Thermal Engineering- I

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THERMODYNAMIC CONCEPT & TERMINOLOGY

Thermodynamics is the branch of Science which deals with energy transformations and relationships between the properties of the Working Substance. These transformations are governed by the various Laws of Thermodynamics.

Thermodynamic System

A prescribed region in space or a finite ~~quali~~ quantity of matter under Consideration for its thermodynamic study is known as a Thermodynamic System.

An envelope enclosing the system is known as Boundary of the system.

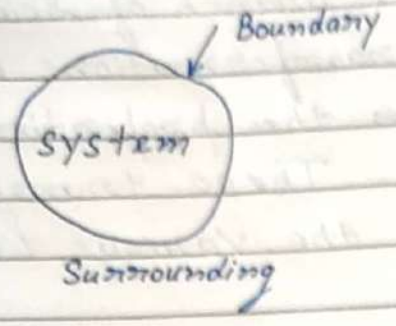
Everything external to the system is known as Surrounding.

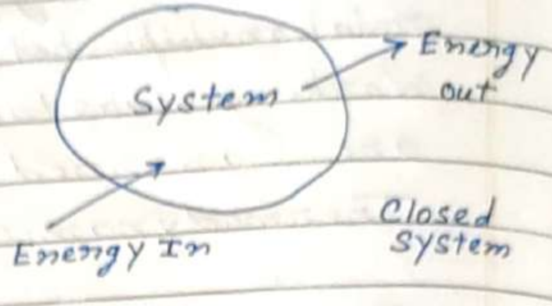
Types of Thermodynamic System

Closed System

It is the thermodynamic system in which the mass Comprising the system is not allowed to Cross the boundary of the system. So no mass Can enter or leave the system and only energy (Heat and work) transfer takes place.

Eg: Piston cylinder



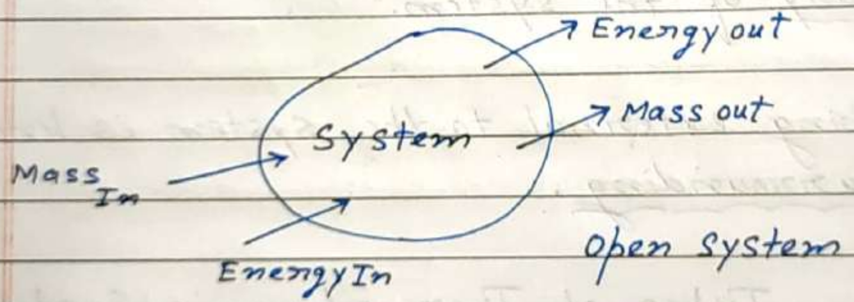


Closed System

Open System

It is the thermodynamic system in which mass and energy of the system are allowed to cross the boundary of the system.

Eg: Turbine, IC Engine



Open system

Isolated System

It is the thermodynamic system in which both mass and energy are not allowed to cross the boundary of the system.

Eg: Thermoflask Bottle

Properties of the System

The property of the system is defined as the fixed characteristic which describes the current state of the system. Pressure, Volume, Temperature, Internal energy and enthalpy are some of the examples of the properties of the system.

Pressure

The pressure is defined as the force per unit area exerted by body on its surface in a direction normal to the surface.

Absolute pressure is the sum of gauge pressure and atmospheric pressure.

$$P_{abs} = P_{atm} + P_{gauge}$$

Gauge pressure is the amount by which the pressure measured in a system exceeds that of the atmospheric pressure.

SI unit of pressure = Newton/square meter or Bar.

$1 \text{ Bar} = 10^5 \text{ N/m}^2$

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Volume

It is the spaced occupied by any working substance in a thermodynamic process.

SI unit : m^3

Temperature

It is an intensive thermodynamic property which determines the hotness or the level of heat intensity of a body.

$°F = 1.8 °C + 32$, $°C = (°F - 32) \div 1.8$

$K = °C + 273$

°C = Celcius, °F = Fahrenheit, K = Kelvin

Enthalpy

It is the sum of the internal energy and the product of the ~~sum~~ pressure and volume of a thermodynamic system.

$$\boxed{H = E + PV}$$

H = Enthalpy, E = Internal Energy

P = Pressure V = Volume

SI unit = Joule

Internal Energy

It is the energy possessed by a system due to its molecular arrangement and activity. It is denoted by E or U.

SI unit = Joule

Entropy

A thermodynamic quantity representing the unavailability of a system's thermal energy ~~for~~ or its the measure of a system's thermal energy per unit temperature that is unavilable for doing useful work.

SI unit: Joules per kelvin (J/k)

Intensive properties

The properties of a system, which are independest of its mass. eg: Temperature, pressure, and density.

Extensive properties

The properties of a system, which are dependent on its mass such as volume, ~~m~~ length, energy etc are known as Extensive properties.

Thermodynamic process

Defined by change in a system, a thermodynamic process is a passage of a thermodynamic system from an initial to a final state of thermodynamic equilibrium.

Path

The succession of states passed through, during a change of state of working substance is called the path.

Cycle

A thermodynamic cycle is defined as a series of state changes such that the final state is identical with the initial state.

Path Function

A path function is a function whose value depends on the path followed by the thermodynamic process irrespective of the initial and final states of the process.

eg: Work done, heat transfer.

Point Function

A point function is a function whose value depends on the final and initial states of the thermodynamic process, irrespective of the path ~~they~~ followed by the process.

eg: Density, enthalpy, internal energy, entropy etc

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Thermodynamic Equilibrium

A thermodynamic system which is in equilibrium; thermally, mechanically as well as chemically is called Thermodynamic Equilibrium.

Quasi-static process

The word quasi means almost and static means rest or constant. So a quasi-static process may be defined as the process during which the equilibrium of the system is almost maintained from its initial state to the final state.

Heat

The heat is defined as the energy transferred, without transfer of mass across the boundary of a system because of a temperature difference between the system and the surroundings.

SI unit of heat is Joule (J)

* The heat can be transferred in three distinct ways that is conduction, convection and radiation.

Work

In mechanics, work is defined as the product of the force (F) and the distance moved (x) in the direction of the force.

Work = Force × distance moved

$= F \times x$

SI unit of Work is 1 N-m = 1 Joule

Comparison of Heat and Work

There are many similarities between Work and heat.

1. The heat and Work are both boundary phenomena.
2. The heat and Work represent the energy crossing the boundary of the system.
3. The both heat and work are path function

Energy

In thermodynamic Energy is the capacity of a physical system to do work. In physics the energy is defined as the capacity to do work. Energy in thermodynamics and physics are ~~th~~ totaly different.

Different Forms of Stored Energy

In thermodynamics, energy can be in two forms:

① Energy in transit ② Energy in Storage

* Work and heat intractions are the forms of energy in transit and it is observed at the boundary of the system.

* Energy in storage can be classified as

① Macroscopic energy ② Microscopic energy

The macroscopic energy mode includes the kinetic energy and potential energy.

$$\text{kinetic energy} = \frac{1}{2} mv^2$$
$$\text{Potential energy} = mgh$$

The microscopic energy mode refers to the energy stored in the molecule and atomic structure of the system, which is called the internal energy.

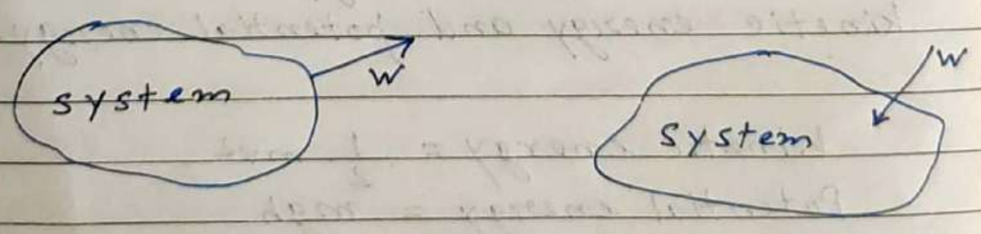
The mechanical equivalent of heat states that motion and heat are mutually interchangeable and that in every case, a given amount of work would generate the same amount of heat, provided the work done is ~~totte~~ totally converted to heat energy.

Work Transfer

The work is done by a force as it acts upon a body moving in the direction of the force.

Work is said to be done by a system if the sole effect on things external to the system can be reduced to the raising of a weight.

When work is done by a system, it is taken as positive and when work is done on a system it is taken as negative.



(Work is +ve) (Work is -ve)

SI unit = N.m or Joule

Difference between Heat & Work

1. Heat is energy interaction due to temperature difference. Work is energy interaction by reasons other than temperature difference.

2. Heat is low grade energy while work is high grade energy.

3. Efficiency of transfer of work to heat is higher but efficiency of transfer of heat is low.

Similarities between heat & Work

1. Both heat and work are path function.

2. Both heat and work are boundary phenomena

3. The heat and work is form of energy and both of them have same SI unit Joule.

4. Both heat and work cannot be stored by system.

Displacement Work in various processes

- Constant pressure process

$$W_{1-2} = \int_{V_1}^{V_2} p\,dV = P(V_2 - V_1)$$

- Constant volume process

$$W_{1-2} = \int p\,dV = 0$$

- Constant temperature or isothermal process

$$W_{1-2} = P_1 V_1 \int_{V_1}^{V_2} \frac{dV}{V} = P_1 V_1 \ln \frac{V_2}{V_1} = P_1 V_1 \frac{P_1}{P_2}$$

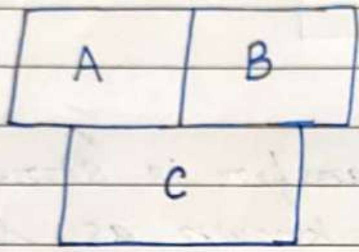
- Adiabatic Process $(PV^n = C)$

$$W_{1-2} = \frac{P_1 V_1 - P_2 V_2}{n - 1}$$

Laws of thermodynamics

Zeroth Law of thermodynamics

This law states that, if two bodies are in thermal equilibrium with a third body separately, then they are also in thermal equilibrium with each other.



If A is in thermal equilibrium with C and B is in thermal equilibrium, then A and B are also in thermal equilibrium with each other

First law of thermodynamic

It states that heat is a form of energy and thermodynamic processes are therefore subject to the principle of conservation of energy. This means that heat can neither be created nor can destroyed, it changes from one form to another form.

In other words the first law of thermodynamics states that " When a thermodynamic system executes a cyclic process, the algebraic sum of the work transfers is propertional to the algebraic sum of the heat transfers".

* The heat and mechanical Work are mutually convertible.

In a cyclic process

$$\oint \delta Q = \oint \delta W$$

* The net energy transfer is stored within the system and it is known as stored energy or Internal energy of the system.

$$\delta Q - \delta W = dE$$

Q = Heat energy, W = Work done, E = Internal Energy

Limitations of First law of thermodynamics

① It does not help to predict whether the certain process is possible or not.

Explanation: It does not specify that heat can not flow from low temperature body to a high temperature body.

② This law does not say anything about the direction of the flow of heat.

Explanation: It put no restriction on the direction of the flow of heat, whether heat can flow from a cold body to a hot body or vise versa.

③ It does not provide and specify whether a process ~~can~~ is reversible or not. It does not tell about how much percentage of one form of energy can be converted to another form of energy.

Explanation: Work can be converted into equivalent amount of heat but heat cannot be converted into equivalent amount of work.

