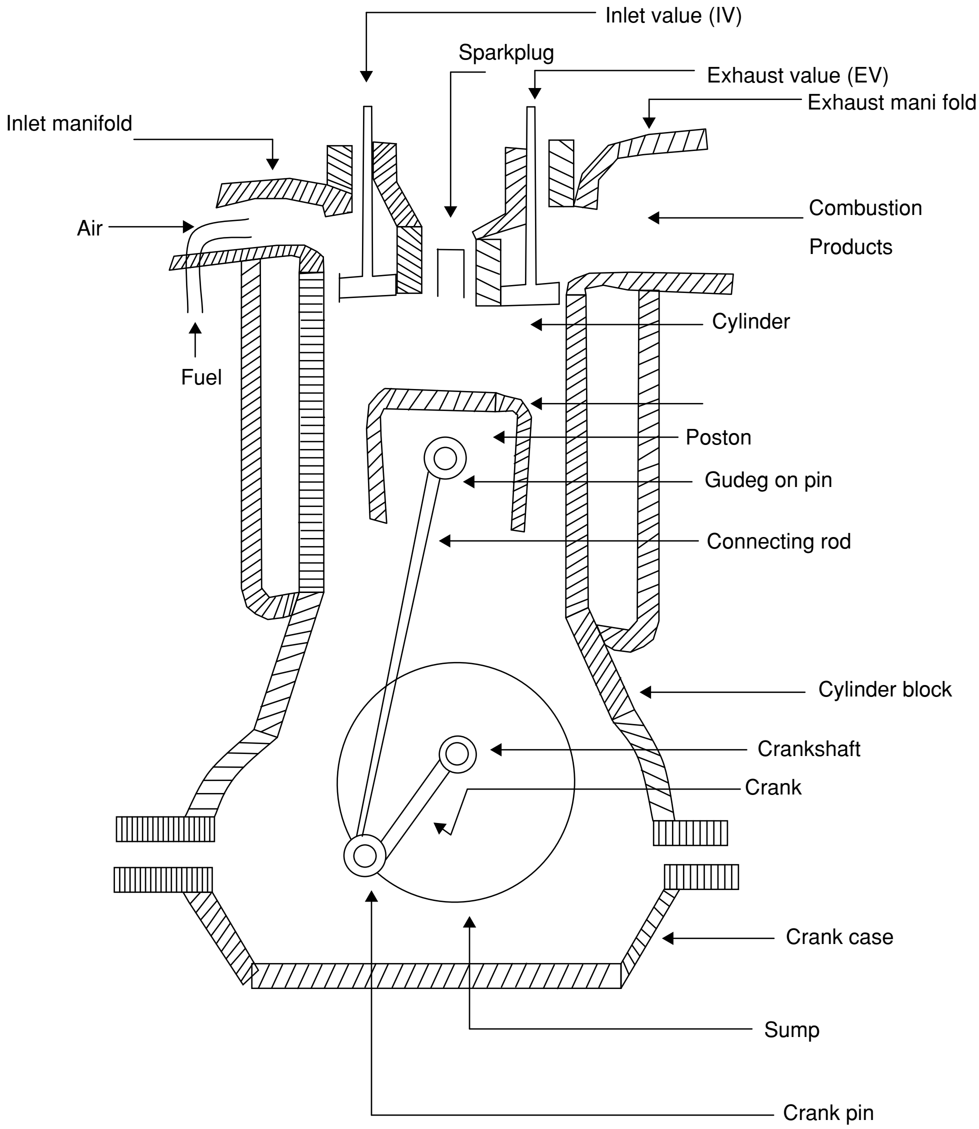


Figure 5 IC Engine components.

Cylinder Made of cast iron for automobile engines, thin steel hardened for air craft engines.

Cylinder head Made of cast iron. It contains both the valves, valve ports and fuel injector.

Cylinder liner Made of cast iron; cylinder is equipped with cylinder liner because if the liner is damaged due to wear and tear it can be replaced easily.

Piston The piston is cylindrical casting made of iron, aluminum alloy and steel.

Function: To transmit the forces created by combustion process to the connecting rod.

Piston rings Made up of grey cast iron

Function: To prevent any leakage of gas past the piston and to prevent the wear and tear of the piston.

Piston is fitted with at least 3 rings

1. Upper ring is called compression ring, prevents the leakage.
2. Lower ring is called the lubricating oil, controls ring.
3. Third ring which scraps up the surplus oil from the cylinder wall.

Water jacket Cooling water is circulated through the water jackets.

Connecting rod Made of forged steel or carbon steel.

- It connects the piston and the crankshaft.

- The small end is attached to the wrist pin located in the piston called piston pin.
- The big end is connected to the crankshaft by means of crank pin.

Function: To transmit the reciprocating motion of the piston into rotary motion of crankshaft.

Crankshaft Made of steel forgings, carbon steels or cast alloys. It serves to convert the forces applied by the connecting rod into a rotational force.

Valves

Function: To admit air or mixture of air-fuel into the cylinder through inlet valve and to exhaust the combustion products into the atmosphere through exhaust valve.

The valve mechanism consists of cams, cam follower, push rod, rocker arm and spring.

Valve types

1. Proppet valves—most commonly used in I.C. engines
2. Sleeve valves
3. Rotary valves

NOTES

1. At inlet valve temperature is same as atmospheric temperature.
2. At outlet valve temperature is around 750°C. Valves made of stainless steel, cobalt-chrome steel, tungsten steel or high speed steel.

Cams and camshaft The cams are mounted on a shaft known as camshaft which is driven by the crankshaft through gears or by timing chain at half of the speed of the engine.

Camshaft: It is used for converting the rotary motion into reciprocating motion. Crankshaft drives the camshaft.

NOTES

1. A camshaft rotates at half the speed of the crankshaft.
2. Camshaft may either chain driven or gear driven.

Manifolds

Inlet manifolds: The piping which connects the inner ports of the various cylinders to a common air intake for the engine is called the inlet manifold.

Exhaust manifolds: The piping which connects the exhaust ports to a common exhaust system and send the exhaust products to the muffler is called the exhaust manifold.

Carburetor Employed in S.I. engine to atomize, vaporize and mix the fuel with air in required proportions at all loads and speed before entering to the engine cylinder.

Fuel pump and injector unit Employed in C.I. engine. The fuel pump supplies the fuel under pressure to the injector or atomizer, which consists of one or more orifices through which the fuel is sprayed into the cylinder.

Spark plug It is located at the top of the cylinder and initiates combustion.

Fly wheel A heavy disc of cast iron attached to the crankshaft at its rear end.

Function

1. To reduce the speed fluctuations.
2. To act as a storage of energy.
3. To make the piston move out of the dead centre position.

NOTES

1. The energy in flywheel is by virtue of its heavy mass.
2. By employing a flywheel the turning moment becomes uniform at the crankshaft.
3. For a single cylinder engine a heavier flywheel is required and for multi cylinder engine lighter flywheel is employed.

Ignition system Provided in S.I. engine. It controls the firing order in S.I. engine cylinder through sparkplug.

Governor It is run by a drive from the crankshaft

Function: To regulate the charge in the petrol engine and amount of fuel in case of diesel engine to maintain the speed of the engine constant, when the load requirement varies.

