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Thermodynamics

Thermodynamics. Thermodynamics deals with relations between heat and work. It predicts many relationships between properties of matter.

Thermodynamic Systems. System is a definite quantity of matter bounded by some closed surface (boundary) which is impervious to the flow of matter. Thermodynamic system is defined as any prescribed and identifiable collection of matter upon which attention is focused for investigation. Everything else other than system *i.e.*, the space and matter external to a system is known as *surroundings*. In the *closed system* there is no interchange of matter between system and surroundings but energy can cross the boundaries and the boundary itself may move or change its position. However in the *open system* interchange of both matter and energy takes place. *Isolated system* is one in which neither mass nor energy cross the boundaries and it is not influenced by the surroundings.

Thermodynamic properties. Properties of system identify the state of system. Property of the system depends solely upon the state of the system and not upon how that state has been reached. A quantity will be the property of the system if it has exact differential. *Extensive properties* are those whose value, for the entire system, equals the sum of their values for the parts of the system, like total volume, total energy etc.; and the ratio of extensive property to the mass is called the *average specific value* of that property. The properties whose value is not equal to sum of their values for parts of system are known as *intensive properties*, like temperature, pressure, density, etc. An intensive property of the system does not depend on the mass of the system whereas extensive property does. *Point function* is known as property of the system. *Path function* depends on the process, *i.e.* path followed by the process, like work. However work done in an adiabatic process between a given pair of end states depends only on the end states and not on the particular adiabatic process.

Any quantity can be called property of the system, if the change in the value of that quantity between two equilibrium states of the system is same, for all parts *e.g.* internal energy is the property of the system.

Processes. Whenever a system undergoes any change, it is said to have described a process.

Reversible process is one in which both the system and the surroundings are returned to their original states, which is not so in the case of irreversible process. In actual practice, all processes are irreversible.

Cyclic process is one in which the end states are identical *i.e.* the system after undergoing a series of processes returns to its original condition.

Quasi-static process is one in which system departs from equilibrium state only infinitesimally at every instant.

Adiabatic process is one in which there is no flow of heat between a system and its surroundings.

Zeroth Law of Thermodynamics states that when any two bodies are in thermal equilibrium with third, they are also in thermal equilibrium with each other.

Equation of state of an ideal gas is $pV = mRT$

p = pressure in N/m^2, V = volume in m^3

T = temperature in °K, m = mass in kg

R = gas constant in Nm/kg °K

According to **Van der Waals,** the following empirical equation holds for *real gases*

$$\left(p + \frac{a}{v^2}\right)(v - b) = RT$$

where a and b are constants for any one gas, but differ for different gases and v = mass specific volume.

Compressibility factor $Z = \frac{pv}{RT}$

First Law of Thermodynamics

It concerns principle of conservation of energy. According to it energy can neither be created nor destroyed. It changes from one form to other. The total sum of all energy remains constant.

According to it, $E_2 - E_1 = JQ - W$

where $E_2 - E_1$ = change in total energy of system

Q = quantity of heat flowing into the system

J = 4.186 joules/calorie

W = work done by the system.

Work. According to thermodynamics, work is defined as the energy in transition which flows from a system to the surroundings during a given process if the sole effect external to the system can be reduced to the raising of a weight.

For quasi-static process, work done can be expressed as

$$W = \int_{V_1}^{V_2} pdV$$

Work done in a free expansion in zero

Heat flow $$Q = m\int_{T_1}^{T_2} cdT$$

where c =specific heat capacity for the process and can be expressed as function of T

Work done in isothermal process = $mRT \log \frac{V_2}{V_1}$ and in adiabatic expansion = $mc_v (T_1 - T_2)$.

Carnot Cycle. It comprises four processes as follows (Refer Fig. 1.1) :

(*i*) Quasi-static isothermal process absorbing heat Q_1 from heat reservoir at temperature T_1.

(*ii*) Quasi-static adiabatic process from T_1 to T_2 and W_1 is the work done.

(*iii*) Quasi-static isothermal heat rejection Q_2 to a low temperature reservoir at temperature T_2.

(*iv*) Quasi-static adiabatic process returning the process to initial state.

Actual heat engines are based on this theoretical cycle and carry the same sequence of processes. It represents the ultimate ideal efficiency of heat engine. Carnot cycle efficiency can be increased by increasing T_1 and lowering T_2.