First law of thermodynamics for an open system

1st law of thermodynamics can be written as:

$$Q = \Delta E + W$$

E is the total energy of the system.

$$E = E_k + E_p + U$$

where E_k = kinetic energy, E_p = Potential Energy and U is the internal Energy

So now the eqn becomes

$$Q = \Delta E_k + \Delta E_p + U + W$$

Throttling process

When a gas or vapour is expanded through an aperture of minute (narrow) dimensions like valve, which is very slightly opened, the process is called throttling process.

Work done ⇒ $W = 0$
Heat supplied ⇒ $Q = 0$
Change in internal energy ⇒ $U = 0$

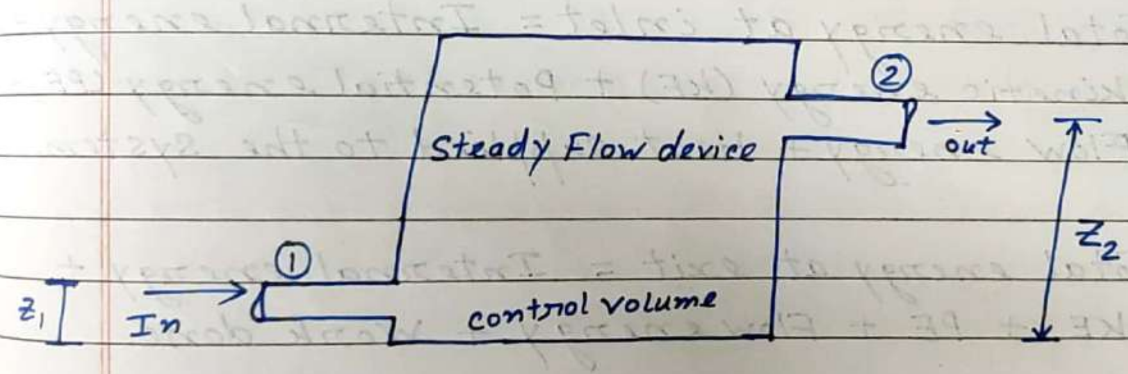
Free Expansion

In this process the fluid expands suddenly into a vaccuum chamber, through an orifice of large dimension.

No heat is supplied or rejected, there is no work done and during the process the temperature remains constant, so in the free expansion process

$$W = 0, \quad Q = 0 \quad \text{and} \quad \Delta U = 0$$

Steady Flow Energy Equation (SFEE)



m = Mass flow rate of the working substance in kg/s at intel and outlet

P_1, P_2 = Absolute pressure of the working substance in N/m^2.

V_1, V_2 = Velocity of the working substance in m/s.

v_1, v_2 = Specific volume in m^3/kg.

Z_1, Z_2 = Height above the datum in m at inlet and outlet.

U_1, U_2 = Specific internal energy in J/kg

Q = Quantity of heat introduced into the system in J.

Q = Heat W = Work

From the law of conservation of energy:

Total energy at inlet = Total energy at outlet.

Total energy at inlet = Internal energy + kinetic energy (KE) + Potential energy (PE) + Flow energy + Heat supplied to the system.

Total energy at exit = Internal energy + KE + PE + Flow energy + Work done.

So,
$$m\left[U_1 + \frac{v_1^2}{2} + gz_1 + P_1v_1\right] + Q = m\left[U_2 + \frac{v_2^2}{2} + gz_2 + P_2v_2\right] + W$$

We know that $\boxed{h = U + Pv}$,

So,
$$m\left[h_1 + \frac{v_1^2}{2} + gz_1\right] + Q = m\left[h_2 + \frac{v_2^2}{2} + gz_2\right] + W$$

This is the Steady Flow energy Equation.

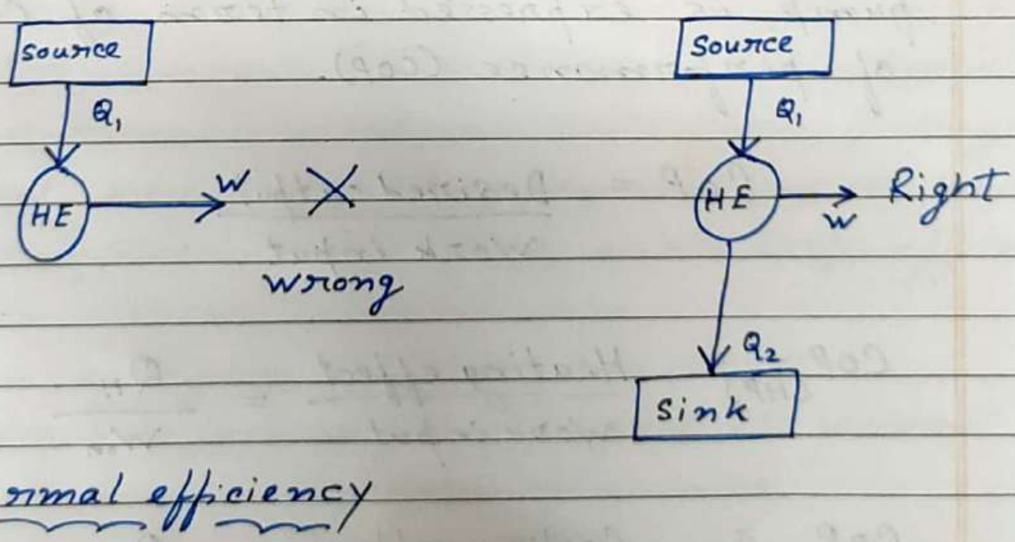
Second Law of Thermodynamics

The Second Law of thermodynamics states that the total entropy of an isolated system never decrease over time and it is constant if and only if all processes are reversible.

Kelvin - Plank Statement

It states that it is impossible to construct an engine working on a cyclic process whose sole purpose is to convert all the heat energy supplied to it into an equivalent amount of mechanical Work.

It is impossible for any device that operates on a cycle to receive heat from a single reservoir and produce a net amount of work. In other words, no heat engine can have a thermal efficency of 100%.

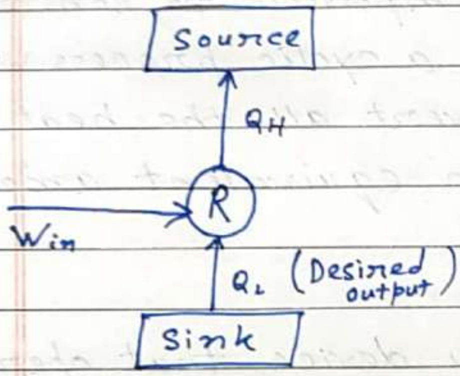


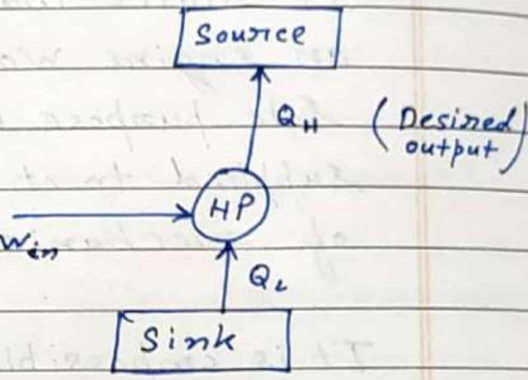
Thermal efficiency

$$\eta = \frac{\text{Heat converted into Work}}{\text{Heat input or supplied}} = \frac{W}{Q_s}$$

Clausius Statement

It states that "Heat flows from a hot body to a Cold body naturally, but it is impossible for heat to flow from a cold body to a hot body without the aid of external Work."





Coefficient of performance (COP)

The performance of refrigerator and Heat pump is expressed in term of coefficient of performance (COP).

$$CoP = \frac{\text{Desired output}}{\text{Work input}}$$

$$CoP_{(HP)} = \frac{\text{Heating effect}}{\text{Work input}} = \frac{Q_H}{W_{in}}$$

$$CoP_{(R)} = \frac{\text{Cooling effect}}{\text{Work input}} = \frac{Q_L}{W_{in}}$$

Perpetual motion machine of the 1st kind

The 1st Law of Thermodynamics states that Energy can neither be created nor destroyed but it can be transformed from one form to another.

There can be no machine which would continuously supply mechanical work without some other form of energy disappearing simultaneously. As machine which does so is called PMM 1.

PMM 1 is impossible and it violates the 1st law of Thermodynamics.

Perpetual Motion Machine of Second kind

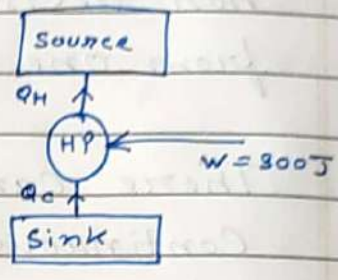
An imaginary machine which would continuously absorb heat from a single hot reservoir and convert all its heat completely into work, with 100% efficiency is called PMM 2.

PMM 2 is impossible and it violates 2nd Law of thermodynamics.

* NoTe → $COP_{HP} = COP_{R} + 1$

Q1) A Heat pump uses 300 J of Work to remove 400 J of heat from the low temperature reservoir. How much heat is delevered to a higher temperature reservior?

Ans:



$W = 300 J$

$Q_c = 400 J$

$Q_H = W + Q_c$

$\Rightarrow Q_H = 300 J + 400 J$

$\Rightarrow Q_H = 700 J$

Heat delivered to the higher temperature reservoir is 700 J.

Q2) How much heat must be supplied to 1.5 kg of a gas to raise its temperature from 90°c to 225°c at constant pressure? Find also the external work done during the supply of heat. Take $C_p = 1$ kJ/kgk. $C_v = 0.7128$ kJ/kgk.

Sol: $m = 1.5 kg$

$T_1 = 90 + 273 = 363 k$

$T_2 = 225 + 273 = 498 k$

$C_p = 1 \quad C_v = 0.7128$

Total Heat supplied,

$$Q = mC_p (T_2 - T_1)$$

$$Q = 1.5 \times 1 (498 - 368)$$
$$= 1.5 \times 135 = 202.5 \text{ kJ} \quad \text{Ans}$$

Change in internal energy

$$\Delta U = m C_v (T_2 - T_1) = 1.5 \times 0.7128 (498 - 368)$$
$$= 144.34 \text{ kJ}$$

$$Q = W + \Delta U$$

∴ External work done,

$$W = Q - \Delta U = 202.5 - 144.34$$
$$= 58.16 \text{ kJ} \quad \text{Ans.}$$

Otto Cycle

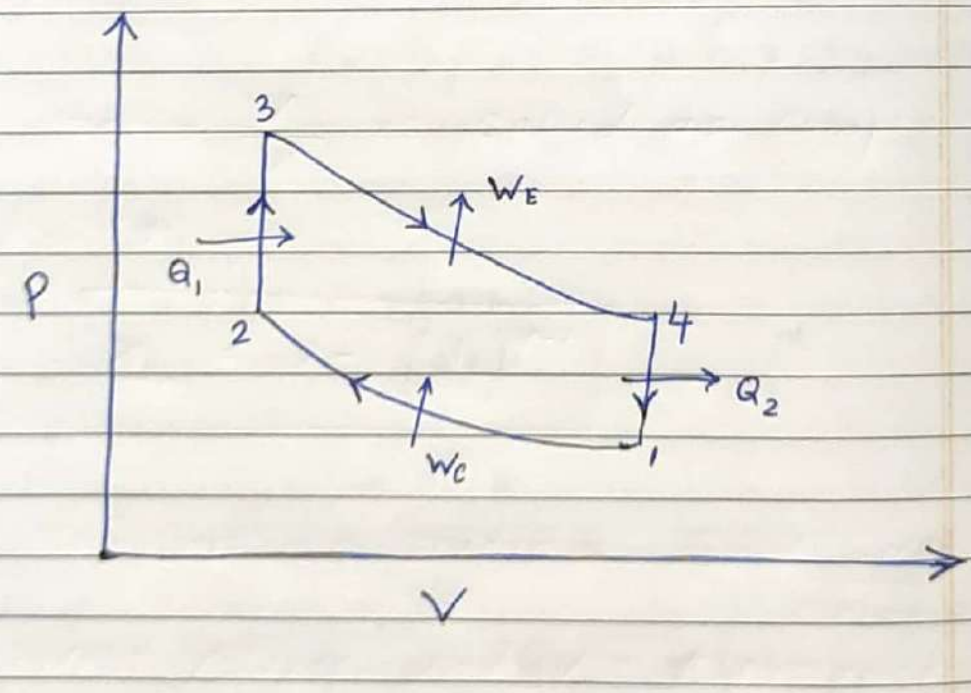
The otto cycle is the air standard cycle of the SI engine. This cycle is shown on P-V and T-s diagrams. The otto cycle 1-2-3-4 consists of following four process.