NOTE

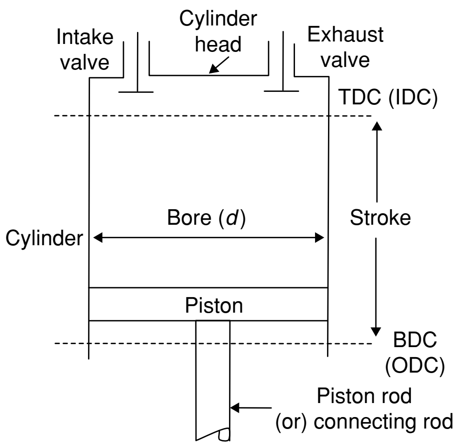
Types of Engine	Applications
1. Inline and V-types	Small aircrafts, automobiles and general purpose
2. Radial engine	Medium and large aircrafts
3. Opposed piston	Large diesel installations
4. H-and X-type	Diesel installations

Note:

Table 1 *Materials for engine components*

Components	Material
Piston	Aluminum alloy, steel
Cylinder	Cast iron
Piston ring	Grey cast iron
Connecting rod	Forged steel or carbon steel
Cylinder liner	Cast iron or nickel alloy steel
Crankshaft	Alloy steel
Bearing	White metal
Valves	HSS, cobalt-chrome steel

Terminology Used in I.C. Engine



Bore The diameter of the piston is called bore (d).

Stoke The maximum distance travelled by the piston in the cylinder in one direction is known as stroke.

1 stroke = 2 × radius of crank

Top dead centre (TDC) or (IDC) The extreme position of piston at the top of the cylinder is called TDC or IDC in case of horizontal engine.

Bottom dead center (BDC) or ODC The extreme position of piston at the bottom of the cylinder is called BDC or ODC in case of horizontal engine.

Stroke length The distance between extreme positions is called stroke length.

Clearance volume (Vc) The volume contained in the cylinder above the top of the piston when the piston is at TDC.

Swept volume (or) piston displacement Volume swept by the piston in moving between TDC and BDC is called swept volume.

NOTES

1. Displacement volume (or) swept volume (V_s) = piston area × stroke

$$V_s = \frac{\pi}{4} d^2 \times L$$

2. Total volume = $V_s + V_C$

Compression ratio (r)

$$\frac{\text{maximum volume formed in the cylinder}}{\text{minimum volume}}$$

$$r = \frac{V_{\max}}{V_{\min}} = \frac{V_{BDC}}{V_{TDC}} = \frac{V_C + V_S}{V_C}$$

$$r = 1 + \frac{V_S}{V_C}$$

NOTES

1. Petrol engine: $r \rightarrow$ 5:1 to 7:1
2. Diesel engine: $r \rightarrow$ 14:1 to 22:1
3. Compression ratio is only volume ratio not related to pressure ratio.

Clearance ratio (C)

$$\frac{\text{clearance volume}}{\text{stroke volume}} = \frac{V_c}{Vs}$$

Relationship between C and r

$$\therefore\ r = 1 + \frac{V_s}{V_c} = 1 + \frac{1}{C}$$

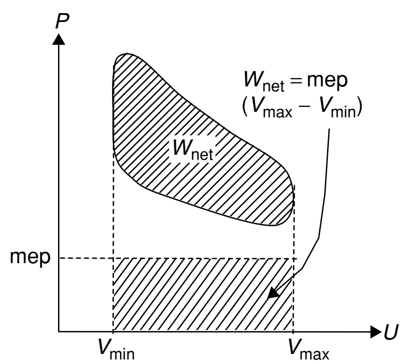
$$r = 1 + \frac{1}{C}$$

Mean effective pressure (P_{mep}) It is defined as average pressure which, if acted on the piston during the entire power or outward stroke, would produce the same work output as the net work output for the actual cyclic process.

W_{net} = mep × piston area × stroke

$$= P_m \times A \times L$$

$$m.e.p = r = \frac{W_{\text{net}}}{V_{\max} - V_{\min}} = \frac{W_{\text{net}}}{\text{stroke volume}}$$



The net work output of a cycle is equivalent to the product of the mean effective pressure and the displacement volume.

S.I. Engine Fuels

Gasoline: Mostly used in the present day S.I. engine.

- The best S.I. engine fuel will be that having the highest antiknock property. Since this permits the use of high compression ratios and thus the engine thermal efficiency and the power output can be greatly increased.
- The sulphur is a corrosive element of the fuel that corrode fuel lines, carburetors and injection pumps and it will combine with oxygen to form sulphur dioxide a low ignition temperature.

The presence of sulphur can reduce the self-ignition temperature, then promoting knock in the S.I. engine.

C.I. Engine Fuels

Knock in the C.I. engine occurs because of an ignition lag in the combustion of the fuel between the time of Injection and the time of actual burning.

Ignition lag increases ↑→ fuel accumulation in the combustion chamber increases (↑).

Abnormal amount of energy is suddenly released causing an excessive rate of pressure rise which results in an audible knock.

Hence a good C.I. engine fuel should have a short ignition lag and will ignite more readily.

Rating of Fuels

Rating of S.I. Engine Fuel

S.I. engine fuel is determined by comparing its antiknock property with a mixture of two reference fuels.

They are iso-octane (C_8H_{18}), normal heptanes ($C_7 H_{16}$).

Iso-octane: chemically very good antiknock fuel.

100 octane number.

Normal heptane: poor antiknock fuel.

'0' (zero) octane number.

NOTES

1. The addition of (tetraethyl/lead) to iso- octane produce fuels of greater antiknock quality (above 100 octane number).
2. New scale on engine performance number PN. Octane number 100 can be computed by

$$\text{ON} = 100 + \frac{PN - 100}{3}$$

Octane number It is defined as the percentage, by volume of iso-octane in a mixture of iso-octane and normal heptane, which exactly matches the knocking intensity of the fuel in a standard engine under a set of standard operating conditions.

Rating of C.I. engine fuels Now rating of diesel engine is found by reference fuel.

1. Normal cetane ($C_{16} H_{34}$) – '100' cetane number
2. Alpha methylnaphthalene ($C_{11}H_{10}$) – '0' cetane number.

Cetane number: It is defined as the percentage by volume of normal cetane in a mixture of normal cetane and α-methylnaphthalene which has the same ignition characteristics.

NOTE

Knock resistance property of diesel oil can be improved by adding small quantities of compounds like amyl nitrate, ethyl nitrate or either.

Table 2 *Comparison between petrol and LPG*

Petrol	LPG
1. Fuel consumption in petrol engine is less when compared to LPG	(a) compared to petrol, 10% increase in consumption
2. Petrol has odour	(b) LPG is odourless
3. Octane rating of petrol is 81	(c) Octane rating of LPG is 110
4. It is not smooth	(d) It is smooth
5. To increase octane number petrol requires lead additives	(e) LPG is lead free with high octane number

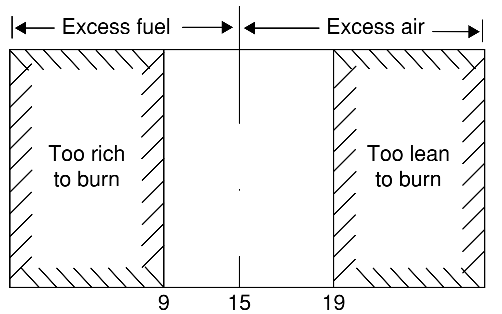
Air–fuel Mixtures

Chemically correct mixture (15:1) It indicates enough required air for complete combustion of the fuel.

