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Mechanical Engineering

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Volume - 7

Thermodynamics Application (IC) & (RAC)

SIERRA INNOVATIONS

INDEX

1 CHAPTER Introduction to Internal Combustion Engine

THEORY

1.1 Heat Engines

A heat engine is a device which transforms the chemical energy of a fuel into thermal energy and used this energy to produce mechanical work. Heat engines are classified into two broad types :

(a) External combustion engines

(b) Internal combustion engines

1.1.1 External Combustion Engines

In an external combustion engine, the products of combustion of air and fuel transfer heat to a second fluid which is the working fluid of the cycle, as in the case of a steam engine or a steam turbine plant where the heat of combustion is employed to generate steam which is used in a piston engine or a turbine. Stirling engine is also an external combustion engine.

Advantage of External Combustion Engines :

- Use of cheaper fuels including solid fuels
- High starting torque.

1.1.2 Internal Combustion Engines

In an internal combustion engine, the products of combustion are directly the motive fluid. Petrol, gas, and diesel engines, Wankel engines and open cycle gas turbines are examples of internal combustion engines. Jet engines and rockets are also internal combustion engines.

Advantages of Internal Combustion Engines :

- Greater mechanical simplicity.
- Lower ratio of weight and bulk to output due to absence of auxiliary apparatus like boiler and condenser.
- Lower cost.
- Higher overall efficiency.
- Lesser requirement of water for dissipation of energy through cooling system.

1.2 Engine Components and Basic Engine Nomenclature

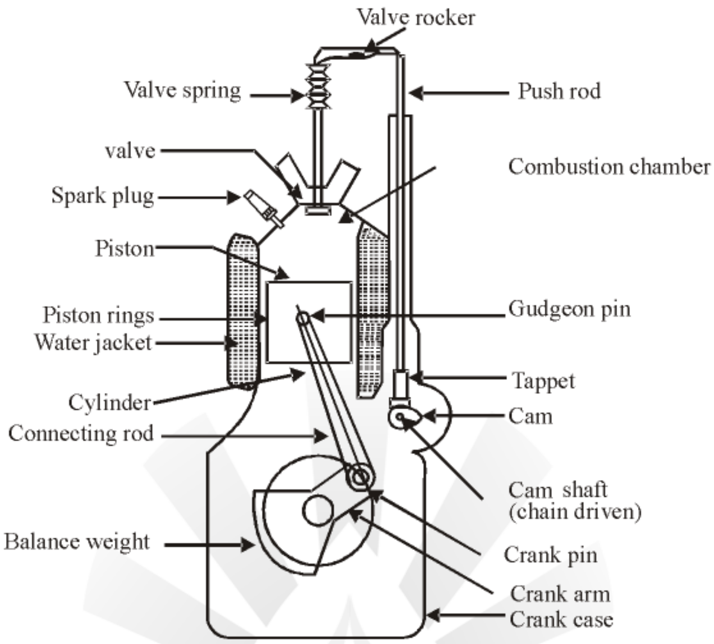


Fig Cross-section of spark-ignition engine

The figure shows the cross-section of a single cylinder spark-ignition internal combustion engine. The cylinder is supported in position by the cylinder block at the top end is covered by cylinder head.

In the cylinder, a piston travels in reciprocating motion. The space enclosed between the upper part of the cylinder and the top of the piston during the combustion process is called the combustion chamber.

(1) Spark Plug : The spark plug supplies the spark that ignites the air/fuel mixture so that combustion can occur. The spark must happen at just the right moment for things to work properly.

(2) Valves : The intake and exhaust valves open at the proper time to let in air and fuel and to let out exhaust. Note that both the valves are closed during compression and combustion so that the combustion chamber is sealed.

(3) Piston : A piston is a cylindrical piece of metal that moves up and down inside the cylinder.

(4) Piston Rings : Piston rings provide a sliding seal between the outer edge of the piston and the inner edge of the cylinder.

(5) The Rings Serve Two Purposes

(i) They prevent the fuel/air mixture and exhaust in the combustion chamber from leaking into the sump during compression and combustion.