Process 1-2: Reversible adiabatic compression of air. Work is done on the system in this process.

Process 2-3: Heat addition at constant Volume.

Process 3-4: Reversible adiabatic expansion of air. Work is done by the system in this process

Process 4-1: Heat rejection at constant volume.



W_C = Work done on the system due to compression.

W_E = Work done by the system due to expansion

Q_1 = Heat added to the system
Q_2 = Heat rejected by the system

Air Standard Efficiency

$$\eta = \frac{\text{Net Workdone}}{\text{Net heat added}}$$

Since processes 1-2 and 3-4 are adiabatic processes, the heat transfer during the cycle takes place only during processes 2-3 and 4-1 respectively. So the thermal efficiency can be written as,

$$\eta = \frac{\text{Heat added} - \text{Heat rejected}}{\text{Heat added}}$$

Consider 'm' kg of working fluid,

$$\text{Heat added} = mC_v (T_3 - T_2)$$

$$\text{Heat rejected} = mC_v (T_4 - T_1)$$

$$\eta_{th} = \frac{mC_v (T_3 - T_2) - mC_v (T_4 - T_1)}{mC_v (T_3 - T_2)}$$

$$= \frac{mC_v (T_3 - T_2)}{mC_v (T_3 - T_2)} - \frac{mC_v (T_4 - T_1)}{mC_v (T_3 - T_2)}$$

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$$\eta_{th} = 1 - \frac{T_4 - T_1}{T_3 - T_2}$$

For the reversible adiabatic processes 3-4 and 1-2, we can write

$$\frac{T_4}{T_3} = \left(\frac{V_3}{V_4}\right)^{\gamma-1} \quad \text{and} \quad \frac{T_1}{T_2} = \left(\frac{V_2}{V_1}\right)^{\gamma-1}$$

$$V_2 = V_3 \quad \text{and} \quad V_4 = V_1$$

So,

$$\frac{T_1}{T_2} = \frac{T_4}{T_3} = \frac{T_4 - T_1}{T_3 - T_2} = \left(\frac{V_2}{V_1}\right)^{\gamma-1}$$

$$\eta_{th} = 1 - \frac{T_4 - T_1}{T_3 - T_2} = 1 - \left(\frac{V_2}{V_1}\right)^{\gamma-1}$$

The ratio $\frac{V_1}{V_2}$ is called as compression ratio (r)

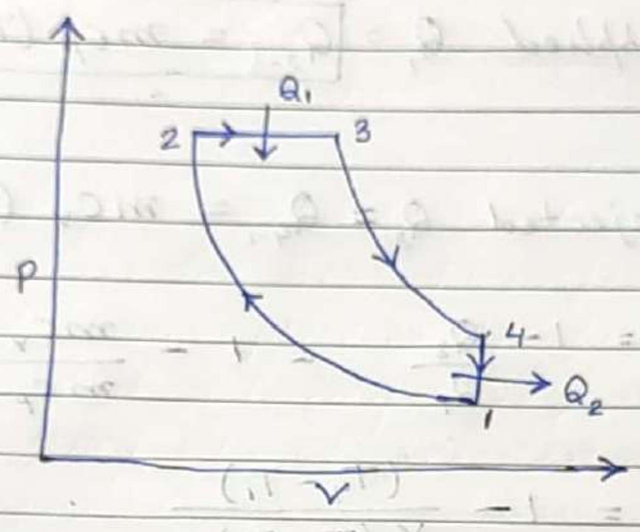
$$\boxed{\eta_{th} = 1 - \left(\frac{1}{r}\right)^{\gamma-1}}$$

compression ratio = ~~Swipt~~ Swept volume / Clerance Volume

$\therefore$ V_1 = Swept volume and V_2 = Clearance volume.

Diesel cycle

The diesel cycle is a Combustion process of a reciprocating internal combusition engine. In it the fuel is ignited by heat generated during the compression of air in the combustion chamber, into which the fuel is then injected.



Diesel cycle consist of two reversible adiabatics cycle, one reversible isobar cycle and one reversible isochore cycle.

Process 1-2 : Air is compressed reversibly and adiabatically.

Process 2-3 : Heat is added reversibly at constant pressure.

Process 3-4 : Air is expanded reversibly and adiabatically.

Process 4-1: Heat is rejected reversibly at constant volume.

For 'm' kg of air in the cylinder, the efficiency analysis of the cycle can be made as given below.

Heat supplied $Q_1 = \boxed{Q_{2-3} = mc_p (T_3 - T_2)}$

Heat rejected $Q_2 = Q_{4-1} = mc_v (T_4 - T_1)$

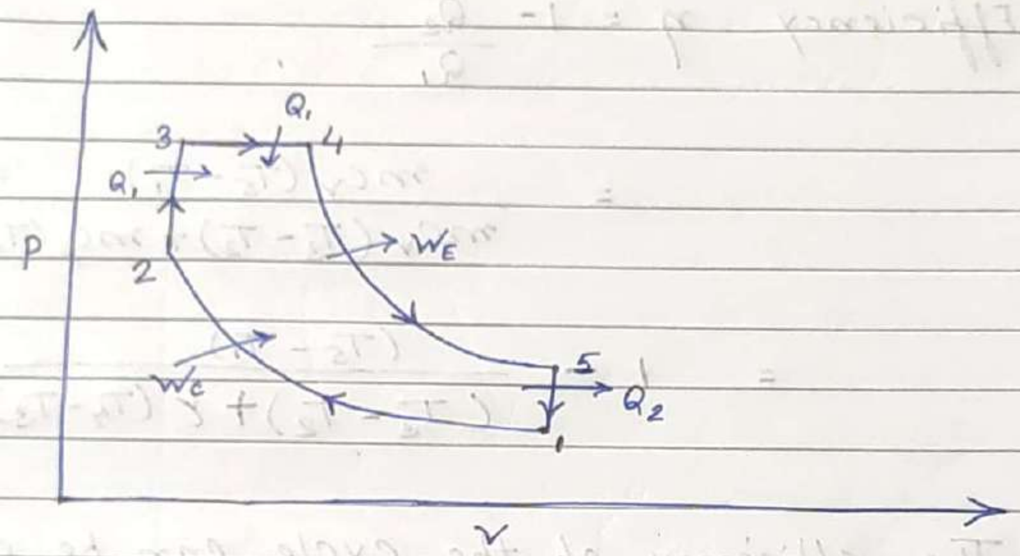
$$\eta = 1 - \frac{Q_2}{Q_1} = 1 - \frac{mc_v (T_4 - T_1)}{mc_p (T_3 - T_2)}$$

$$= 1 - \frac{(T_4 - T_1)}{\gamma (T_3 - T_2)}$$

$\boxed{\gamma = \frac{c_p}{c_v}}$

Dual Cycle

Dual cycle is a thermodynamic cycle that combines the otto cycle and diesel cycle. The combustion occurs partly at constant volume and partly at constant pressure.



Process 1-2 : Compression is done reversibly ~~at~~ and adiabatically.

Process 2-3 : Heat is added partly at constant volume

Process 3-4 : Heat is added partly at constant pressure

Process 4-5 : Expansion is done reversibly and adiabatically

Process 5-1 : Heat is rejected at constant volume.

Heat supplied $Q_1 = mC_v (T_3 - T_2) + mC_p (T_4 - T_3)$

Heat rejected $Q_2 = mC_v (T_5 - T_1)$

Efficiency $\eta = 1 - \frac{Q_2}{Q_1}$

$$= \frac{mC_v (T_5 - T_1)}{mC_v (T_3 - T_2) + mC_p (T_4 - T_3)}$$

$$= 1 - \frac{(T_5 - T_1)}{(T_3 - T_2) + \gamma (T_4 - T_3)}$$

The efficiency of the cycle can be expressed in term of the following ratios.

Compression ratio : $r_k = \frac{V_1}{V_2}$

Expansion ratio : $r_e = \frac{V_5}{V_4}$

Cut off ratio : $r_c = \frac{V_4}{V_3}$

Constant volume pressure ratio: $r_p = \frac{P_3}{P_2}$

$$r_k = r_c \times r_e$$

$$\eta_{Dual} = 1 - \frac{1}{r_k^{\gamma-1}} \times \frac{r_p \cdot r_c^{\gamma} - 1}{r_p - 1 + \gamma r_p (r_c - 1)}$$

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13.1 CARNOT CYCLE (1824)

The Carnot cycle (Fig. 13.1) has been discussed in Chapters 6 and 7. It consists of two reversible isotherms and two reversible adiabatics. If an ideal gas is assumed as the working fluid. Then for 1 kg of gas,

$$Q_{1-2} = RT_1 \ln \frac{v_2}{v_1}; \quad W_{1-2} = RT_1 \ln \frac{v_2}{v_1}$$

$$Q_{2-3} = 0; \quad W_{2-3} = -c_v (T_3 - T_2)$$

$$Q_{3-4} = RT_2 \ln \frac{v_4}{v_3}; \quad W_{3-4} = RT_2 \ln \frac{v_4}{v_3}$$

$$Q_{4-1} = 0; \quad W_{4-1} = -c_v(T_1 - T_4)$$

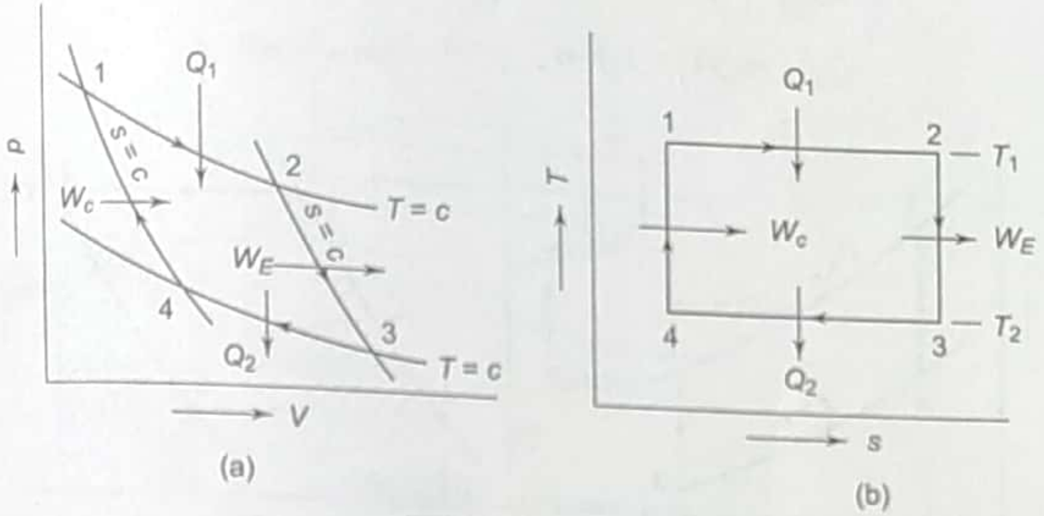


Fig. 13.1 *Carnot cycle*

$\therefore$
$$\sum_{\text{cycle}} đQ = \sum_{\text{cycle}} dQ$$

Now
$$\frac{v_2}{v_3} = \left(\frac{T_2}{T_1}\right)^{1/(\gamma-1)}$$

and
$$\frac{v_1}{v_4} = \left(\frac{T_2}{T_1}\right)^{1/(\gamma-1)}$$

$\therefore$
$$\frac{v_2}{v_3} = \frac{v_1}{v_4} \text{ or } \frac{v_2}{v_1} = \frac{v_3}{v_4}$$