Example: To burn 1 kg of octane (C_8H_{18}) completely, 15.12 kg of air is required.

NOTE

Complete combustion means all carbon in the fuel is converted into CO_2 and all hydrogen into H_2O.



Lean mixture Contains more air than stoichiometric requires mixture.

Example: A/F ratio 17:1, 20:1, etc.

Rich mixture Contains less air than stoichiometric mixture.

Example: A/F ratio 10:1, 12:1, etc.

Mixture Requirement at Different Loads and Speeds

Best power mixture Point corresponding to maximum power output curve, i.e., 12:1 A/F ratio.

Best economy mixture Corresponding to minimum point on the BSFC curve, i.e., 16:1 A/F ratio.

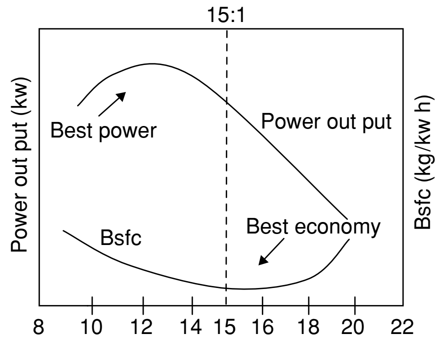


Figure 6 A/F ratio (kg of air/kg off fuel)

Combustion in S.I. Engine

Homogeneous mixture In S.I. engine mixture of air and fuel is formed in the carburetor, outside the engine cylinder.

Combustion is initiated inside the cylinder at the end of compression stroke.

Normal flame velocity $\rightarrow$ velocity of flame i.e., 40 cm/s

$$\text{Equivalence ratio } (\phi) = \frac{\text{actual fuelair ratio}}{\text{stoichio metric fuel}} = 1.0$$

In S.I. engine maximum flame speed at $\phi - 1.1$ to 1.2. That is, when φ is out of the above range, flame speed drops rapidly to a low valve.

Heterogeneous mixture Combustion can take place in an overall lean mixture.

Stages of Combustion in S.I. Engine

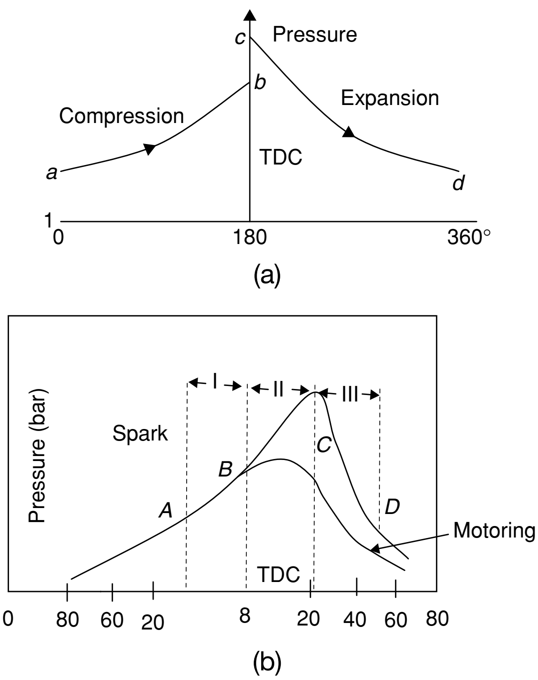
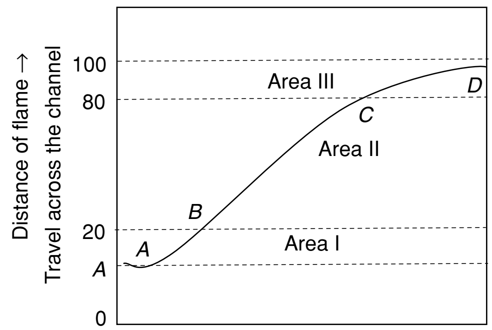


Figure 6 (a) Theoretical pressure–angle diagram, (b) Crank angal (θ)°

1. Ignition lag
2. Propagation of flame
3. After burning
   - spark 20° before TDC
   - Beginning of pressure rise say 8° before TDC
   - Point C attainment of peak pressure
   - The point where the combustion departs from the compression line (point *B*). This can be seen as the deviation from the main line.

Flame front propagation Factors affecting the movement of the flame front

1. Reaction rate: Results purely chemical combination process.
2. Transposition rates: Results due to physical movement of flame front relative to the cylinder wall and also pressure difference between the burning gases and the unburnt gases.



Time of flame front travel across flame front propagation:

$A \rightarrow B$: Flame front is relatively slow. Due to low transposition rate and low turbulence since small mass of charge burnt at the start.

$B \rightarrow C$: Flame front propagation is relatively high due to more turbulence.

$C \rightarrow D$: Flame front progress relatively low.

Factors influencing the flame speed

Turbulence: Flames speed is quite low in non-turbulent zone, Turbulence $\uparrow \rightarrow$ flame speed $\uparrow$

Fuel-air ratio: Highest flame speed is obtained with richer mixture.

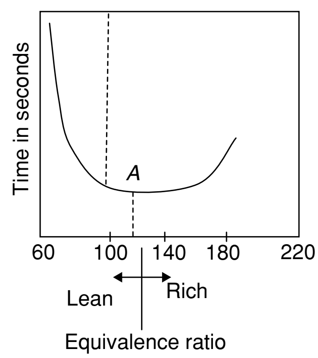


Figure 7 Equivalence ratio

Temperature and pressure: (Temp and pressure) ↑→ flame speed ↑

Compression ratio: r ↑ flame speed ↑

Engine speed: N ↑ → flame speed ↑

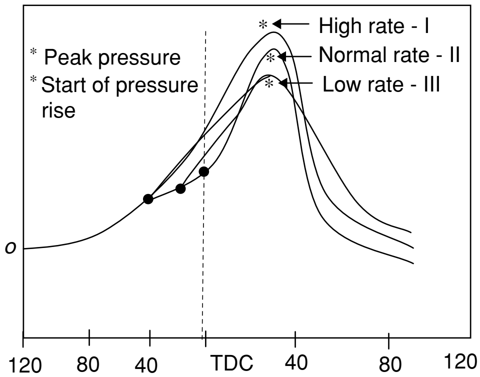
Engine output: Pressure ↑, when the engine output ↑ with the increased throttle, → higher density engine out put ↑ flame speed ↑

Engine size: Size of engine does not have any effect.