If W =net work done by system in Carnot cycle, and as the system is carried through a cycle, there is no change in its internal energy, therefore, $Q_1 - Q_2 = W$.

$$\eta \text{ of heat engine} = \frac{\text{Work output}}{\text{Heat input}}$$

$$= \frac{W}{Q_1} = \frac{Q_1 - Q_2}{Q_1}$$

Also isothermal work $W_{AB} = mRT_1 \log \frac{V_B}{V_A}$

Work done in adiabatic expansion from

$$B \text{ to } C = W_{BC} = mc_v (T_1 - T_2)$$

Isothermal work $W_{CD} = mRT_2 \log \frac{V_D}{V_C}$

Work done in adiabatic compression from D to A

$$(W_{DA}) = mc_v (T_2 - T_1)$$

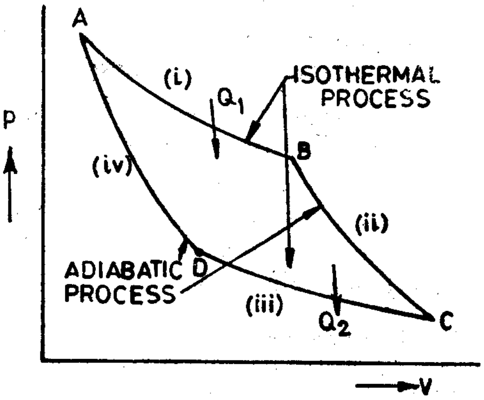


Fig. 1.1. Carnot cycle.

$$\therefore \quad W = W_{AB} + W_{BC} + W_{CD} + W_{DA} \text{ and } Q_1 = W_{AB}$$

$$\therefore \quad \eta = \frac{mR\left(T_1 \log \frac{V_B}{V_A} + T_2 \log \frac{V_D}{V_C}\right)}{mRT_1 \log \frac{V_B}{V_A}}$$

As points B and C lie on same adiabatic as the points D and A

$$T_1^{\frac{1}{\gamma - 1}} V_B = T_2^{\frac{1}{\gamma - 1}} V_C \quad \text{and} \quad T_1^{\frac{1}{\gamma - 1}} V_A = T_2^{\frac{1}{\gamma - 1}} V_D$$

Dividing these, $\frac{V_B}{V_A} = \frac{V_C}{V_D}$ and $\eta = \frac{T_1 - T_2}{T_1}$

If this cycle is operated in the reverse direction, we get Carnot refrigerator, for which coefficient of performance $= T_2/(T_1 - T_2)$.

Enthalpy $H = U + pV$ where $U =$ internal energy

Specific enthalpy $h = u + pv$

Heat — Energy in transition flowing by virtue of temperature difference from one system to other when two are in contact is called heat.

Specific Heat — Specific heat is the heat required by a unit mass of a substance to raise temperature by one degree.

c_p = specific heat capacity at constant pressure $= \left(\frac{\partial h}{\partial T}\right)_p$

c_v = specific heat capacity at constant volume $= \left(\frac{\partial u}{\partial T}\right)_v$

For atmospheric air, c_p and c_v are 0.24 and 0.171 respectively.

Further $c_p - c_v = R/J$ and $c_p/c_v = \gamma = 1.4$ (also expressed as k)

Energy Equation for Steady Flow

According to *energy equation* for *steady flow,*

$$(\text{Enthalpy}_1 + \text{P.E.}_1 + \text{K.E.}_1) - (\text{Enthalpy}_2 + \text{P.E.}_2 + \text{K.E.}_2) - \text{Work} + \text{Heat} = 0$$

Second Law of Thermodynamics

According to **Kelvin-Plank statement** — No cyclic process is possible whose result is the flow of heat from a single heat reservoir and the performance of an equivalent amount of work on a work reservoir.

According to **Clausius statement** — No cyclic process is possible whose result is the flow of heat out of a heat reservoir at one temperature and the flow of an equal quantity of heat into a second reservoir at a high temperature.

Second law of thermodynamics is sometimes also stated as : A perpetual motion machine of second kind (a cyclic device, which would continuously abstract heat from a single reservoir and convert it completely to mechanical work) is impossible.

Reversible process. A process is reversible if, at the end of the process, the initial states of all systems taking part in the process can be restored, by any means whatsoever, without any outstanding changes in the states of other systems. Otherwise the process is *irreversible.*

The two important derivations from second law of thermodynamics for heat engines operating between two reservoirs at different temperatures are :

(*i*) It is impossible to construct a heat engine, operating in cycle between two reservoirs at different temperatures, having more efficiency than a reversible engine operating between the same two reservoirs. Or, no cycle can be more efficient than reversible cycle operating between given temperature limits.