Therefore

$$Q_1 = \text{Heat added} = RT_1 \ln \frac{v_2}{v_1}$$

$$W_{\text{net}} = Q_1 - Q_2 = R \ln \frac{v_2}{v_1} (T_1 - T_2)$$

$\therefore$
$$\eta_{\text{cycle}} = \frac{W_{\text{net}}}{Q_1} = \frac{T_1 - T_2}{T_1} \tag{13.1}$$

INTERNAL COMBUSTION ENGINE & GAS TURBINES

<u>Module - I</u>

<u>INTRODUCTION</u>

<u>Heat engine:</u>

A heat engine is a device which transforms the chemical energy of a fuel into thermal energy and uses this energy to produce mechanical work. It is classified into two types-

(a) External combustion engine
(b) Internal combustion engine

External combustion engine:

In this engine, the products of combustion of air and fuel transfer heat to a second fluid which is the working fluid of the cycle.

Examples:

*In the steam engine or a steam turbine plant, the heat of combustion is employed to generate steam which is used in a piston engine (reciprocating type engine) or a turbine (rotary type engine) for useful work.

*In a closed cycle gas turbine, the heat of combustion in an external furnace is transferred to gas, usually air which the working fluid of the cycle.

Internal combustion engine:

In this engine, the combustion of air and fuels take place inside the cylinder and are used as the direct motive force. It can be classified into the following types:

1. According to the basic engine design- (a) Reciprocating engine (Use of cylinder piston arrangement), (b) Rotary engine (Use of turbine)

2. According to the type of fuel used- (a) Petrol engine, (b) diesel engine, (c) gas engine (CNG, LPG), (d) Alcohol engine (ethanol, methanol etc)

3. According to the number of strokes per cycle- (a) Four stroke and (b) Two stroke engine

4. According to the method of igniting the fuel- (a) Spark ignition engine, (b) compression ignition engine and (c) hot spot ignition engine

5. According to the working cycle- (a) Otto cycle (constant volume cycle) engine, (b) diesel cycle (constant pressure cycle) engine, (c) dual combustion cycle (semi diesel cycle) engine.

6. According to the fuel supply and mixture preparation- (a) Carburetted type (fuel supplied through the carburettor), (b) Injection type (fuel injected into inlet ports or inlet manifold, fuel injected into the cylinder just before ignition).

7. According to the number of cylinder- (a) Single cylinder and (b) multi-cylinder engine

8. Method of cooling- water cooled or air cooled

9. Speed of the engine- Slow speed, medium speed and high speed engine

10. Cylinder arrangement-Vertical, horizontal, inline, V-type, radial, opposed cylinder or piston engines.

11. Valve or port design and location- Overhead (I head), side valve (L head); in two stroke engines: cross scavenging, loop scavenging, uniflow scavenging.

12. Method governing- Hit and miss governed engines, quantitatively governed engines and qualitatively governed engine

14. Application- Automotive engines for land transport, marine engines for propulsion of ships, aircraft engines for aircraft propulsion, industrial engines, prime movers for electrical generators.

Comparison between external combustion engine and internal combustion engine:

External combustion engine	Internal combustion engine
*Combustion of air-fuel is outside the engine cylinder (in a boiler)	* Combustion of air-fuel is inside the engine cylinder (in a boiler)
*The engines are running smoothly and silently due to outside combustion	* Very noisy operated engine
*Higher ratio of weight and bulk to output due to presence of auxiliary apparatus like boiler and condenser. Hence it is heavy and cumbersome.	* It is light and compact due to lower ratio of weight and bulk to output.
*Working pressure and temperature inside the engine cylinder is low; hence ordinary alloys are used for the manufacture of engine cylinder and its parts.	* Working pressure and temperature inside the engine cylinder is very much high; hence special alloys are used
*It can use cheaper fuels including solid fuels	*High grade fuels are used with proper filtration
*Lower efficiency about 15-20%	*Higher efficiency about 35-40%
* Higher requirement of water for dissipation of energy through cooling system	*Lesser requirement of water
*High starting torque	*IC engines are not self-starting

Main components of reciprocating IC engines:

Cylinder: It is the main part of the engine inside which piston reciprocates to and fro. It should have high strength to withstand high pressure above 50 bar and temperature above

2000 ^{o}C. The ordinary engine is made of cast iron and heavy duty engines are made of steel alloys or aluminum alloys. In the multi-cylinder engine, the cylinders are cast in one block known as cylinder block.

Cylinder head: The top end of the cylinder is covered by cylinder head over which inlet and exhaust valve, spark plug or injectors are mounted. A copper or asbestos gasket is provided between the engine cylinder and cylinder head to make an air tight joint.

Piston: Transmit the force exerted by the burning of charge to the connecting rod. Usually made of aluminium alloy which has good heat conducting property and greater strength at higher temperature.

Figure 1 shows the different components of IC engine.

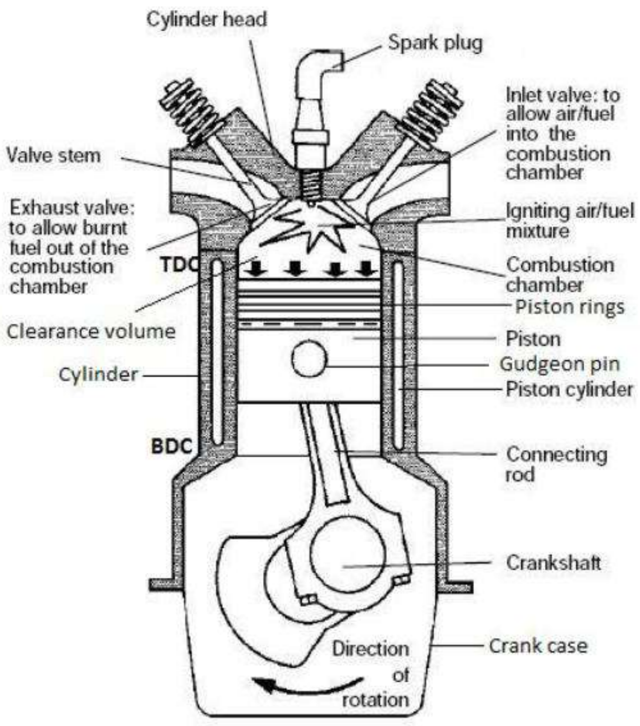


Fig. 1. Different parts of IC engine

Piston rings: These are housed in the circumferential grooves provided on the outer surface of the piston and made of steel alloys which retain elastic properties even at high temperature. 2 types of rings- compression and oil rings. Compression ring is upper ring of the piston which provides air tight seal to prevent leakage of the burnt gases into the lower portion. Oil ring is lower ring which provides effective seal to prevent leakage of the oil into the engine cylinder.

Connecting rod: It converts reciprocating motion of the piston into circular motion of the crank shaft, in the working stroke. The smaller end of the connecting rod is connected with the piston by gudgeon pin and bigger end of the connecting rod is connected with the crank with crank pin. The special steel alloys or aluminium alloys are used for the manufacture of connecting rod.

Crankshaft: It converts the reciprocating motion of the piston into the rotary motion with the help of connecting rod. The special steel alloys are used for the manufacturing of the crankshaft. It consists of eccentric portion called crank.

Crank case: It houses cylinder and crankshaft of the IC engine and also serves as sump for the lubricating oil.

Flywheel: It is big wheel mounted on the crankshaft, whose function is to maintain its speed constant. It is done by storing excess energy during the power stroke, which is returned during other stroke.

Terminology used in IC engine:

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

2. Piston area (A): The area of circle of diameter equal to the cylinder bore.

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 position 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).

(a) Bottom dead centre (BDC): Dead centre when the piston is nearest to the crankshaft.

(b) Top dead centre (TDC): Dead centre when the position is farthest from the crankshaft.

5. Displacement volume or swept volume (V_s): The nominal volume generated by the working piston when travelling from the one dead centre to next one and given as,

$$V_s = A \times L$$

6. Clearance volume (V_c): the nominal volume of the space on the combustion side of the piston at the top dead centre.

7. Cylinder volume (V): Total volume of the cylinder.

$$V = V_s + V_c$$

8. Compression ratio (r): $r = \frac{\text{Vs}}{\text{Vc}}$

Four stroke engine:

- Cycle of operation completed in four strokes of the piston or two revolution of the piston.

(i) Suction stroke (suction valve open, exhaust valve closed)-charge consisting of fresh air mixed with the fuel is drawn into the cylinder due to the vacuum pressure created by the movement of the piston from TDC to BDC.

(ii) Compression stroke (both valves closed)-fresh charge is compressed into clearance volume by the return stroke of the piston and ignited by the spark for combustion. Hence pressure and temperature is increased due to the combustion of fuel

(iii) Expansion stroke (both valves closed)-high pressure of the burnt gases force the piston towards BDC and hence power is obtained at the crankshaft.

(iv) Exhaust stroke (exhaust valve open, suction valve closed)- burned gases expel out due to the movement of piston from BDC to TDC.

Figure 2 show the cycle of operation of four stroke engine.