(ii) They keep oil in the from leaking into the combustion area, where it would be burned and lost. Most cars that "burn oil" and have a quart added every 1,000 miles are burning it because the engine is old and the rings no longer seal things properly.

(6) Connecting Rod : The connecting rod connects the piston to the crankshaft. It can rotate at both ends so that its angle can change as the piston moves and the crankshaft rotates.

(7) Crank Shaft : The crank shaft turns the piston up and down motion into circular motion just like a crank on a jack-in-the-box does.

(8) Sump : The sump surrounds the crankshaft. It contains some amount of oil, which collects in the bottom of the sump (the oil pan.)

- A mixture of air and fuel enters the cylinder through the carburettor in spark-ignition engine via the inlet manifold i.e. the pipe which connects the inlet port of the engine of the air intake.
- In carburettor a throttle is provided to control the mass of mixture entering the combustion chamber. In the cylinder head there are inlet valves for taking the charge in the cylinder and exhaust valves for discharging the products of combustion. A spark plug near the top of the cylinder initiates the combustion.
- The energy of the expanding gas is transmitted by the piston (having piston rings to prevent leakage) through the gudgeon pin to the connecting rod.
- The connecting rod and the crank arm of the crankshaft translate the reciprocating motion of the piston into rotational motion of the crank shaft. The crankshaft is supported in bearings attached to the crankcase.
- The crankcase is the main body of the engine to which the cylinder is attached. The products of the combustion leave through exhaust port and exhaust manifold, both the intake and exhaust valves are operated by the valve mechanism.
- Crankshaft is driven by the crankshaft through timing gears. Lobed cams on the camshaft actuate the push rods and rocker arms for opening the valve against the force of valve springs.

1.3 The Standard Terminology Used in Internal Combustion Engines

(1) Cylinder Bore (D) : The nominal inner diameter of the working cylinder.

(2) Piston Area (A) : The area of a circle of diameter of the working cylinder.

Note : For an engine, in which a piston rod passes through the combustion space, as in a double-acting engine, this area must be reduced by the area of the cross-section of the piston rod

(3) Stroke (L) : The nominal distance through which a working piston moves between two successive reversals of its direction of motion.

(4) Dead Centre : The piston of the working piston and the moving parts which are mechanically connected to it at the moment when the direction of the piston motion is reversed (at either end point of the stroke).

(5) Bottom Dead Centre (BDC) : Dead centre when the piston is nearest to the crankshaft. In horizontal engines it is also called outer dead centre (ODC).

(6) Top Dead Centre (TDC) : Dead centre when the piston is farthest from the crankshaft. In horizontal engines it is also called inner dead centre (IDC).

(7) Displacement Volume or Piston Swept Volume (Vs) : The nominal volume generated by the working piston when travelling from one dead centre to next one, calculated as the product of piston area and stroke.

$$V_s = A \times L$$

(8) Clearance Volume (Vc) : The nominal volume of the space on the combustion side of the piston at top dead centre.

(9) Cylinder Volume (V) : The sum of piston swept volume and clearance volume.