NOTE

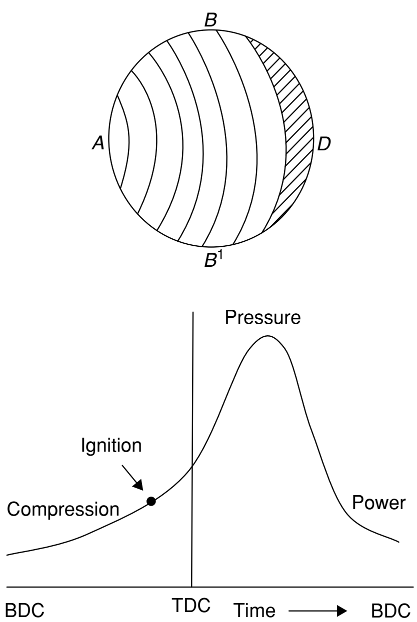
'↑' – increases
'↓' – decreases

Rate of pressure rise Indicated by the slope of the curves between start of pressure rise and the peak pressure.



Curve I → for high rate of combustion → point closer to TDC
Curve II → for normal rate of combustion
Curve III → for low rate of combustion

The phenomenon of knock in S.I. engine If the temperature of the unburnt mixture exceeds the self-ignition temperature of the fuel auto ignition occurs at various pinpoint locations. This phenomenon is called knocking.



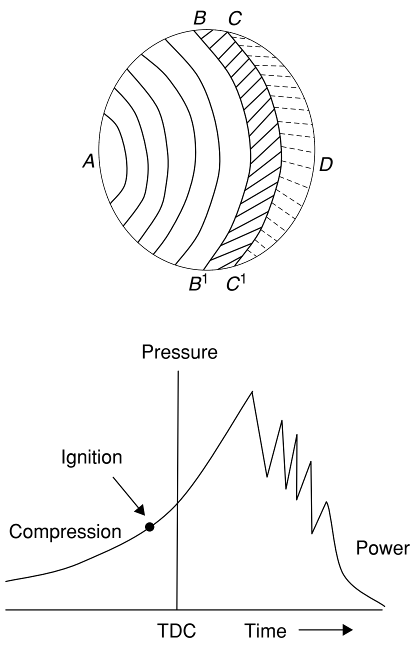


Figure 8 Abnormal combustion.

Abnormal combustion or knocking results loss of power, recurring pre-ignition and mechanical damage to the engine.

Knock limited parameters:

1. Knock limited compression ratio
2. Knock limited inlet pressure
3. Knock limited indicated mean effective pressure

Effect of engine variables on knock

1. Density factor: P↑, reduce the possibility of knocking
2. Compression ratio: (Pressure and temperature) ↑→ increase the tendency of knocking
3. Mass of inducted charge: m ↑→ increasing the tendency of knocking.
4. Inlet temperature and pressure: (T and P) ↑→ increasing the tendency of knocking.
5. Power output: power ↓ decreasing the tendency of knocking.
6. Retarding the spark time: Increasing the tendency for knowing.
7. Turbulence ↑→ flame speed ↑ reduces the time available for the end charge to attain autoignition, thereby decreasing the tendency to knock.
8. Engine speed: N↑→ reducing the tendency of knocking
9. Flame travel distance:
   time required for the flame front to traverse ↑→ the knocking tendency is reduced.
10. Engine size: size ↑→ increasing the tendency for knock.

NOTE

S.I. engines limited to size about 150 mm bore k.

11. Combustion chamber shape: should be spherical in shape to minimize the length of the flame travel for given volume.

Composition factors

1. Fuel-air ratio: maximum flame temperature is obtained, when $\varphi \approx 1.1$ to 1.2
   When $\varphi = 1$ given minimum reaction time for autoignition
2. Octane value of the fuel:
   Self-ignition temp $\uparrow \rightarrow$ octane no $\uparrow$ and low pre flame velocity would reduce the tendency of knocking.

NOTES

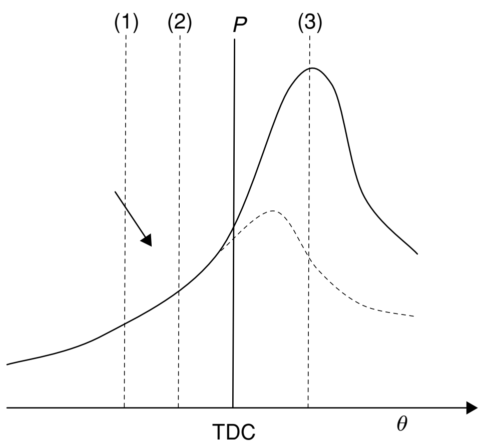
1. Parafin series have the maximum tendency to knock.
2. Aromatic series have the minimum tendency to knock.
3. Naphthalene series comes in between these two.

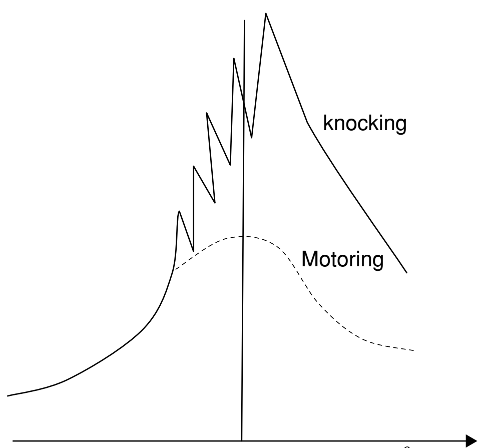
Combustion in C.I. Engines

In C.I. engine the air-fuel mixture is not homogeneous and AFR in the various parts of the combustion chamber is different.

Fuel is injected all at once but continuous over a number of degrees of crank angles/up to about 35°)

In S.I. engine too lean mixture cannot support the combustion, but in C.I. engine burning can take place in a mixture which is infinitely lean.





Abnormal combustion

1. Start of ignition
2. Start of combustion
3. End of ignition

$1-2 \rightarrow$ Delay period or ignition lag
$1-3 \rightarrow$ Injection period

In C.I. engines knock is due to detonation, occurs at the beginning of combustion.

Ignition delay causes to detonate in C.I. engine.

Ignition delay of a C.I. engine fuel may be reduces adding certain additives to the fuel.

Factors Which Influence Ignition Delay

1. Compression ratio: $r \uparrow \rightarrow$ ignition lay $\downarrow$
2. Inlet air temperature: $T \uparrow \rightarrow$ ignition lag $\downarrow$
3. Coolant temperature: $N \uparrow \rightarrow$ cylinder air Temp $\uparrow$-ignition tag $\downarrow$ $N \uparrow \rightarrow$ turbulence $\uparrow \rightarrow$ ignition $\downarrow$

Performance I.C. Engines

Engine Performance Parameters

Continuous power Power which the engine is capable of delivering continuously b/w the normal maintenance intervals.

Indicated power (IP) Power developed in its cylinder measured by pressure indicator connected to cylinder head.

Work done per minute $= Pm \times A \times L \times n\ N-m$

Power developed at the engine cylinder

$$IP = \frac{P_m ALn}{60}$$

$$IP = \frac{P_m ALnk}{60} W$$

$$IP = \frac{P_m ALnk}{60,000} kW$$

where P_m = m.e.p. in N/m^2
A = Area of c/s of piston in m^2
L = Length of stroke in m
n = Number of working stroke per minute or number of explosions per minute
K = Number of cylinders

NOTE

$n = N$ for 2-stroke engine $n = \frac{N}{2}$ for 4-stroke engine.
where N = speed in rpm

Indicated mean effective pressure

$$P_m = \frac{a \times s}{\ell} N/m^2$$

where a = area of Indicator diagram cm^2
l = length of Indicator diagram cm
s = spring number or spring strength in N/m^2 per cm

Brake power (BP) The power available at the crankshaft of the engine for doing external work.