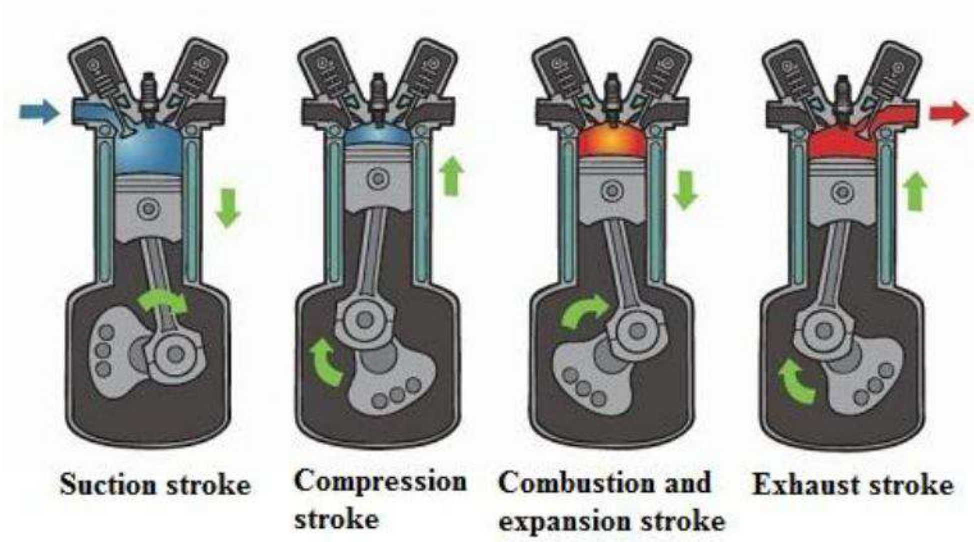


Fig. 2. Cycle of operation in four stroke engine

Two stroke engine:

-No piston stroke for suction and exhaust operations

-Suction is accomplished by air compressed in crankcase or by a blower

-Induction of compressed air removes the products of combustion through exhaust ports

-Transfer port is there to supply the fresh charge into combustion chamber

Figure 3 represents operation of two stroke engine

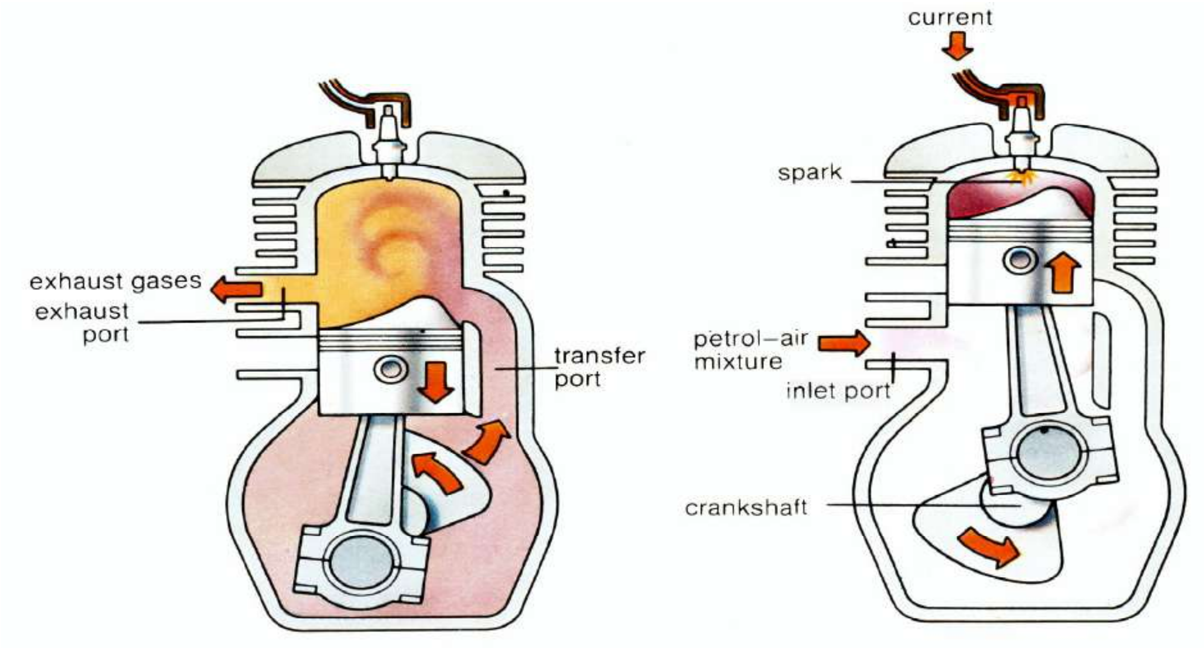


Fig. 3. Cycle of operation in two stroke engine

Comparison of Four-stroke and two-stroke engine:

	Four-stroke engine	Two-stroke engine
1.	Four stroke of the piston and two revolution of crankshaft	Two stroke of the piston and one revolution of crankshaft
2.	One power stroke in every two revolution of crankshaft	One power stroke in each revolution of crankshaft
3.	Heavier flywheel due to non-uniform turning movement	Lighter flywheel due to more uniform turning movement
4.	Power produce is less	Theoretically power produce is twice than the four stroke engine for same size
5.	Heavy and bulky	Light and compact
6.	Lesser cooling and lubrication requirements	Greater cooling and lubrication requirements
7.	Lesser rate of wear and tear	Higher rate of wear and tear
8.	Contains valve and valve mechanism	Contains ports arrangement
9.	Higher initial cost	Cheaper initial cost
10.	Volumetric efficiency is more due to greater time of induction	Volumetric efficiency less due to lesser time of induction
11.	Thermal efficiency is high and also part load efficiency better	Thermal efficiency is low, part load efficiency lesser
12.	It is used where efficiency is important. Ex-cars, buses, trucks, tractors, industrial engines, aero planes, power generation etc.	It is used where low cost, compactness and light weight are important. Ex-lawn mowers, scooters, motor cycles, mopeds, propulsion ship etc.

Comparison of SI and CI engine:

SI engine	CI engine
Working cycle is Otto cycle.	Working cycle is diesel cycle.
Petrol or gasoline or high octane fuel is used.	Diesel or high cetane fuel is used.
High self-ignition temperature.	Low self-ignition temperature.
Fuel and air introduced as a gaseous mixture in the suction stroke.	Fuel is injected directly into the combustion chamber at high pressure at the end of compression stroke.
Carburettor used to provide the mixture. Throttle controls the quantity of mixture introduced.	Injector and high pressure pump used to supply of fuel. Quantity of fuel regulated in pump.
Use of spark plug for ignition system	Self-ignition by the compression of air which increased the temperature required for combustion
Compression ratio is 6 to 10.5	Compression ratio is 14 to 22
Higher maximum RPM due to lower weight	Lower maximum RPM
Maximum efficiency lower due to lower compression ratio	Higher maximum efficiency due to higher compression ratio
Lighter	Heavier due to higher pressures

Valve timing diagram:

The exact moment at which the inlet and outlet valve opens and closes with reference to the position of the piston and crank shown diagrammatically is known as valve timing diagram. It is expressed in terms of degree crank angle. The theoretical valve timing diagram is shown in Fig. 4.

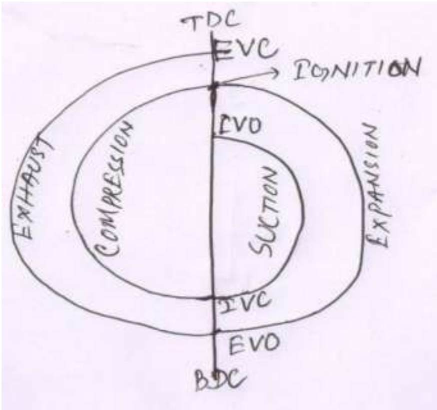


Fig. 4. Theoretical valve timing diagram

But actual valve timing diagram is different from theoretical due to two factors-mechanical and dynamic factors. Figure 4 shows the actual valve timing diagram for four stroke low speed or high speed engine.

Opening and closing of inlet valve

-Inlet valve opens 12 to 30° CA before TDC to facilitate silent operation of the engine under high speed. It increases the volumetric efficiency.

-Inlet valve closes 10-60° CA after TDC due to inertia movement of fresh charge into cylinder i.e. ram effect.

Figure 5 represents the actual valve timing diagram for low and high speed engine.

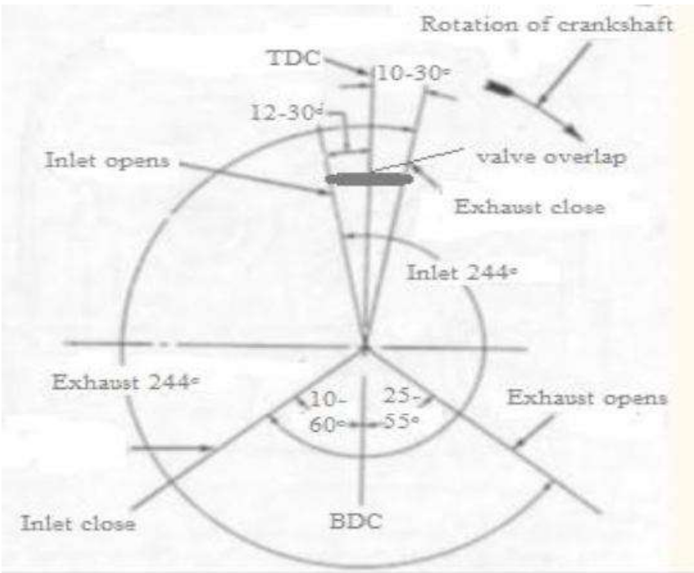


Fig. 5. Actual valve timing diagram for low and high speed engine

Opening and closing of exhaust valve

Exhaust valve opens 25 to 55° CA before BDC to reduce the work required to expel out the burnt gases from the cylinder. At the end of expansion stroke, the pressure inside the chamber is high, hence work to expel out the gases increases.

Exhaust valve closes 10 to 30° CA after TDC to avoid the compression of burnt gases in next cycle. Kinetic energy of the burnt gas can assist maximum exhausting of the gas. It also increases the volumetric efficiency.

Note: For low and high speed engine, the lower and upper values are used respectively

Valve overlap

During this time both the intake and exhaust valves are open. The intake valve is opened before the exhaust gases have completely left the cylinder, and their considerable velocity assists in drawing in the fresh charge. Engine designers aim to close the exhaust valve just as the fresh charge from the intake valve reaches it, to prevent either loss of fresh charge or unscavenged exhaust gas.