$$V = V_S + V_C$$

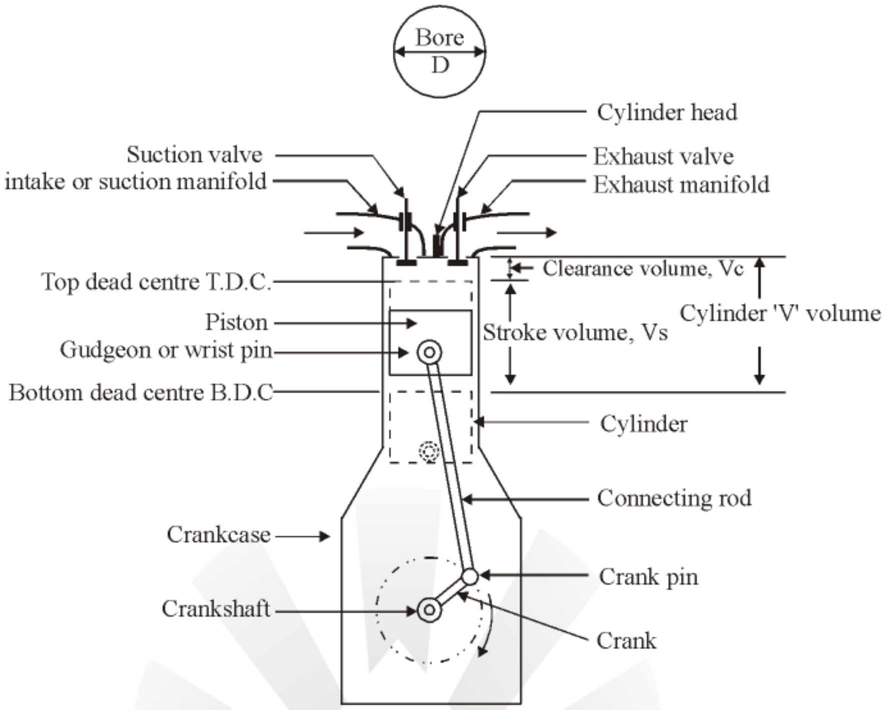


Fig. Important positions and volumes in reciprocating engine

(10) Compression Ratio (CR or r) : The numerical value of the cylinder volume divided by the numerical value of the combustion space volume or clearance volume.

$$\text{Compression ratio} = r = \frac{V}{V_c}$$

1.4 IC Engine Classification

- **Basic engine design :** Reciprocating engines, rotary (Wankel) engines.
- **Working cycle :** Engines working on Otto cycle (spark-ignition or S.I. engines), and engines working on diesel cycle (Compression -ignition or C.I. engines).
- **Number of strokes :** Four-stroke engines and two-stroke engines (both SI and CI engines).
- **Method of cooling :** Water cooled or air cooled.

1.5 Four-Stroke cycle spark-ignition engine

The cycle of operation is completed in four-strokes of the piston or two revolutions of the crankshaft. Each stroke consists of 180° of crankshaft rotation and hence a cycle consists of 720° of crankshaft rotation.

- **Suction Stroke :** Suction stroke 0-1 starts when the piston is at top dead centre and about to move downwards. The inlet valve is open at this time and the exhaust valve is closed. Due to the suction created by the motion of the piston towards bottom dead centre, the charge consisting of fresh air mixed with the fuel is drawn into the cylinder. At the end of the suction stroke the inlet valve closes.
- **Compression Stroke :** The fresh charge taken into the cylinder during suction stroke is compressed by the return stroke of the piston 1-2. During this stroke both inlet and exhaust valves remain closed.

The air which occupied the whole cylinder volume is now compressed into clearance volume. Just before the end of the compression stroke the mixture is ignited.

- **Expansion or Power Stroke :** Due to high pressure the burnt gases force the piston towards bottom dead centre, stroke 3-4, both the inlet and exhaust valves remains closed. Thus, power is obtained during this stroke. Both pressure and temperature decrease during expansion.