(*ii*) All reversible engines operating between two reservoirs at given temperatures have the same efficiency.

Clausius Inequality. It provides a relation between the temperatures of an arbitrary number of heat reservoirs and the quantities of heat given up or absorbed by them during a cyclic process (reversible or irreversible) involving interchange of heat with the reservoirs.

According to it $\sum \frac{Q}{T} \leq 0$

If a system is carried around a reversible cycle and the heat dQ added to it at every point is divided by its temperature at that point, then the sum of all such quotients is zero, *i.e.*

$$\int \frac{dQ}{T} = 0, \qquad \text{where } \int = \text{integration along cyclic path.}$$

Entropy. Entropy is an index of the unavailability or degradation of energy. Heat always flows from hot to cold bodies and thus becomes degraded or less available.

Energy that goes down the sink becomes less available for useful work even though most of it may be recovered by heat economy devices. This unavailability of energy is measured by entropy. We are usually, interested in changes in entropy. The change in entropy of a system between any two equilibrium states is found by taking the system along any reversible path connecting the states, dividing the heat added to the system at each point of the path by the temperature of the system, and summing the quotients thus obtained.

Entropy is the property of a substance like pressure, volume, or internal energy.

Entropy changes always accompany actual heat transfers, but entropy changes also occur without transfer of heat.

For a reversible transfer of heat, change in entropy

$$\Delta S = S_2 - S_1 = \int \frac{dQ}{T}$$

For reversible adiabatic process, change of entropy is zero.

In a reversible process, if the entropy of the system increases then the entropy of the surroundings decreases by an equal amount. In irreversible process, the entropy is not conserved and the net difference of two is more than zero. No process between two equilibrium states is possible if it would result in a decrease in the total entropy of a system and its surroundings.

Gas Laws

Perfect gas. A perfect gas is one which strictly obeys all the five gas laws given below under all conditions of pressure and temperature.

Boyle's law. $PV =$ constant, if temperature T is constant.

Charles' law. $V \propto T$ or $V/T =$ constant if P is constant, or in other words all perfect gases change in volume by 1/273 of its original volume at 0°C for every 1°C change in temperature, when pressure is kept constant.

Gay-Lussac law. $P \propto T$, if V is constant.

Joule's law. Change of internal energy $dU \propto dT$.

Avogadro's law. Molecular weight of all the perfect gases occupy the same volume under same pressure and temperature, or equal volumes of all gases, at the same pressure and temperature, contain equal number of molecules.

The molecular weight expressed in gm (*i.e.* 1 gm mole) of all gases, at NTP, occupies a volume of 22.4 litres.

General gas equation $\qquad \dfrac{p_1 V_1}{T_1} = \dfrac{p_2 V_2}{T_2} = \dfrac{p_3 V_3}{T_3} = \ldots =$ constant

Characteristic equation of a gas $\qquad pV = mRT = nMRT$

where (m = mass of gas)

n = no. of moles of gas and R is the gas constant

M = molecular weight, and its value is 29.27 Kgm/kg/ °K or 287 J/kg/ °K

Universal gas constant or *molar constant.* It is the product of the gas constant and the molecular weight of the gas. Its value for atmospheric air is equal to 848 kgm per kg mole per °K or 8314 J/kg mole/°K.

General Property Relations for Perfect Gases

$$\Delta U = \int_1^2 C_v\, dT, \text{ if } C_v \text{ is a function of } T.$$

or

$$= C_v (T_2 - T_1), \text{ if } C_v = \text{constant}$$

$$= \frac{1}{J(k-1)} (p_2 V_2 - p_1 V_1) \qquad \left(k = \frac{C_p}{C_v};\ C_p - C_v = R/J\right)$$