Port timing diagram:

-Drawn for 2-stroke engine

-No valve arrangement

-3 ports- inlet, transfer and exhaust

Figure 6 shows port timing diagram for 2-stroke engine

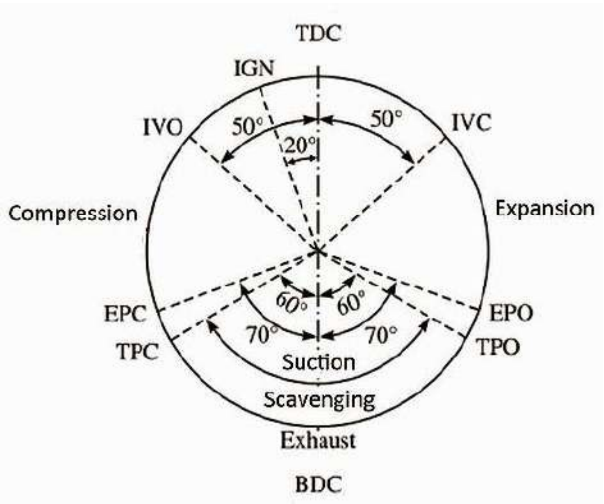


Fig. 6. Port timing diagram for 2-stroke engine

Working cycle:

(a) ***Otto cycle-*** thermodynamic cycle for SI/petrol engine

-Reversible adiabatic compression and expansion process

-Constant volume heat addition (combustion) and heat rejection process (exhaust)

Figure 7 depicts the Otto cycle

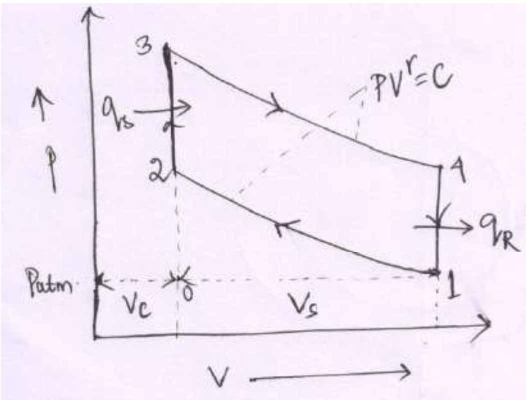


Fig. 7. Otto cycle

Heat supplied, $q_s=C_v(T_3-T_2)$

Heat rejection, $q_R=C_v(T_4-T_1)$

Compression ratio, $r_k=\frac{V_1}{V_2}$

Thermal efficiency, $\eta_{th}=\frac{q_s-q_R}{q_s}=\frac{Cv(T3-T2)-Cv(T4-T1)}{Cv(T3-T2)}=1-\frac{T4-T1}{T3-T2}$

In process 1-2, adiabatic compression process,

$$\frac{T_2}{T_1} = \left(\frac{V_1}{V_2}\right)^{\gamma-1}$$

$$=> T_2 = T_1.(r_k)^{\gamma-1}$$

In adiabatic expansion process, i.e. 3-4,

$$\frac{T_4}{T_3} = \left(\frac{V_3}{V_4}\right)^{\gamma-1} = \left(\frac{V_2}{V_1}\right)^{\gamma-1}$$

$$=> T_3 = T_4.(r_k)^{\gamma-1}$$

$$\eta_{th} = 1 - \frac{T_4 - T_1}{T_4.(r_k)^{\gamma-1} - T_1.(r_k)^{\gamma-1}}$$

$$= 1 - \frac{1}{(r_k)^{\gamma-1}}$$

<u>Work done (W)</u>

Pressure ratio, $r_p = \frac{P_3}{P_2} = \frac{P_4}{P_1}$

$$\frac{P_2}{P_1} = \frac{P_3}{P_4} = \left(\frac{V_1}{V_2}\right)^{\gamma} = (r_k)^{\gamma}$$

$$W = \frac{P_3V_3 - P_4V_4}{\gamma - 1} - \frac{P_2V_2 - P_1V_1}{\gamma - 1}$$

$$= \frac{1}{\gamma - 1}\left[P_4V_4\left(\frac{P_3V_3}{P_4V_4} - 1\right) - P_1V_1\left(\frac{P_2V_2}{P_1V_1} - 1\right)\right]$$

$$= \frac{1}{\gamma - 1}\left[P_4V_1({r_k}^{\gamma-1} - 1) - P_1V_1({r_k}^{\gamma-1} - 1)\right]$$

$$= \frac{P_1V_1}{\gamma - 1}\left[r_p({r_k}^{\gamma-1} - 1) - ({r_k}^{\gamma-1} - 1)\right]$$

$$= \frac{P_1V_1}{\gamma - 1}\left[({r_k}^{\gamma-1} - 1)(r_p - 1)\right]$$

Mean effective pressure, $P_m = \frac{work\ done}{Swept\ volume} = \frac{work\ done}{V_1 - V_2}$

$$P_m = \frac{\frac{P_1V_1}{\gamma - 1}\left[({r_k}^{\gamma-1} - 1)(r_p - 1)\right]}{V_1 - V_2} = \frac{P_1r_k\left[({r_k}^{\gamma-1} - 1)(r_p - 1)\right]}{(\gamma - 1)(r_k - 1)}$$

(b) ***<u>Diesel cycle-</u>*** thermodynamic cycle for low speed CI/diesel engine

-Reversible adiabatic compression and expansion process

-Constant pressure heat addition (combustion) and heat rejection process (exhaust)

Figure 8 depicts the diesel cycle.

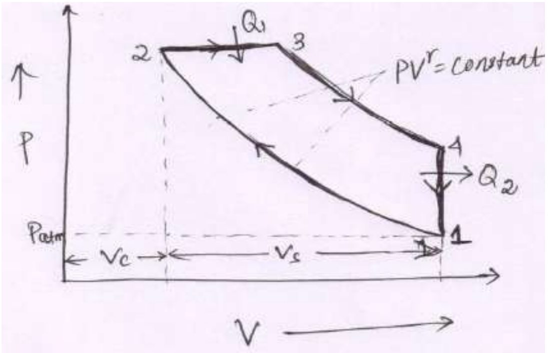


Fig. 8. Diesel cycle

Heat supplied, Q_1=C_p(T_3-T_2)
Heat rejection, Q_2=C_v(T_4-T_1)
Compression ratio, r_k=$\frac{V_1}{V_2}$
Cut off ratio, r_c=$\frac{V_3}{V_2}$
Thermal efficiency, $\eta_{th} = \frac{Q_1-Q_2}{Q_1} = \frac{C_p(T_3-T_2)-C_v(T_4-T_1)}{C_p(T_3-T_2)} = 1 - \frac{1}{\gamma}\frac{(T_4-T_1)}{(T_3-T_2)}$
In adiabatic compression process i.e. 1-2,

$$\frac{T_2}{T_1} = \left(\frac{V_1}{V_2}\right)^{\gamma-1}$$

$$=> T_2 = T_1.(r_k)^{\gamma-1}$$

In process 2-3, pressure constant, then

$$\frac{T_3}{T_2} = \frac{V_3}{V_2} = r_c$$

$$=> T_3 = T_2.r_c = T_1.(r_k)^{\gamma-1}.r_c$$

In adiabatic expansion process i.e. 3-4,

$$\frac{T_4}{T_3} = \left(\frac{V_3}{V_4}\right)^{\gamma-1} = \left(\frac{V_3}{V_2} * \frac{V_2}{V_4}\right)^{\gamma-1} = (r_c)^{\gamma-1} * \frac{1}{(r_k)^{\gamma-1}}$$

$$=> T_4 = T_3.(r_c)^{\gamma-1} * \frac{1}{(r_k)^{\gamma-1}} = T_1.(r_k)^{\gamma-1}.r_c.(r_c)^{\gamma-1} * \frac{1}{(r_k)^{\gamma-1}} = T_1.r_c$$

$$\eta_{th} = 1 - \frac{1}{\gamma}\frac{(T_4-T_1)}{(T_3-T_2)} = 1 - \frac{1}{\gamma.(r_k)^{\gamma-1}}\left[\frac{(r_c)^{\gamma}-1}{r_c-1}\right]$$

Work done (W)

$$W = P_2(V_3 - V_2) + \frac{P_3V_3-P_4V_4}{\gamma-1} - \frac{P_2V_2-P_1V_1}{\gamma-1}$$

$$= P_2(r_cV_2 - V_2) + \frac{P_2r_cV_2-P_4r_kV_2}{\gamma-1} - \frac{P_2V_2-P_1r_kV_2}{\gamma-1} \qquad \text{since } V_4 = V_1$$

$$= P_2V_2\left[\frac{(r_c-1)(\gamma-1)+(r_c-r_c{}^{\gamma}.r_k{}^{-\gamma}.r_k)-(1-r_k{}^{1-\gamma})}{\gamma-1}\right]$$

$$= P_1V_1.r_k{}^{\gamma-1}\left[\frac{\gamma(r_c-1)-r_k{}^{1-\gamma}(r_c{}^{\gamma}-1)}{\gamma-1}\right]$$

Mean effective pressure,

$$P_m = \frac{P_1 V_1 . r_k^{\gamma-1}\left[\frac{\gamma(r_c-1)-r_k^{1-\gamma}(r_c^{\gamma}-1)}{\gamma-1}\right]}{V_1-V_2} = \frac{P_1 r_k^{\gamma}\left[\gamma(r_c-1)-r_k^{1-\gamma}(r_c^{\gamma}-1)\right]}{(\gamma-1)(r_k-1)}$$

<u>(c) Dual cycle or limited pressure cycle-</u>thermodynamic cycle for high speed diesel and hot spot ignition engine

-Reversible adiabatic compression and expansion process

-Constant pressure and constant volume heat addition (combustion) and heat rejection
process

Total heat supplied, $Q_1= C_v(T_3-T_2)+ C_p(T_4-T_3)$

Heat rejection, $Q_2=C_v(T_5-T_1)$

Compression ratio, $r_k=\frac{V_1}{V_2}$

Cut off ratio, $r_c=\frac{V_4}{V_3}$

Pressure ratio, $r_p=\frac{P_3}{P_2}$

Figure 9 shows the P-V diagram of Dual cycle.

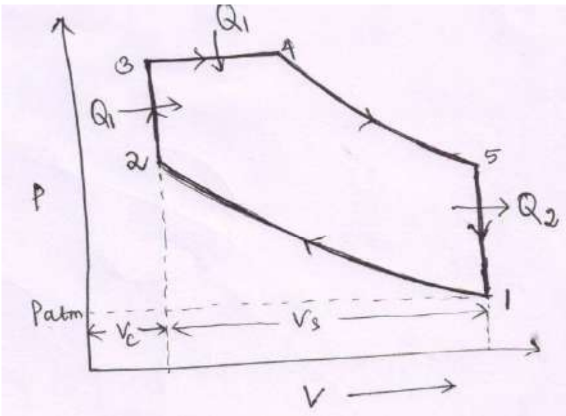


Fig. 9. Dual cycle

Thermal efficiency, $\eta_{th} = \frac{Q_1-Q_2}{Q_1} = \frac{C_v(T_3-T_2)+C_v(T_4-T_3)-C_v(T_5-T_1)}{C_v(T_3-T_2)+C_v(T_4-T_3)} = 1 - \frac{(T_5-T_1)}{(T_3-T_2)+\gamma(T_4-T_3)}$

In adiabatic compression process i.e. 1-2,

$$\frac{T_2}{T_1} = \left(\frac{V_1}{V_2}\right)^{\gamma-1} = (r_k)^{\gamma-1}$$

In constant volume combustion process i.e. 2-3,

$\frac{P_3}{P_2} = \frac{T_3}{T_2} = r_p$

$$=> T_2 = \frac{T_3}{r_p}$$

In constant pressure combustion process i.e. 3-4,

$\frac{V_3}{V_4} = \frac{T_3}{T_4}$

$$=> T_4 = T_3 . r_c$$

In adiabatic expansion process i.e. 4-5,

$$\frac{T_4}{T_5} = \left(\frac{V_5}{V_4}\right)^{\gamma-1} = \left(\frac{V_1}{V_4}\right)^{\gamma-1} = \left(\frac{r_k}{r_c}\right)^{\gamma-1}$$

$$=> T_5 = r_c * T_3 * \left(\frac{r_c}{r_k}\right)^{\gamma-1}$$

$$\eta_{th} = 1 - \frac{(T_5 - T_1)}{(T_3 - T_2) + \gamma(T_4 - T_3)} = 1 - \frac{1}{(r_k)^{\gamma-1}}\left[\frac{r_p.(r_c)^{\gamma} - 1}{(r_p - 1) + \gamma r_p(r_c - 1)}\right]$$