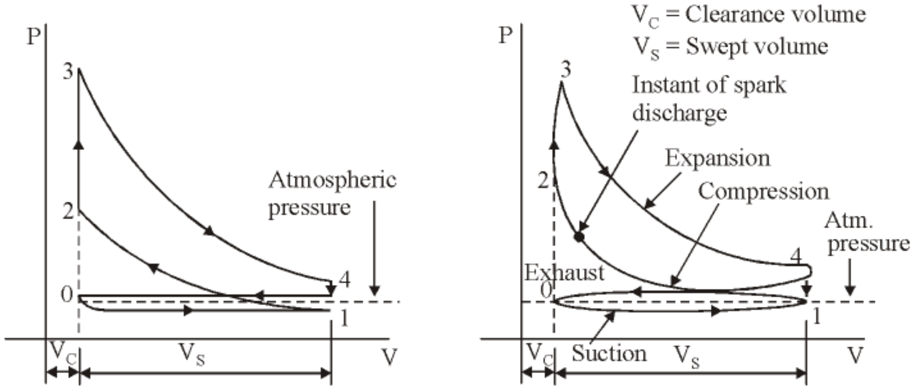
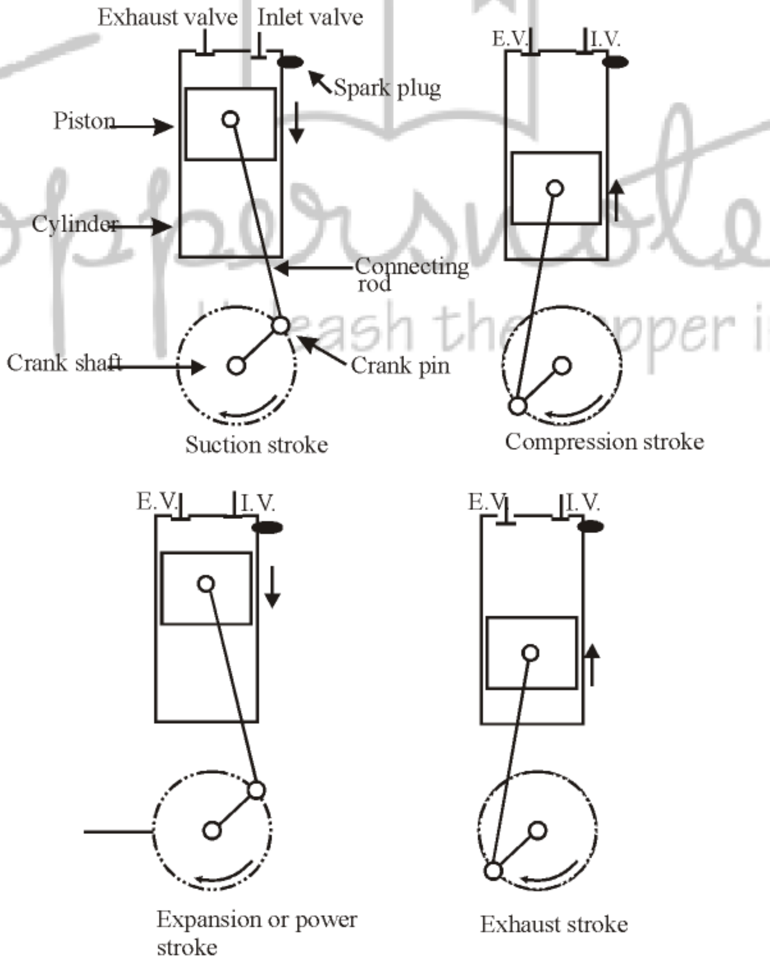


Fig. Ideal and actual indicator diagrams for four-stroke SI engine

- **Exhaust Stroke :** At the end of the expansion stroke the exhaust valve opens, the inlet valve remains closed, and the piston is moving form bottom dead centre to top dead centre sweeps out the burnt gases from the cylinder, stroke 4-0.



Stroke	Valve position
Suction stroke.	Suction valve open. Exhaust valve closed.
Compression stroke.	Both valve closed.
Expansion stroke.	Both valves closed.
Exhaust stroke.	Exhaust valve open. Suction valve closed.

Note : *The exhaust valve closes at the end of the exhaust stroke and some 'residual' gases remain in the cylinder. One revolution of the crankshaft occurs during the suction and compression stroke, and second revolution during the power and exhaust strokes.*

Most of the spark-ignition internal combustion engines are of the four-stroke type.

Acutal Valve timing of four-stroke Petrol Engine

Valve timing is the regulation of the points in the cycle at which the valves are set to open and close. As described above in the ideal cycle inlet and exhaust valves open and close at dead centres, but in actual cycles they open or close before or after dead centres as explained below.

There are two factors, one mechanical and other dynamic, for the actual valve timing to be different from the theoretical valve timing.