Brake power $BP = \frac{2\pi NT}{60} W$ where N – speed in rpm; T – engine torque in Nm

NOTES

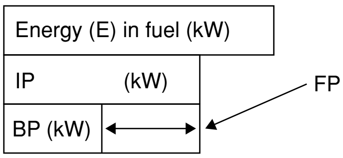
1. *BP* is measured by some break arrangement hence it is named brake power.
2. Brake power is measured by following arrangements.
   - Rope brake arrangement
   - Prony brake arrangement
   - Band brake arrangement

Brake mean effective pressure

$$\text{b.m.e.p.} = \frac{\text{BP} \times 60}{\text{LAN}}\ \text{N/m}^2$$

Frictional power (FP) The power lost due to friction is called *FP*.

Frictional power FP = IP – BP



$$Bp = \frac{2\pi NT}{60} = \frac{\text{b.m.e.p.} \times \text{LAN}}{60}$$

$$\text{b.m.e.p.} = \frac{2\pi NT}{LAN} \times T = C(T)$$

$$b_{\text{mep}} \alpha\, T$$

$\therefore$ b_{mep} is directly proportional to engine torque and is independent of the engine speed.

Mean piston speed $(\overline{S_p})$

piston speed $\boxed{(\overline{S_p}) = 2LN}$

Average value $\overline{S_p} = 8$ to 15 m/s

where $N \rightarrow$ rev/min
$L \rightarrow m$

Specific fuel consumption (SFC) Amount of fuel consumed per unit of power developed per hour.

Specific fuel consumption

$$= \frac{\text{Fuel consumed in kg/h}}{\text{power developed}}$$

NOTES

1. Automobile engines operate at higher means specific speed.
2. Marine diesel engines at the lower mean specific speed.
3. Specific fuel consumption (s.f.c) $= \dfrac{1}{\eta\text{th}}$

Specific power output (P_s)

- Power output per unit piston area.
- Specific power output $P_s = \dfrac{BP}{A}$
- $P_s \propto P_{mep} \times \overline{S_p}$

Inlet Valve Mach Index (Z)

Gas velocity through the inlet valve the smallest flow area

$$= V = \frac{A_p}{A_i C_i} V_p$$

where

A_p = piston Area
C_i = inlet valve flow co-efficient
A_i = normal intake valve opening area

$$\frac{V}{\alpha} = \frac{A_p}{A_i} \frac{V_p}{C_i \alpha} = \left(\frac{b}{Di} \cdot \frac{V_p}{C_i \alpha}\right) = z$$

where

b = cylinder diameter
D_i = inlet valve diameter
V_p = mean piston speed

NOTES

1. For good design of the engine, volumetric efficiency should be maximum.
2. (η_{vol}) at $z = 0.55$

Equivalence ratio (ϕ)

$$\phi = \frac{\text{Actual fuel} - \text{air raio}}{\text{stoichiometric fuel} - \text{air ratio}}$$

NOTES

1. $\phi = 1$ for chemically correct mixture
2. $\phi > 1$ for rich mixture
3. $\phi < 1$ for lean mixture

Efficiencies

Indicated thermal efficiency

$$(\eta_{I^{th}}) = \frac{IP}{\text{Energy supplied per second (kJ/S)}} = \frac{IP}{m_f \times c.v}$$

where *mf* = mass of fuel; *CV* = calorific value of fuel

The indicated thermal efficiency of modern engines is about 28%.

Brake thermal efficiency

$$\text{Brake thermal efficiency} = \frac{BP}{m_f \times C.V}$$

For S.I. engine $\eta_{b\text{th}} = 25\% - 33\%$

For C.I. engine $\eta_{b\text{th}} = 30\% - 45\%$

Mechanical Efficiency

$$\eta_m = \frac{BP}{IP}$$

Mechanical efficiency of engines varies from 65 to 85%

Volumetric efficiency Important parameters, which decides the performance of 4-stroke engines.

Engine must be able to take in as much air as possible.

$$\eta_{vol} = \frac{\text{volume flow rate of air in to the intake system}}{\text{Total volume displaced}}$$

It is the ratio of volume of air drawn in to the volume of air that can be drawn in at standard pressure temperature conditions

$$\eta_{vol} = \frac{m_a}{\rho_a V_{disp}}\left(\frac{N}{2}\right), \ \rho a = \text{density of air}$$

$$\eta_{vol} = \frac{m_a}{\rho_a V_d}$$

NOTES

1. $\eta_{vol} = 80 \textit{ to } 85\%$ for S.I. engine
2. $\eta_{vol} = 85$ to 90% for C.I. engine
3. Gas engines have much low η_{vol}

Relative efficiency (or) efficiency ratio

$$\eta_{rel} = \frac{\text{Actual thermal efficiency}}{\text{air standard efficiency}}$$

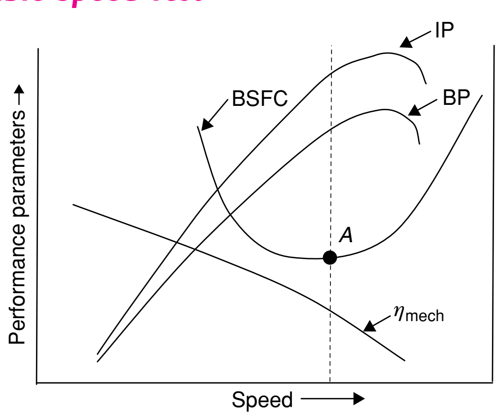
η_{rel} indicates the degree of development of the engine.

Table 2 *Measurement of Engine variables*

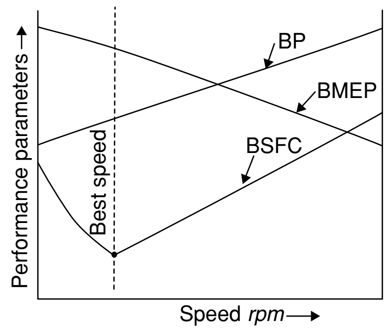
Variable	Method of measurement
1. Brake power	Dynamometer
2. Friction power	Morse test, motoring test, Willan's line method
3. Speed	Tachometer

Performance curves

Variable Speed Test



(a)



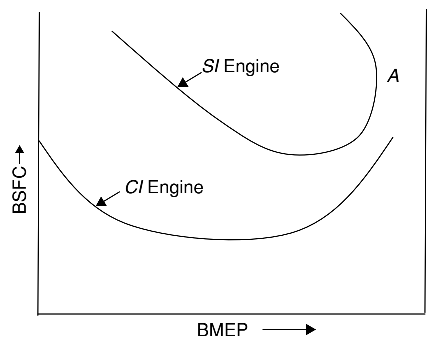
(b)

Figure 2 For S.I. engine.

In Figure 1 if the speed increases beyond point '*A*' the fuel consumption per bp will increase though more power output will obtained.

In Figure 2 speed where BSFC is minimum is called best speed.

Constant Speed Test



As shown in the above figure, the BSFC of S.I. engine first decreases with increasing load, attains minimum value and then starts increasing rapidly with further increase in load.