<u>Work done (W)</u>

$$W = P_3(V_4 - V_3) + \frac{P_4V_4 - P_5V_5}{\gamma - 1} - \frac{P_2V_2 - P_1V_1}{\gamma - 1}$$

$$= P_3V_3(r_c - 1) + \frac{(P_4r_cV_3 - P_5r_kV_3) - (P_2V_3 - P_1r_kV_3)}{\gamma - 1}$$

$$= \frac{P_1V_1.r_k{}^{\gamma-1}\left[\gamma r_p(r_c - 1) + \left(r_p - 1\right) -.r_k{}^{\gamma-1}(r_pr_c{}^{\gamma} - 1)\right]}{\gamma - 1}$$

Mean effective pressure,

$$P_m = \frac{\frac{P_1V_1.r_k{}^{\gamma-1}\left[\gamma r_p(r_c - 1) + \left(r_p - 1\right) -.r_k{}^{\gamma-1}(r_pr_c{}^{\gamma} - 1)\right]}{\gamma - 1}}{V_1 - V_2}$$

$$= \frac{P_1r_k{}^{\gamma}\left[r_p(r_c - 1) + \left(r_p - 1\right) -.r_k{}^{1-\gamma}(r_pr_c{}^{\gamma} - 1)\right]}{(\gamma - 1)(r_k - 1)}$$

<u>Comparison of Otto, Diesel and Dual cycle:</u>

(a) For same compression ratio and same heat input

$$(\eta_{th})_{Otto} > (\eta_{th})_{Dual} > (\eta_{th})_{Diesel}$$

(b) For constant maximum pressure and same heat input

8.2. CLASSIFICATION OF FUELS

Fuels can be classified according to whether :

1. They occur in nature called **primary fuels** or are prepared called **secondary fuels;**
2. They are in solid, liquid or gaseous state. The detailed classification of fuels can be given in a summary form as follows :

Type of fuel	Natural (Primary)	Prepared (Secondary)
Solid	Wood Peat Lignite coal	Coke Charcoal Briquettes
Liquid	Petroleum	Gasoline Kerosene Fuel oil Benzol Alcohol Shale oil
Gaseous	Natural gas	Petroleum gas Producer gas Coal gas Coke-oven gas Blast furnace gas Carburetted gas Sewer gas

8.3. SOLID FUELS

(*i*) **Coal.** Its main constituents are carbon, hydrogen, oxygen, nitrogen, sulphur, moisture and ash. Coal passes through different stages during its formation from vegetation. These stages are enumerated and discussed below :

(*ii*) Plant debris – Peat – Lignite – Brown coal – Sub-bituminous coal – Bituminous coal – Semi-bituminous coal – Semi-anthracite coal – Anthracite coal – Graphite.

(*iii*) **Peat.** It is the first stage in the formation of coal from wood. It contains huge amount of moisture and therefore it is dried for about 1 to 2 months before it is put to use. It is used as a domestic fuel in Europe and for power generation in Russia. In India it does not come in the categories of good fuels.

(*iv*) **Lignites and brown coals.** These are intermediate stages between peat and coal. They have a woody or often a clay like appearance associated with high moisture, high ash and low heat contents. Lignites are usually amorphous in character and impose transport difficulties as they break easily. They burn with a smoky flame. Some of this type are suitable for local use only.

(*v*) **Bituminous coal.** It burns with long yellow and smoky flames and has high percentages of volatile matter. The average calorific value of bituminous coal is about 31350 KJ/kg. It may be of two types, namely *caking* or *noncaking*.

(*vi*) **Semi-bituminous coal.** It is softer than the anthracite. It burns with a very small amount of smoke. It contains 15 to 20 percent volatile matter and has a tendency to break into small sizes during storage or transportation.

(*vii*) **Semi-anthracite.** It has less fixed carbon and less lustre as compared to true anthracite and gives out longer and more luminous flames when burnt.

(*viii*) **Anthracite.** It is very hard coal and has a shining black lustre. It ignites slowly unless the furnace temperature is high. It is non-caking and has high percentage of fixed carbon. It burns either with very short blue flames or without flames. The calorific value of this fuel is high to the tune of 35500 kJ/kg and as such is *very suitable for steam generation*.

(*ix*) **Wood charcoal.** It is obtained by destructive distillation of wood. During the process the volatile matter and water are expelled. The physical properties of the residue (charcoal), how depends upon the rate of heating and temperature.

(*x*) **Coke.** It consists of carbon, mineral matter with about 2% sulphur and small quantities of hydrogen, nitrogen and phosphorus. It is solid residue left after the destructive distillation of certain kinds of coals. It is smokeles and clear fuel and can be produced by several processes. It is *mainly used in blast furnace* to produce heat and at the same time to reduce the iron ore.

(*xi*) **Briquettes.** These are prepared from fine coal or coke by compressing the material under high pressure.

8.4. LIQUID FUELS

The chief source of liquid fuels is *petroleum* which is obtained from wells under the earth's crust. These fuels have proved *more advantageous in comparison to solid fuels* in the following aspects.

Advantages :

1. Require less space for storage.
2. Higher calorific value.
3. Easy control of consumption.
4. Staff economy.
5. Absence of danger from spontaneous combustion.
6. Easy handling and transportation.
7. Cleanliness.
8. No ash problem.
9. Non-deterioration of the oil in storage.

Petroleum. There are different opinions regarding the origin of petroleum. However, now it is accepted that petroleum has originated probably from organic matter like fish and plant life etc. by bacterial action or by their distillation under pressure and heat. It consists of mixture of gaseas, liquids and solid hydrocarbons with small amounts of nitrogen and sulphur compounds. In India, the main sources of Petroleum are Assam and Gujarat.

Heavy fuel oil or crude oil is imported and then refined at different refineries. The refining of crude oil supplies the most important product called *petrol*. Petrol can also be made by polymerization of refinery gases.

Other liquid fuels are kerosene, fuels oils, colloidal fuels and alcohol.

8.5. GASEOUS FUELS

(*i*) **Natural gas.** The main constituents of natural gas are *methane* (CH_4) and *ethane* (C_2H_6). It has calorific value nearly 21000 kJ/m^3. Natural gas is used alternately or simultaneously with oil for internal combustion engines.

(*ii*) **Coal gas.** Mainly consists of *hydrogen, carbon monoxide* and *hydrocarbons*. It is prepared by carbonization of coal. It finds its use in boilers and sometimes used for commercial purposes.

(*iii*) **Coke-oven gas.** It is obtained during the production of coke by heating the bituminous coal. The volatile content of coal is driven off by heating and major portion of this gas is utilized in heating the ovens. This gas *must be thoroughly filtered before using in gas engines.*

(*iv*) **Blast furnace gas.** It is obtained from smelting operation in which air is forced through layers of coke and iron ore, the example being that of pig iron manufacture where this gas is produced as by product and contains about 20% carbon monoxide (CO). After filtering it may be blended with richer gas or used in gas engines directly. The heating value of this gas is very low.

(*v*) **Producer gas.** It results from the partial oxidization of coal, coke or peat when they are burnt with an insufficient quantity of air. It is produced in specially designed retorts. It has low heating value and in general is suitable for large installations. It is also used in steel industry for firing open hearth furnaces.

(*vi*) **Water or illuminating gas.** It is produced by blowing steam into white hot coke or coal. The decomposition of steam takes place liberating free hydrogen, and oxygen in the steam combines with carbon to form carbon monoxide according to the reaction :

$$C + H_2O \longrightarrow CO + H_2$$

The gas composition varies as the hydrogen content if the coal is used.

(*vii*) **Sewer gas.** It is obtained from sewage disposal vats in which fermentation and decay occur. It consists of mainly marsh gas (CH_4) and is collected at large disposal plants. It works as a fuel for gas engines which in turn drive the plant pumps and agitators.

Gaseous fuels are becoming popular because of following *advantages* they possess.

Advantages :

1. Better control of combustion.
2. Much less excess air is needed for complete combustion.
3. Economy in fuel and more efficiency of furnace operation.
4. Easy maintenance of oxidizing or reducing atmosphere.
5. Cleanliness.
6. No problem of storage if the supply is available from public supply line.
7. The distribution of gaseous fuels even over a wide area is easy through the pipe lines and as such handling of the fuel is altogether eliminated.
8. Gaseous fuels give economy of heat and produce higher temperatures (as they can be preheated in regenerative furnaces and thus heat from hot flue gaseous can be recovered).

8.6. BASIC CHEMISTRY

Before considering combustion problems it is necessary to understand the construction and use of chemical formulae. This involves elementary concepts which are discussed below briefly.

Atoms. It is not possible to divide the chemical elements *indefinitely*, and *the smallest particle which can take part in a chemical change* is called an '**atom**'. If an atom is split as in nuclear reaction, the *divided atom does not retain the original chemical properties*.

Molecules. It is rare to find elements to exist naturally as single atom. Some elements have atoms which exist in pairs, each pair forming a molecule (*e.g.*, oxygen), and the atoms of each molecule are held together by stronger *inter-atomic forces*. The isolation of a molecule of oxygen would be a tedious, but possible; the isolation of an atom of oxygen would be different prospect. The molecules of some substances are formed by the mating up of atoms of different elements. For example, water has a molecule which consists of two atoms of hydrogen and one atom of oxygen. The atoms of different elements have different masses and these values are important when a quantitative analysis is required. The actual masses are infinitesimally small, and the ratios of the masses of atoms are used. These ratios are indicated by **atomic weight** quoted on a scale which defines the atomic weight of oxygen as 16.

The symbols and molecular weights of some important elements, compounds and gases are given in Table 8.1.

Table 8.1. Symbols and Molecular Weights.

Elements/Compounds/Gases	Molecule		Atom	
	Symbol	Molecular weight	Symbol	Molecular weight
Hydrogen	H_2	2	H	1
Oxygen	O_2	32	O	16
Nitrogen	N_2	28	N	14
Carbon	C	12	C	12
Sulphur	S	32	S	32
Water	H_2O	18	–	–
Carbon monoxide	CO	28	–	–
Carbon dioxide	CO_2	44	–	–
Sulphur dioxide	SO_2	64	–	–
Marsh gas (Methane)	CH_4	16	–	–
Ethylene	C_2H_4	28	–	–
Ethane	C_2H_6	30	–	–

Octaine Number & Cetane Number

Cetane Number → Diesel Fuel

Octane Number → Petrol Fuel

* The cetane Number refers to the eace with which desel fuel ignites easily at a relatively low temperature.

Cetane Number

- Higher cetane number means
  - (i) Improved combustion
  - (ii) Improved cold starting
  - (iii) Reduced Noise, White Smoke, HC, CO & particulate emissions

* Diesel fuel contains more heat energy than petrol fuel.

* It is defined by the comparison of mixture of Cetane and methylnapthalene.

Octane number

Octain number is also known as anti-knock rating. It measure the ability of a fuel to resist knocking when ignited in a mixture with air in the cylinder of an internal-combustion engine.

It is defined by the comparison with the mixture of iso-octane and heptane.

Advantages of high octane number

(1) It prevent knocking inside the engine cylinder

(2) It allows engine manufactures to design more powerful & efficient engines.

Coal

- Also called **black gold**.
- Found in sedimentary strata [layers of soil].
- Contains **carbon, volatile matter, moisture** and **ash** [in some cases **Sulphur** and **phosphorous**]
- Mostly used for power generation and metallurgy.
- Coal reserves are six times greater than oil and petroleum reserves.