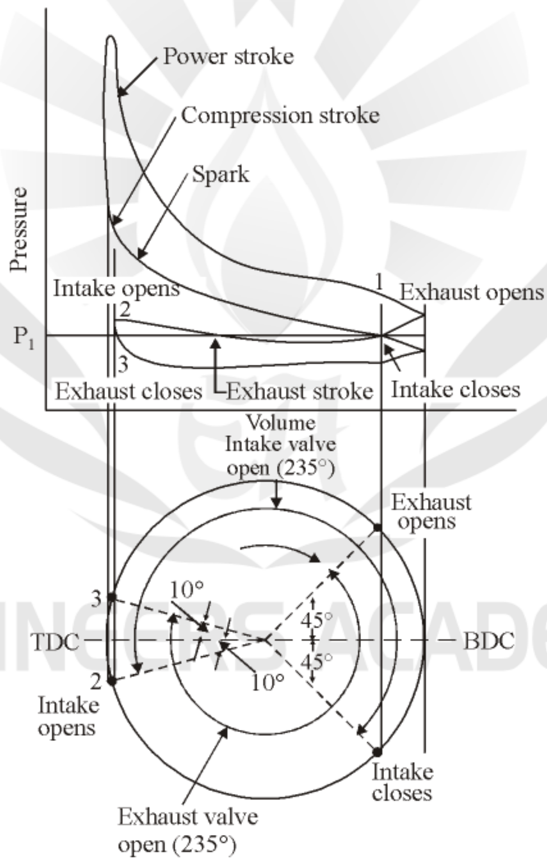


Fig. Four-stroke petrol engine valve timing diagram in relation to the pressure volume diagram

1.6 Four-Stroke Compression Ignition (CI) Engines

Due to high compression ratio, the temperature at the end of compression stroke is sufficient to ignite the fuel which is injected into the combustion chamber. In the CI engine a high pressure fuel pump and an injector is provided to inject fuel into combustion chamber.

- **Suction Stroke :** Only air is inducted during the suction stroke. During this stroke intake valve is open and exhaust valve is closed.
- **Compression Stroke :** Both valves remain closed during compression stroke.
- **Expansion or Power Stroke :** Fuel is injected in the beginning of the expansion stroke. The rate of injection is such that the combustion maintains the pressure constant. After the injection of fuel is over (i.e. after fuel cut-off) the products of combustion expand. Both valves remains closed during expansion stroke.
- **Exhaust Stroke :** The exhaust valve is open and the intake valve remains closed in the exhaust stroke.

The typical valve timing diagram of a four-stroke CI engine is as follows :

IVO up to 30° before TDC

IVO up to 50° after BDC

EVO about 45° before BDC

Injection about 15° before TDC

1.7 Two-Stroke Engine

The cycle is completed in two stroke, i.e., one revolution of the crankshaft as against two revolutions of four-stroke cycle. the difference between two-stroke and four-stroke engines is the method of filling the cylinder with the fresh charge and removing the burned gases from the cylinder. In a four-stroke engine, the operations are performed by the engine piston during the suction and exhaust strokes, respectively. In a two stroke engine, suction is accomplished by air compressed in crankcase or by a blower. The induction of compressed air removes the products of combustion through exhaust ports.

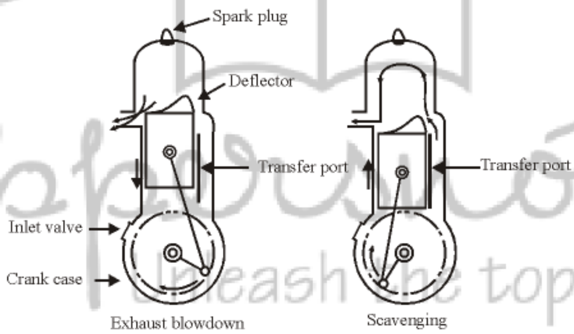


Fig. Crankcase-scavenged two-stroke engine.