At point '*A*', the BSFC starts to loop backwards showing a drop in output but increase in fuel consumption.

This indicates that the mixture becomes too rich after point '*A*' and some of the fuel goes unburnt. This condition is called chocking.

Chocking occurs in S.I. engine.

NOTES

1. $(BSFC)_{SI} > (BSFC)_{C.I}$
2. $(\eta_{th})_{SI} < (\eta_{th})_{CI}$

Firing Order

The firing order is the sequence of power delivery of each cylinder in a multicylinder reciprocating engine.

No. of cylinders	Firing order
1. 4-cylinder	1 – 3 – 4 – 2 or 1– 4 – 3 – 2
2. 6-cylinder	1– 5 – 3 – 6 – 2 – 4 (or) 1 – 4 – 2 – 6 – 3 – 5
3. 8-cylinder	1 – 6 – 2 – 5 – 8 – 3 – 7 – 4 (or) 1 – 8 – 7 – 3 – 6 – 5 – 4 – 2

Hint

Example: 4-cylinder engine 1 – 2 – 3 – 4

1 – 2 – 3 – 4 Sequence of group is $\boxed{1 - 2 - 1}$

{1, 4 } → select first number, i.e., 1
{2, 3 } → select second number, i.e., 3
∴ 1 – 3 – 4 – 2

Example: 6-cylinder engine

1 – 2 – 3 – 4 – 5 – 6

Order of groups 1 – 2 – 1
{1, 6 } → first number, i.e., 1
{2, 5 } → second number, i.e., 5
{3, 4 } → first number, i.e., 3
∴ 1 – 5 – 3 – 6 – 2 – 4

Solved Examples

Example 1: The cubic capacity of 4-stroke over-square S.I. engine is 300 cm^3. The ratio of stroke to bore is 0.9. If the clearance volume is 30 cm^3 then the stroke (in cm) and compression ratio will be

(A) 7 and 10 (B) 8 and 12
(C) 7.5 and 11 (D) 7.5 and 12

Solution:

$$V_s = \frac{\pi}{4} d_2 L = \frac{\pi}{4} \times d^2 \times 0.9d = 300$$

$\therefore\ d = 7.515$ cm

Now stroke, $L = \dfrac{7.515}{1} \times 0.9 = 6.763$ cm

Compression ratio, $r = \dfrac{V_S + V_C}{V_C} = \dfrac{300 + 30}{30} = 11$

Example 2: If the mechanical efficiency of a single cylinder, 4-stroke engine is 85% and frictional power is 30 kW then the indicated power (kW) and brake power (in kW) are respectively

(A) 190 and 160 (B) 230 and 200
(C) 210 and 180 D) 200 and 170

Solution:

$$\eta_m = \frac{bp}{ip} = 0.85$$

$\Rightarrow bp = 0.85ip$
Now, $fp = ip - bp = 30$
$\therefore\ ip - 0.85ip = 30$
$\Rightarrow 0.15ip = 30 \Rightarrow ip = 200$ kW and $bp = 170$ kW

Example 3: A 4-stroke, 4-cylinder diesel engine running at 1200 rpm develops 70 kW. Given parameter are:

Brake thermal efficiency = 30%

Calorific value of fuel = 42,000 kJ/kg

Engine bore = 150 mm

Engine stroke = 120 mm

Air-fuel ratio = 15:1

Mechanical efficiency = 0.85

Density of air = 1.15 kg/m^3

Calculate

i. Fuel consumption (in kg/s)
(A) 3.33×10^{-3} (B) 3.77×10^{-3}
(C) 5.55 × 10–3 (D) 4.55 × 10–3

ii. Volumetric efficiency (in %)
(A) 91.37 (B) 85.42
(C) 89.34 (D) 94.36

iii. Brake mean effective pressure (in bar)
(A) 7.19 (B) 8.25
(C) 7.74 (D) 8.73

iv. Indicated power (in kW)
(A) 75.67 (B) 89.36
(C) 85.49 (D) 82.35

v. Air consumption (in m^3/s)
(A) 0.07246 (B) 0.06124
(C) 0.1294 (D) 0.007432

Solution:

(i) (C)
Fuel consumption

$$m_f = \frac{bp}{CV \times \eta_{bth}}$$

$$\Rightarrow \quad m_f = \frac{70}{42000 \times 0.3}$$

$m_f = 5.55 \times 10^{-3}$ kg/s

(v) (A)

Air consumption

$$m_a = \frac{m_f}{\rho a} \times \frac{A}{F} = \frac{5.55 \times 10^{-3} \times 15}{1.15}$$

$\Rightarrow m_a = 0.07246$ m^3/s

(iv) (D)
Indicated power

$$ip = \frac{bp}{\eta_m} = \frac{70}{0.85} = 82.35 \text{ kW}$$

(ii) (B)

Volumetric efficiency

$$\eta_v = \frac{\left(\frac{0.07246}{4}\right)}{\frac{\pi}{4}\times 0.15^2 \times 0.12 \times \frac{1200}{120}} \times 100$$

$\Rightarrow \quad \eta_v = 85.42\%$

(iii) (B)

$$P_{bm} = \frac{bp}{Lank}$$

$$= \frac{70\times 10^3}{0.12\times \frac{\pi}{4}\times 0.15^2 \times \frac{1200}{120}\times 4}$$

$\Rightarrow P_{\text{bm}} = 825247.85$ Pa or 8.25 bar

Exercises

Practice Problems I

1. An automobile engine operates at a fuel-air ratio of 0.06, volumetric efficiency of 90% and indicated thermal efficiency of 25%. Given that the calorific value of the fuels is 50 MJ/kg and the density of air at intake is 1.02 kg/m^3, the indicated mean effective pressure for the engine is
   (A) 0.675 bar (B) 6.75 bar
   (C) 67.5 bar (D) 675 bar
2. A gas engine has a swept volume of 320 CC and clearance volume of 27 CC. Its volumetric efficiency is 0.90 and mechanical efficiency is 0.85. The volume of the mixture taken in per stroke is
   (A) 288 CC (B) 300 CC
   (C) 320 CC (D) 272 CC
3. An engine produces 12 kW brake power while working with a brake thermal efficiency of 28%. If the calorific value of the fuel used is 45,000 kJ/kg then the fuel consumption in kg/hr is
   (A) 0.25 (B) 0.278
   (C) 2.5 (D) 3.428
4. For an engine operating on air standard Otto cycle, the clearance volume is 8% of the swept volume. The specific heat ratio of air is 1.4. The air standard cycle efficiency is
   (A) 61.67% (B) 63.25%
   (C) 64.67% (D) 70.01%
5. The stroke and bore of a 4-stroke spark ignition engine are 250 mm and 200 mm, respectively. The clearance volume is 0.001 m^3. If the specific heat ratio $\gamma = 1.4$, the air standard cycle efficiency of the engine is
   (A) 46.40% (B) 56.10%
   (C) 58.20% (D) 65.80%
6. During a Morse test on a 4-cylinder engine, the following measurements of brake power were taken at constant speed.