Carboniferous Coal

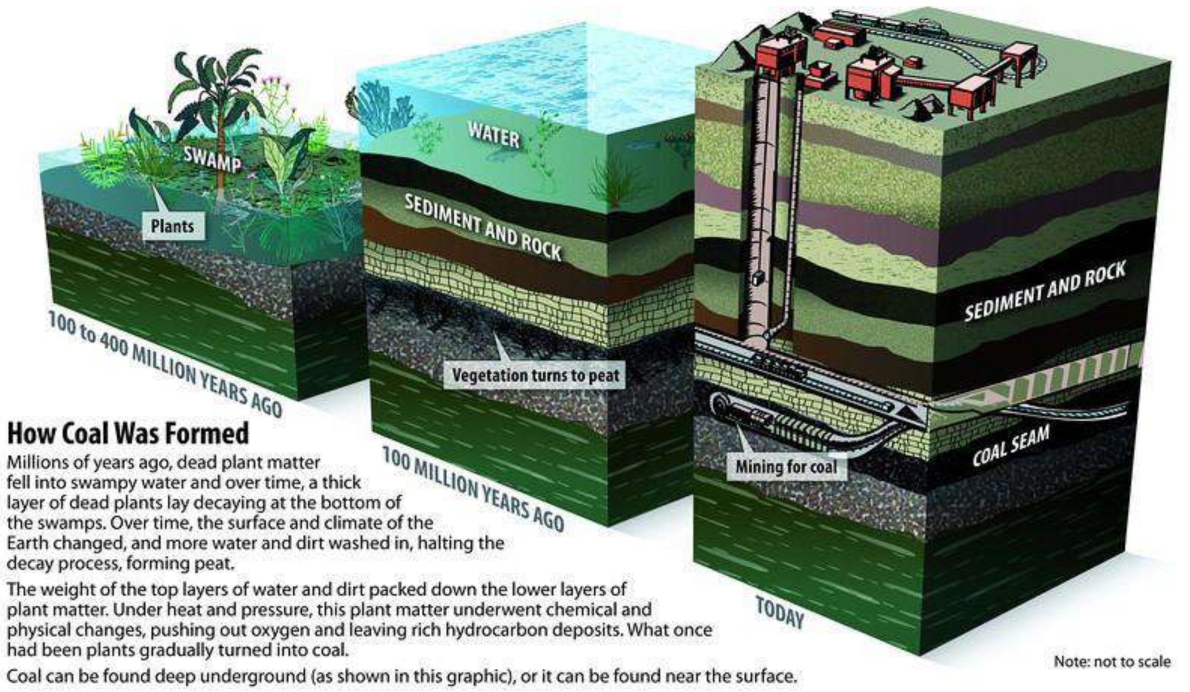
- Most of the world's coal was formed in **Carboniferous age [350 million years ago][Best quality coal].**
- **Carboniferous age:** In terms of absolute time, the Carboniferous Period began approximately 358.9 million years ago and ended 298.9 million years ago. Its duration is approximately 60 million years.
- The name Carboniferous refers to coal-bearing strata.

Formation of Coal

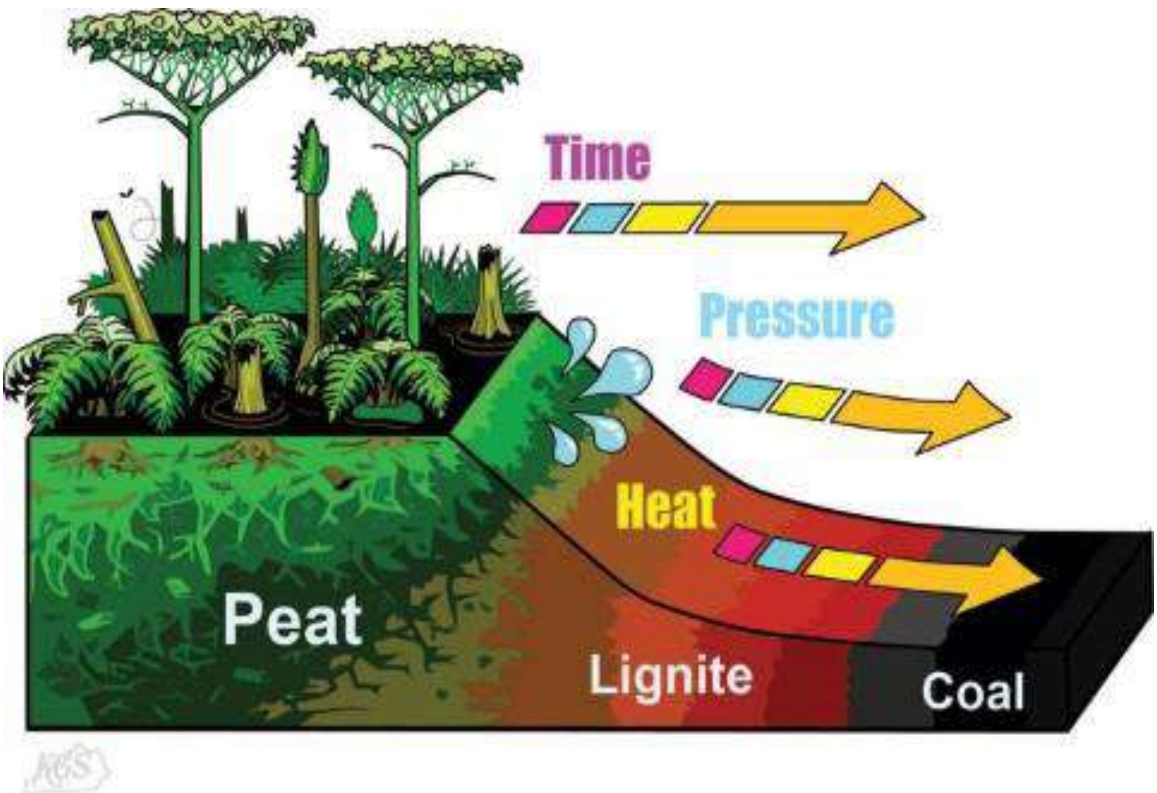
Amount of **oxygen, nitrogen and moisture content decreases** with time while the **proportion of carbon increases** [The quantity of carbon doesn't increase, only its proportion increases due to the loss of other elements].

Capacity of coal to give energy depends upon the percentage or carbon content [Older the coal, much more is its carbon content].

Percentage of carbon in coal depends upon the duration and intensity of heat and pressure on wood. [carbon content also depends on depth of formation. **More depth == more pressure and heat == better carbon content**].

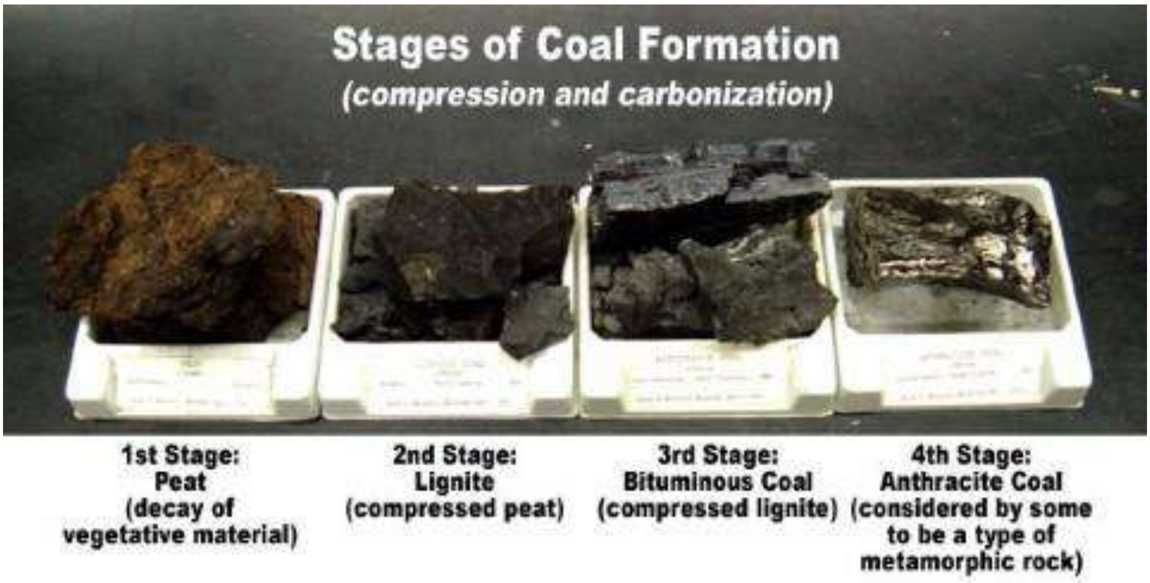


- Coal formed millions of years ago when the earth was covered with huge swampy [marshy] forests where plants – giant ferns and mosses – grew.
- As the plants grew, some died and fell into the swamp waters. New plants grew up to take their places and when these died still more grew.
- In time, there was thick layer of dead plants rotting in the swamp. The surface of the earth changed and water and dirt washed in, **stopping the decaying process**.
- More plants grew up, but they too died and fell, forming separate layers. After millions of years many layers had formed, one on top of the other.
- The weight of the top layers and the water and dirt packed down the lower layers of plant matter.
- Heat and pressure produced chemical and physical changes in the plant layers which **forced out oxygen and left rich carbon deposits**. In time, material that had been plants became coal.
- Coals are classified into three main ranks, or types: **lignite, bituminous coal, and anthracite.**
- These classifications are based on the **amount of carbon, oxygen, and hydrogen present in the coal.**
- Coals other constituents include **hydrogen, oxygen, nitrogen, ash, and sulfur.**
- Some of the undesirable chemical constituents include **chlorine and sodium**.
- In the process of transformation (coalification), ***peat is altered to lignite, lignite is altered to sub-bituminous, sub-bituminous coal is altered to bituminous coal, and bituminous coal is altered to anthracite.***



Types of Coal

- Peat, Lignite, Bituminous & Anthracite Coal.
- This division is based on carbon, ash and moisture content.



Peat

- First stage of transformation.
- Contains **less than 40 to 55 per cent carbon == more impurities.**
- Contains sufficient volatile matter and **lot of moisture** [more smoke and more pollution].
- Left to itself, it burns like **wood**, gives less heat, emits more smoke and leaves a **lot of ash.**

Lignite

- **Brown coal.**
- Lower grade coal.
- **40 to 55 per cent carbon.**
- Intermediate stage.
- Dark to black brown.
- Moisture content is high (over 35 per cent).
- It undergoes **SPONTANEOUS COMBUSTION** [Bad. Creates fire accidents in mines]

Bituminous Coal

- Soft coal; most widely available and used coal.
- Derives its name after a liquid called bitumen.
- **40 to 80 per cent carbon.**
- Moisture and volatile content (15 to 40 per cent)
- Dense, compact, and is usually of black colour.
- **Does not have traces of original vegetable material.**
- Calorific value is **very high** due to high proportion of carbon and low moisture.
- Used in production of **coke and gas**.

Anthracite Coal

- **Best quality**; hard coal.
- **80 to 95 per cent carbon**.
- Very little volatile matter.
- Negligibly small proportion of moisture.
- Semi-metallic lustre.
- **Ignites slowly** == less loss of heat == highly efficient.
- Ignites slowly and burns with a nice short **blue flame. [Complete combustion == Flame is BLUE == little or no pollutants. Example: LPG]**
- In India, it is found only in Jammu and Kashmir and that too in small quantity.

<u>Petroleum Formation</u>