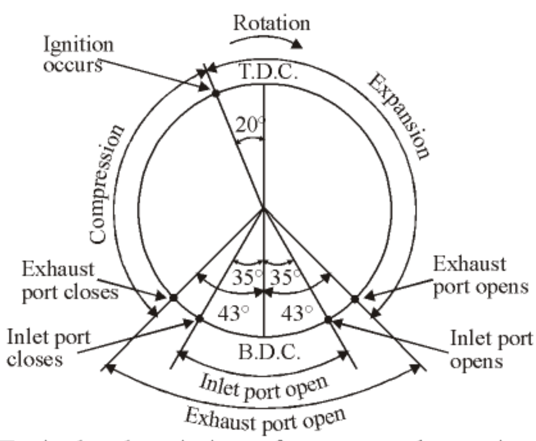


Fig. Typical valve timing of a two-stroke engine

1.8 Table Comparison of Four-Stroke and Two-Stroke Cycle Engines

	Four-stroke cycle	Two-stroke cycle
1.	The cycle is completed in four strokes of the piston or in two revolutions of the crankshaft. Thus, one power stroke is obtained in every two revolutions of the crankshaft.	The cycle is completed in two stroke of the piston or in one revolution of the crankshaft. Thus, one power stroke is obtained in each revolution of the crank-shaft.
2.	Because of the above, turning moment is not so uniform and hence heavier flywheel is needed.	More uniform turning moment and hence lighter flywheel is needed.
3.	Again, because of one power stroke for two revolutions, power produced for same size of engine is small, or for the same power the engine is heavy and bulky.	Because of one power stroke for one revolution, the power produced for same size of engine is more (theoretically twice, actually about 1.3 times), or for the same power the engine is light and compact.
4.	Because of one power stroke in two revolutions lesser cooling and lubrication requirements. Lesser rate of wear and tear.	Because of one power stoke in one revolution greater cooling and lubrication requirement. Greater rate of wear and tear.
5.	The four-stroke engine contains valves and valve mechanisms.	Two-stroke engines have no valves but only ports (some two stroke engines are fitted with conventional exhaust valve or reed valve).
6.	Because of the heavy weight and complication of valve mechanism, higher in initial cost.	Because of light weight and simplicity due to the absence of valve mechanism, cheaper in initial cost.
7.	Volumetric efficiency more due to greater time of induction	Volumetric efficiency less due to lesser time for induction.
8.	Thermal efficiency higher, part load efficiency better than two-stroke cycle engine.	Thermal efficiency lower, part load efficiency lesser than four-stoke cycle engine. In two-stroke petrol engines some fuel is exhausted during scavenging.
9.	Used where efficiency is important, in cars, buses, trucks, tractors, industrial engines, aero planes, power generation, etc.	Used were (a) low cost, and (b) compactness and light weight important. Two-stroke (air-cooled) petrol engines used in very small sizes only: lawn movers, scooters, motor cycles, mopeds etc. (lubricating oil mixed with petrol). Two-stroke diesel engines used in very large sizes, more than 60 cm bore, for ship propulsion because of low weight and compactness.

1.9 Table Comparison of SI and CI Engines

Description	SI Engine	CI engine
1. Basic cycle	Based on Otto cycle.	Based on Diesel cycle.
2. Fuel	Petrol (Gasoline). High self-ignition temperature desirable.	Diesel oil. Low self-ignition temperature desirable.
3. Introduction of fuel	Fuel and air introduced as a gaseous mixture in the suction stroke. Carburetor necessary to provide the mixture in the suction stroke. Carburetor necessary to provide the mixture-(except in not so common petrol injection engines). Throttle controls the quantity of mixture introduced.	Fuel is injected directly into combustion chamber at high pressure at the end of compression stroke. Carburetor is eliminated but a high pressure fuel pump and injector necessary. Quantity of fuel regulated in pump.
4. Ignition	Requires an ignition system with spark plug in the combustion chamber.	Self ignition due to high temperature caused by high compression of air, when fuel is injected. Ignition system and spark plug is eliminated.
5. Compression ratio range	6 to 10.5 Upper limit of C.R. fixed by antiknock quality of fuel.	14 to 22. Upper limit of C.R. is limited by the rapidly increasing weight of the engine structure as the compression ratio is further increased.
6. Speed	Higher maximum revolution per minute due to lighter weight.	Maximum r.p.m. lower.
7. Efficiency	Maximum efficiency is lower due to low compression ratio.	Higher maximum efficiency due to higher compression ratio.
8. Weight	Lighter	Heavier due to higher pressures.