All cylinders firing	: 3037 kW
Number 1 cylinder not firing	: 2012 kW
Number 2 cylinder not firing	: 2012 kW
Number 3 cylinder not firing	: 2100 kW
Number 4 cylinder not firing	: 2098 kW

   The mechanical efficiency of the engine is
   (A) 81.07% (B) 85.07%
   (C) 91.53% (D) 95.25%
7. A 35 kW engine has mechanical efficiency of 85%. If the frictional power is assumed to be constant with load, what is the approximate value of the mechanical efficiency at 60% of rated load?
   (A) 45% (B) 55%
   (C) 65% (D) 75%
8. An IC engine gives an output of 3.5 kW when the input is 10,000 J/s. The thermal efficiency of the engine is
   (A) 35% (B) 36.5%
   (C) 60% (D) 66.6%
9. A 4-stroke gas engine has a bore of 25 cm and stroke of 35 cm and runs at 400 rpm firing every cycle. The air-fuel ratio is 4:1 by volume and volumetric efficiency on NTP basis is 85%. If the calorific value of the gas is 7.5 MJ/m^3 at NTP and the brake thermal efficiency is 30%, the brake power of the engine is
   (A) 7.54 kW (B) 21.9 kW
   (C) 25 kW (D) 30 kW
10. A single-cylinder engine running at 2,000 rpm develops a torque of 10 Nm. The indicated power of the engine is 4 kW. The loss due to friction power as the percentage of Indicated power is
    (A) 15.2% (B) 22.4%
    (C) 35.25% (D) 47.62%
11. The venturi of a simple carburetor has a throat diameter of 25 mm and the fuel orifice has a diameter of 2 mm. If density of air and fuel are 2 kg/m^3 and 900 kg/m^3, respectively, the air-fuel ratio, neglecting the co-efficient of flow is
    (A) 20 (B) 12.5
    (C) 7.36 (D) 5
12. The diameter of the piston of an oil engine which develops 35 kW under the following conditions is
    Mean effective pressure = 6.5 bar
    No of explosions/min = 80
    Ratio of stroke to dia = 2
    Mechanical efficiency = 80%
    (A) 318 mm (B) 350 mm
    (C) 420 mm (D) None

Direction for questions 13 to 15: The following results refer to a test on a petrol engine:

Indicated power = 35 kW

Brake power = 30 kW

Engine speed = 900 rpm

Fuel per brake power hour = 0.45 kg

Calorific value of the fuel used = 42,500 kJ/kg

13. The indicated thermal efficiency of the engine is
(A) 20% (B) 21.9%
(C) 23.5% (D) 25%

14. The brake thermal efficiency of the engine is
(A) 22.5% (B) 20.5%
(C) 18.8% (D) 18%

15. Mechanical efficiency of the engine is
(A) 85.71% (B) 86.2%
(C) 87.3% (D) 88%

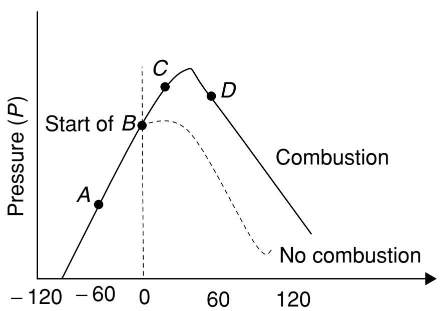
Practice Problems 2

1. A 2-stroke engine has speed of 750 rpm. A 4-stroke engine having an identical cylinder size runs at 1500 rpm. The theoretical output of the 2-stroke engine will
(A) be twice that of the 4-stroke engine.
(B) be half that of the 4-stroke engine.
(C) be the same as that of the 4-stroke engine.
(D) depend upon whether it is a C.I. or S.I. engine.

2. A 4-stroke diesel engine, when running at 2,000 rpm has an injection of duration 1.52 milliseconds. What is the corresponding duration of the crank angle in degrees?
(A) 9.5° (B) 15°
(C) 18.24° (D) 38°

3. A 4-cylinder engine running at 1200 rev/min gave output of 20 kW. The average torque when one cylinder was cut out was 105 Nm. Then the indicated thermal efficiency if calorific value of the fuel is 42,000 kJ/kg and the engine uses 0.25 kg petrol per kWh is
(A) 36% (B) 39.8%
(C) 40% (D) 46.8%

4. Hypothetical pressure diagram for a compression ignition engine is shown in the given figure. The diesel knock is generated during the period.



(A) *AB* (B) *BC*
(C) *CD* (D) after *D*

5. Match List-I (S.I. engine operating mode) and List-II (Desired air-fuel ratio) and select the correct answer using the codes given in the following lists:

List-I	List-II
a. Idling	1. 13.0
b. Cold starting	2. 4.0
c. Cruising	3. 16.0
d. Full throttle	4. 9.0

Codes:	a	b	c	d
(A)	4	3	2	1
(B)	2	4	1	3
(C)	4	2	1	3
(D)	4	2	3	1

6. A single-cylinder petrol engine working on 2-stroke cycle develops indicated power of 6 kW. If the mean effective pressure is 7.5 bar and piston diameter is 100 mm, the average piston speed in m/s is
(A) 125 (B) 122
(C) 120 (D) 118

Direction for questions 7 and 8: An IC engine rotates at 2,400 rpm. The 4-stroke engine has a cylinder bore diameter of 100 mm and crank radius of 100 mm. From indicator diagram mep is found as 100 kpa.

7. The indicated power of the engine in kW is
(A) 3.14 (B) 5.2
(C) 7 (D) 10.5

8. If mechanical efficiency is 80%, then its brake power in kW is
(A) 12.5 (B) 7.8
(C) 3.14 (D) 2.5

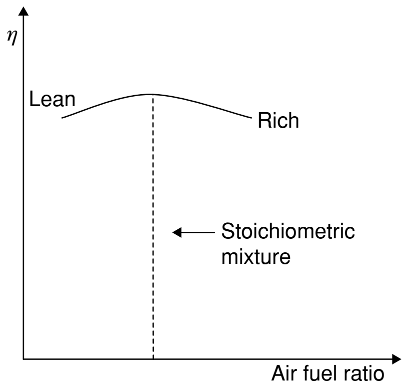
Direction for questions 9 and 10: A 4-stroke engine has a specific fuel consumption of 315 kg/bp/hr and its calorific value is 45×10^3 J/kg.

9. If the brake power developed by the engine is 2.5 kW the thermal efficiency of the engine is
(A) 30% (B) 25.3%
(C) 22.5% (D) 20%

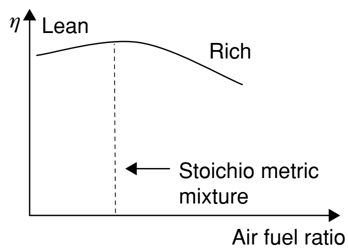
10. If the compression ratio is 6, the relative efficiency is
(A) 49.4% (B) 50.5%
(C) 52% (D) 58%

11. Which one of the following figures correctly represents the variation of thermal efficiency (y-axis) with mixture strength (x-axis)?