(k is also sometimes denoted by γ)

$$\Delta H = \int_1^2 C_p\, dT, \text{ if } C_p \text{ is function of } T$$

$$= C_p (T_2 - T_1), \text{ if } C_p = \text{constant}$$

$$= \frac{k}{J(k-1)} (p_2 V_2 - p_1 V_1) \left[C_p - C_v = \frac{R}{J} \text{ or } C_p = \frac{Rk}{J(k-1)}\right]$$

$$\Delta S = \int_1^2 C_v \frac{dT}{T} + \frac{R}{J} \log_e \frac{V_2}{V_1}, \text{ if } C_v = f(T)$$

$$= C_v \log_e \frac{T_2}{T_1} + \frac{R}{J} \log_e \frac{V_2}{V_1}, \text{ if } C_v = \text{constant}$$

$$= \int_1^2 C_v \frac{dT}{T} - \frac{R}{J} \log_e \frac{p_2}{p_1}, \text{ if } C_v = f(T)$$

$$= C_p \log_e \frac{T_2}{T_1} - \frac{R}{J} \log_e \frac{p_2}{p_1}, \text{ if } C_v = \text{constant}$$

$$= c_p \log_e \frac{V_2}{V_1} + C_v \log_e \frac{p_2}{p_1}, \text{ if } C_p \text{ and } C_v \text{ are constant.}$$

For irreversible polytropic and adiabatic processes

$$pV^n = \text{constant} \qquad n = \text{polytropic index} = \frac{\log (p_2/p_1)}{\log (V_1/V_2)}$$

$$TV^{n-1} = \text{constant}$$

$$\frac{T}{p^{\frac{n-1}{n}}} = \text{constant}$$

$$\Delta U = \int_1^2 C_v dT \qquad \text{or} \qquad \Delta U = \frac{R}{J(k-1)} T_1 \left[\left(\frac{p_2}{p_1}\right)^{\frac{n-1}{n}} - 1 \right]$$

$$\Delta H = \int_1^2 C_p \, dT \qquad \text{or} \qquad \Delta H = \frac{kR}{J(k-1)} T_1 \left[\left(\frac{p_2}{p_1}\right)^{\frac{n-1}{n}} - 1 \right]$$

Work done $= \dfrac{p_1 v_1 - p_2 v_2}{J(n-1)} = \dfrac{mR\,(T_1 - T_2)}{J\,(n-1)}$

$= mC_v\,(T_1 - T_2)$

and heat transfer $= \dfrac{k-n}{k-1} \times$ work done

$$\Delta S = C_v \frac{n-k}{n} \log_e \frac{p_2}{p_1}$$

where $\left[\begin{array}{l} n > k \text{ in a compression process} \\ n < k \text{ in an expansion process} \end{array}\right]$

Graphical Representation of Gas State Changes (Refer Figs. 1.2 and 1.3).

Thermodynamic Non-flow Processes

Constant volume process. No work is done in this process. Addition of heat increases the temperature and hence internal energy. For this process $dQ = dW + dU = dU$ (since work done = 0).

The ratio of increase of internal energy to the corresponding increase of temperature is called the specific heat at constant volume.

Constant pressure process. Heating causes increase in volume and temperature, and external work is done.

$$dQ = dW + dU = pdV + dU = d(pV + U) = dH$$

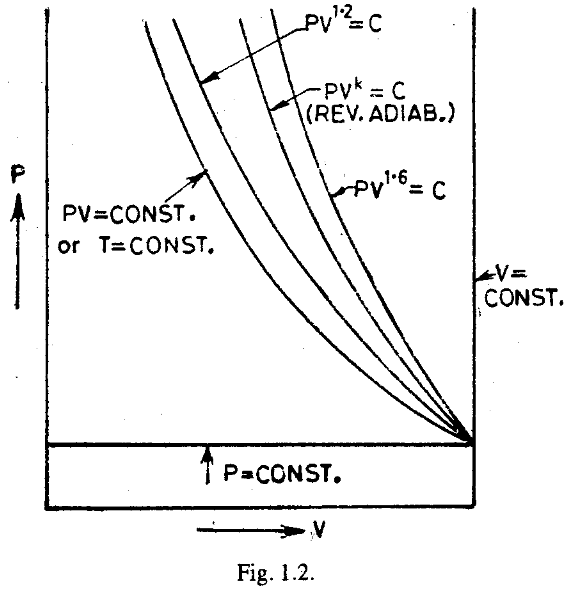


Fig. 1.2.

Hence addition of heat increases temperature and hence enthaply. The ratio of increase in enthaply to the corresponding increase in temperature is called C_p.