1.10 Applications of IC Engines

- **Small Two-Stroke Petrol Engine :** Used where simplicity and low cost of the prime mover are the main considerations.
- **Small Four-Stroke Petrol Engines :** The most important application of small four-stroke petrol engines is in automobiles.
- **Radial Piston Engine in Small Aircraft Propulsion :** The small aircrafts generally use radial four-stroke petrol engines.

  Note : The modern large aircrafts use gas turbine plant as turboprop engine or turbojet engine,
- **Four-Stroke Diesel Engines :** The four-stroke diesel engine is one of the most versatile prime mover. It is manufactured in diameters from 5 cm to 60 cm.

  Diesel engines have been installed in many cars, particularly taxies. Diesel engines are used in diesel-hydraulic and diesel-electric locomotives. Diesel engines are also used in boats and in ships.
- **Two-Stroke Diesel Engines :** Very high power diesel engines for ship propulsion are generally two-stroke diesel engines. In fact, all engines over 60 cm bore are two-stroke engines.

1.11 First Law Analysis of Engine Cycle

- Fuel is fed in the combustion chamber where it burns in air, converting its chemical energy into heat. The whole of this energy cannot be utilized for driving the piston as there are losses to the exhaust, to the coolant, and to radiation. The remaining energy, converted to power is called the indicated power (ip). This is utilized to drive the piston.
- The energy applied to the piston passes through the connecting rod to the crankshaft. In this transmission there are energy losses due to friction, pumping etc. The sum of all these losses, converted to power, is termed as friction power (fp).
- The remaining energy is the useful mechanical energy, it is termed brake power (bp).

$$bp = ip - fp$$

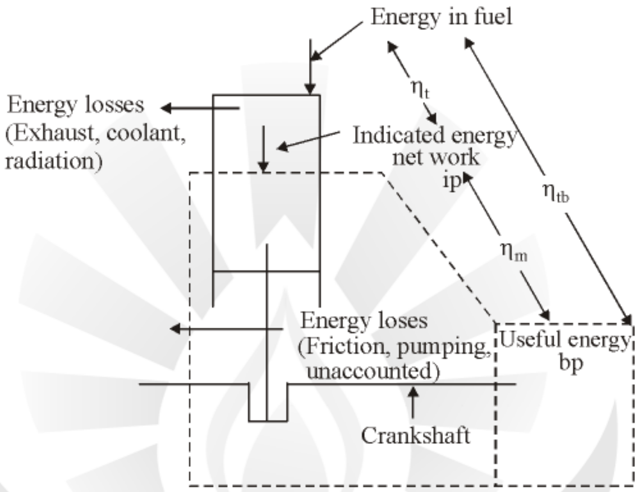


Fig. Energy flow through the reciprocating system

1.12 Thermal Efficiency

1.12.1 Indicated Thermal Efficiency (η_{it})

Indicated thermal efficiency is the ratio of energy in the indicated horse power to the fuel energy.

$$\eta_{it} = \frac{\text{Energy equivalent of the ip / s}}{\text{Energy supplied by fuel/s}}$$

$$= \frac{ip}{m_f \times Q_{LHV}}$$

Where, m = mass of fuel/s (volume in case of gaseous fuel)

Q_{LHV} = Lower calorific value of fuel

Thus, fuel consumption is inversely proportional to power.

1.12.2 Brake Thermal Efficiency (η_{bt})

Brake thermal efficiency is the ratio of energy in the brake power to the fuel energy.

$$\eta_{bt} = \frac{\text{energy equivalent of bp/s}}{\text{energy supplied by fuel /s}}$$

or

$$= \frac{b.p.}{m_f \times Q_{LHV}}$$

1.12.3 *Mechanical Efficiency* (η_m)

The mechanical efficiency of an engine is defined as ratio of brake power (delivered power) to the indicated horsepower (power provided to the piston).

$$\eta_m = \frac{b.p}{i.p.}$$

$$= \frac{\eta_{b.t}}{\eta_{i.t}}$$

or $$\eta_{b.t} = \eta_m \times \eta_{i.t}$$

1.12.4 *Volumetric Efficiency* (η_v)

The engine output is limited by the maximum amount of air that can be taken in during the suction stroke, because only a certain amount of fuel can be burned effectively with a given quantity of air.