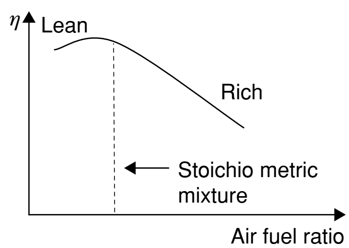
(A)



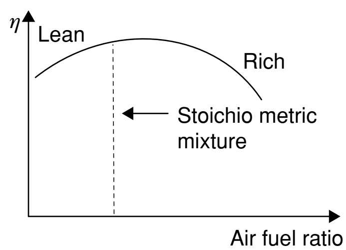
(B)



(C)



(D)



12. The volumetric efficiency of a well designed S.I. engine is in the range of

(A) 40%–50% (B) 50%–60%
(C) 60%–70% (D) 70%–90%

13. Match List-I with List-II and select the correct answer using the codes given below the lists.

List-I	List-II
a. Ignition quality of petrol	1. Aircraft engine
b. Heterogeneous combustion	2. C.I. engine
c. Morse test	3. Octane number
d. Super charging	4. Multi-cylinder engine

Codes:	a	b	c	d
(A)	1	2	3	4
(B)	2	1	3	4
(C)	3	2	4	1
(D)	3	2	1	4

14. The bore and stroke of the cylinder of a 6-cylinder engine working on an Otto cycle are 17 cm and 30 cm, respectively. If the total clearance volume is 9,225 cm^3, then what is the compression ratio?

(A) 7.8 (B) 6.2
(C) 15.8 (D) 5.4

15. The most popular firing order in case of 4-cylinder inline IC engine is

(A) 1 – 3 – 4 – 2 (B) 1 – 2 – 3 – 4
(C) 1 – 4 – 2 – 3 (D) 1 – 2 – 4 – 3

16. The intake charge in a diesel engine consists of

(A) air alone
(B) air + lubricating oil
(C) air + fuel
(D) air + fuel + lubricating oil

17. Disadvantage of reciprocating IC engine is

(A) use of fossil fuels
(B) vibration
(C) balancing problems
(D) All of the above

18. Gudgeon pin forms the link between

(A) piston and big end of connecting rod
(B) piston and small end of connecting rod
(C) connecting rod and crank
(D) bid end and small end

19. In a 4-stroke IC engine camshaft rotates at

(A) same speed as crankshaft
(B) twice the speed of crankshaft
(C) half the speed of crankshaft
(D) None of the above

20. Compression ratio in diesel engines is of the order of

(A) 5 – 7 (B) 7 – 10
(C) 10 – 12 (D) 14 – 20

21. Engines used for ships are normally

(A) 4-stroke S.I. engines of very high power
(B) 2-stroke C.I. engines of very high power
(C) 4-stroke C.I. engines of high speed
(D) 2-stroke S.I. engines of high power

22. Equivalence ratio is

(A) $\dfrac{\text{stoichiometric fuel-air ratio}}{\text{actual fuel-air ratio}}$

(B) $\dfrac{\text{actual fuel-air ratio}}{\text{stoichiometric fuel-air ratio}}$

(C) $\dfrac{\text{stoichiometric fuel-air ratio}}{\text{actual air-fuel ratio}}$

(D) None of these

23. If L is the stroke and N is the rpm, mean piston speed of 2-stroke engine is

(A) LN (B) $\frac{LN}{2}$
(C) $2LN$ (D) None of these

24. The range of volumetric efficiency of an engine is
(A) 65–75% (B) 75–85%
(C) 85–90% (D) 90–95%

25. The actual efficiency of a good engine is about _____of the estimates fuel-air cycle efficiency.
(A) 25% (B) 50%
(C) 85% (D) 100%

26. When the mixture is lean
(A) efficiency is less.
(B) power output is less.
(C) maximum temperature and pressure are higher.
(D) All of the above

27. The major loss in a C.I. engine is
(A) pumping loss
(B) rubbing friction loss
(C) direct heat loss
(D) loss due to incomplete combustion

28. The most preferred fuels for S.I. engines are
(A) aromatics (B) paraffin's
(C) olefins (D) naphthenes

29. Octane number of iso-octane is
(A) 100 (B) 60
(C) 30 (D) 0

30. Ignition quality of diesel fuel is indicated by its
(A) octane number (B) cetane number
(C) flash point (D) fire point

31. The most preferred fuels for C.I. engines are
(A) naphthenes (B) paraffin's
(C) olefins (D) aromatics

32. Stoichiometric air-fuel ratio of petrol is roughly
(A) 50:1 (B) 25:1
(C) 15:1 (D) 1:1

33. The choke is closed when the engine is
(A) idling (B) cold
(C) hot (D) accelerating

34. The limits of air-fuel ratio for S.I. engine are
(A) 50/1 to 100/1 (B) 25/1 to 50/1
(C) 8/1 to 50/1 (D) 8/1 to 18/1

35. The most important property of the lubricant is
(A) density
(B) viscosity
(C) thermal conductivity
(D) None of the above

Previous Years' Questions

1. At the time of starting, idling and low speed operation, the carburetor supplies a mixture, which can be termed as **[2004]**
(A) lean
(B) slightly leaner than stoichiometric
(C) stoichiometric
(D) rich

2. During a Morse test on a 4-cylinder engine, the following measurements of brake power were taken at constant speed:

All cylinders firing	3037 kW
Number 1 cylinder not firing	2102 kW
Number 2 cylinder not firing	2102 kW
Number 3 cylinder not firing	2100 kW
Number 4 cylinder not firing	2100 kW

The mechanical efficiency of the engine is **[2004]**
(A) 91.53% (B) 85.07%
(C) 81.07% (D) 61.22%

3. Air (ρ = 1.2 kg/m^3 and kinematic viscosity, $\delta = 2 \times 10^{-5}$ m^2/s) with a velocity of 2 m/s flows over the top surface of a flat plate of length 2.5 m. If the average value of friction coefficient is $C_f = \frac{1.328}{\sqrt{\mathrm{Re}_x}}$, the total drag force (in N) per unit width of the plate is ______. **[2015]**

4. Couette flow is characterized by: **[2015]**
(A) steady, incompressible, laminar flow through a straight circular pipe.
(B) fully developed turbulent flow through a straight circular pipe.
(C) steady, incompressible, laminar flow between two fixed parallel plates.
(D) steady, incompressible, laminar flow between one fixed plate and the other moving with a constant velocity.

5. Propane (C_3H_8) is burned in an oxygen atmosphere with 10% deficit oxygen with respect to the stoichiometric requirement. Assuming no hydrocarbons in the products, the volume percentage of CO in the products is _______. **[2016]**

Answer Keys

Exercises

Practice Problems 1

1. B	**2.** A	**3.** D	**4.** C	**5.** C	**6.** A	**7.** D	**8.** A	**9.** B	**10.** D
11. C	**12.** A	**13.** B	**14.** C	**15.** A					

Practice Problems 2

1. C	**2.** C	**3.** D	**4.** B	**5.** D	**6.** B	**7.** A	**8.** D	**9.** B	**10.** A
11. C	**12.** D	**13.** C	**14.** D	**15.** A	**16.** A	**17.** D	**18.** B	**19.** C	**20.** D
21. B	**22.** A	**23.** C	**24.** C	**25.** C	**26.** B	**27.** D	**28.** A	**29.** A	**30.** B
31. B	**32.** C	**33.** B	**34.** D	**35.** B					

Previous Years' Questions

1. B	**2.** A	**3.** 0.0158 to 0.0162	**4.** D	**5.** 14.2 to 14.3