Isothermal process. (Hyperbolic expansion) (T = constant). No change in internal energy. pV = constant

Polytropic expansion.

$$pv^n = c (n = \text{index of expansion})$$

Work done $= \dfrac{p_1V_1 - p_2V_2}{n-1}$

$$= \frac{p_1V_1}{n-1}\left[1 - \left(\frac{V_2}{V_1}\right)^{n-1}\right]$$

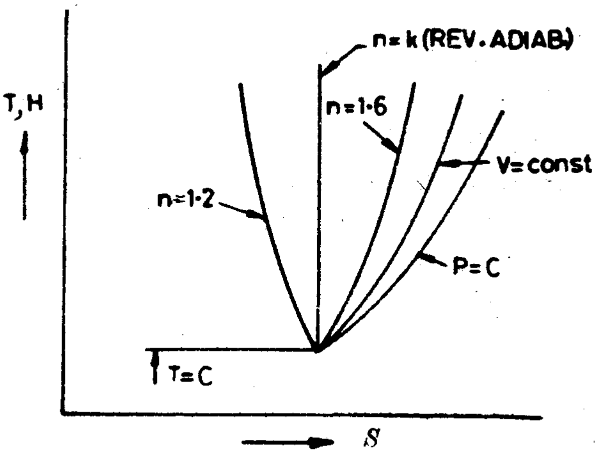


Fig. 1.3.

Change of entropy $= \dfrac{\gamma - n}{\gamma - 1}\dfrac{R}{J}\log_e\dfrac{V_2}{V_1}$

Adiabatic expansion. No heat exch-ange takes place, $pv^\gamma = c$.

Work done $= \dfrac{p_1V_1 - p_2V_2}{\gamma - 1}$

$$= \frac{mR\,(T_1 - T_2)}{\gamma - 1}$$

$$= mC_v\,(T_1 - T_2)$$

For miscellaneous process $p = \dfrac{C_1}{V^2} + C_2$

Work done $= C_1\left(\dfrac{1}{V_1} - \dfrac{1}{V_2}\right) + C_2\,(V_2 - V_1)$

Free expansion. Fluid expands suddenly into vacuum chamber through an orifice of large size ($H = c$). Work done = 0.

Throttling. Fluid expands from high pressure to low pressure without doing any work. No heat transfer takes place.

Relations for Ideal Gas Processes. It is possible to tabulate the equations applicable for determination of heat, work etc. for simplest processes in cases where ideal gas is the medium and the process is reversible with constant specific heats. (Refer Table 1.1 on next page).

Ideal Gas Power Cycles. These use perfect gas as a working medium.

Efficiency of the engines

(*i*) **Air standard efficiency** is a hypothetical efficiency, which is used for comparing the efficiencies of various cycles. It is defined as the ratio of ideal work done to heat supplied or is equal to ratio of (heat supplied – heat rejected) and heat supplied.

(*ii*) **Thermal efficiency** of an engine is the ratio of indicated work done to heat supplied.

(*iii*) **Relative efficiency** is the ratio of thermal efficiency to air standard efficiency.

(*iv*) **Mechanical efficiency** is the ratio of brake or actual work done to the indicated work done.

(*v*) **Overall efficiency** is the ratio of brake or actual work done to the heat supplied. This is also called brake thermal efficiency.

Mean effective pressure. It is defined as the ratio of work done per cycle to the stroke volume. It can be determined by dividing the area of pressure volume (p-V) diagram by length of the diagram.

Carnot Cycle. It consists of two isothermals and two isentropics (Refer Fig. 1.4). Heat is supplied at constant temperature T_1 (process 2—3) and rejected at constant temperature T_2 (process 4—1).

Table. Relations for Ideal Gas Processes

Process	*Isothermal* *T = const.*	*P = constant*	*v = constant*	*Isentropic* *S = constant*	
p, v, T relations	$pv = \text{const.}$	$\frac{v}{T} = \text{const.}$	$\frac{p}{T} = \text{const.}$	$pv^k = \text{const.}$ $\frac{p^{\frac{k-1}{k}}}{T}$ = constant	$Tv^{(k-1)} =$ constant same as isentropic with $k = n$
Polytropic index n	$n = 1$	$n = 0$	$n = \infty$	$n = k$	$n = n$
Now-flow work $\int pdv$	$pv \log_e \frac{v_f}{v_i}$ $= mRT \log_e \frac{v_f}{v_i}$	$p \, \Delta \, v$ $= mR\Delta T$	0	$mC_v\Delta T$	$\frac{p_fV_f - p_iV_i}{1-n}$
Steady flow work — $\int vdp$	$pv \log_e \frac{pi}{pf}$	0	$v\Delta p$	$mC_p\Delta T$	$C_n \Delta \, T =$ $C_v \, \Delta \, T \, (k-1)$
Heat $\int Tds$	$pv \log_e \frac{p_i}{p_f}$	$mC_p\Delta T$	$mC_v\Delta T$	0	$C_n \, \Delta T =$ $C_v \left(\frac{k-n}{1-n}\right) \Delta \, T$
ΔU	0	$mC_v\Delta T$	$mC_v\Delta T$	$mC_v\Delta T$	$C_v \, \Delta T$
ΔH	0	$mC_p\Delta T$	$mC_p\Delta T$	$mC_p\Delta T$	$C_p \, \Delta \, T$
ΔS	$mR \log_e \frac{p_i}{p_f}$ Or $mR \log_e \frac{v_f}{v_i}$	$mC_p \log_e \frac{T_f}{T_i}$	$mC_v \log_e \frac{T_f}{T_i}$	0	$C_v \left(\frac{k-n}{1-n}\right)$ $\log_e \frac{T_f}{T_i}$
Specific heat	α	C_p	C_v	0	$C_n = C_v \left(\frac{k-n}{1-n}\right)$