$$\eta_v = \frac{\text{mass of charge actually indicated}}{\text{mass of charge represented by cylinder volume at intake temperature and pressure condition}}$$

$$\eta_v = \frac{\text{charge aspirated per stroke reduced to intake conditions}}{\text{swept volume}} = \frac{V}{V_S}$$

1.12.5 *Specific Fuel Consumption (sfc)*

Brake specific fuel consumption and indicated specific fuel consumption, abbreviated as bsfc and isfc.

$$\text{bsfc} = \frac{\text{Fuel used in kg/h}}{\text{b.p. in kW}} = \frac{m_f}{\text{b.p.}} \text{kg / kWh}$$

$$\text{isfc} = \frac{\text{Fuel used in kg/h}}{\text{i.p. in kW}} = \frac{m_f}{\text{i.p.}} \text{kg / kWh}$$

1.12.6 *Fuel-Air (F/A) or Air-Fuel(A/F) Ratio*

This is expressed either as the ratio of the mass of the fuel to that of the air or *vice versa*.

$$\frac{F}{A} = \frac{m_f}{m_a}$$

$$\frac{A}{F} = \frac{\dot{m}_a}{\dot{m}_f}$$

Example :

Distinguish between the swept and clearance volume of a reciprocating engine. Define compression ratio. The engine of the fiat car has four cylinders of 68 mm bore and 75 mm stroke. The compression ratio is 8. Determine the cubic capacity of the engine and the clearance volume of each cylinder.

Solution :

Swept volume of one cylinder is

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

$$= \frac{\pi}{4}(6.8)2 \times 7.5$$

$$= 272.38 \text{ cm}^3 \text{ (or c.c)}$$

Cubic capacity of the engine

= Total swept volume of all cylinders

$= 272.38 \times 4 = 1089.5 \text{ cm}^3$ **Ans.**

Compression ratio is

$$r = \frac{V}{V_c}$$

$$= \frac{V_c + V_s}{V_c}$$

$$8 = 1 + \frac{V_s}{V_c}$$

or $$\frac{V_s}{V_c} = r - 1$$

$$\frac{V_s}{V_c} = 8 - 1 = 7$$

Thus, clearance volume of each cylinder is

$$V_c = \frac{V_s}{7}$$

$$= \frac{272.38}{7} = 38.9\text{cm}^3$$

Example :

A diesel engine develops 5 kW. Its indicated thermal efficiency is 30% and mechanical efficiency 57%. Estimate the fuel consumption of engine in (a) kg/hr, (b) liters/hr, (c) indicated specific fuel consumption, and (d) brake specific fuel consumption.

Solution :

Mechanical efficiency, $$\eta_m = \frac{\text{b.p.}}{\text{i.p.}}$$

$\therefore \quad \text{i.p.} = \frac{\text{b.p.}}{\eta_m}$

$$= \frac{5}{0.75} = 6.67$$

Indicated thermal efficiency

$$\eta_{it} = \frac{\text{i.p.}}{\dot{m}_f \times \text{C.V.}}$$

$$\therefore \quad 0.30 = \frac{6.67 \times 3600}{\dot{m}_f / \text{hr} \times 42,000}$$

$\therefore$ Fuel consumption

(a) $$\dot{m}_f = \frac{6.67 \times 3600}{0.30 \times 42000}$$

$$= 1.905 \text{ kg/hr}$$ **Ans.**

(b) Fuel consumption in litres per hr

$$\dot{\upsilon}_f = \frac{\text{mass}}{\text{density}}$$

$$= \frac{1.905}{0.87} = 2.19 l/\text{hr}$$ **Ans.**

(c) Indicated specific fuel consumption

$$\text{i.s.f.c.} = \frac{\dot{m}_f}{\text{i.p.}}$$

$$= \frac{1.905}{6.67} = 0.286 \text{ kg/kWh}$$ **Ans.**

Brake specific fuel consumption

$$\text{b.s.f.c.} = \frac{\dot{m}_f}{\text{b.p.}}$$

$$= \frac{1.905}{5} = 0.381 \text{ kg/kWh}$$ **Ans.**

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