(i and f represent initial and final conditions, $\Delta T = T_f - T_i$, Compression ratio = expansion ratio

$$Q_{net} = W_{net} = (T_3 - T_4) \, R \log_e \frac{p_2}{p_3}$$

$$Q_{12} = Q_{34} = 0, \; Q_{23} = W_{23} = p_2 v_2 \log_e \frac{p_2}{p_3}$$

$$W_{12} = C_v(T_2 - T_1),\ W_{34} = C_v(T_4 - T_3)$$

$$U_3 - U_2 = 0,\ U_1 - U_4 = 0,\ Q_{41} = W_{41} = p_4v_4 \log_e \frac{p_4}{p_1}$$

$$\eta = \frac{T_2 - T_1}{T_2} = \frac{T_3 - T_4}{T_3}$$

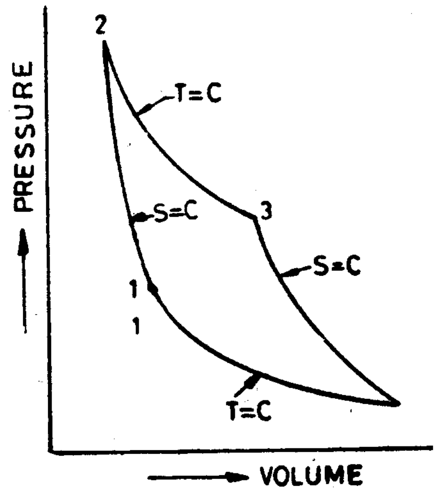


Fig. 1.4. Carnot cycle.

Otto Cycle. It consists of two insentropics and two constant volume processes (Refer Fig. 1.5). Heat is supplied at constant volume process 1—2 and rejected at constant volume 3—4. Compression ratio is assumed to be equal to expansion ratio $= r$

$$Q_{net} = W_{net} = C_v\,[(T_2 - T_1) - (T_3 - T_4)]$$

$$Q_{12} = C_v(T_2 - T_1),\ Q_{34} = C_v\,(T_4 - T_3),$$

$$Q_{23} = Q_{41} = 0$$

$$W_{12} = W_{34} = 0\ ;\ W_{41} = C_v\,(T_4 - T_1),$$

$$W_{23} = C_v\,(T_3 - T_2)$$

$$\eta = 1 - \frac{T_3 - T_4}{T_2 - T_1} = 1 - \frac{(T_2/r^{\gamma-1} - T_1/r^{\gamma-1})}{(T_2 - T_1)}$$

$$= 1 - \frac{1}{r^{\gamma-1}}$$

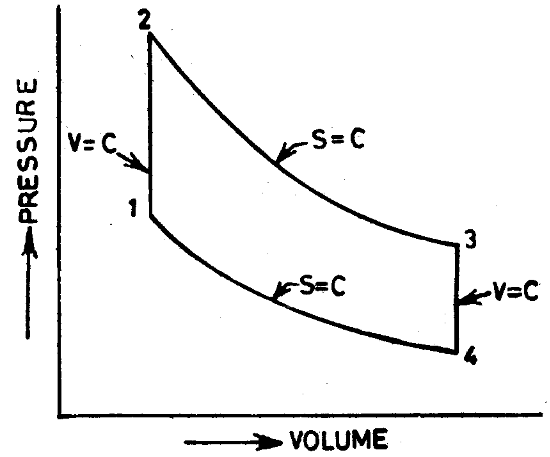


Fig. 1.5. Otto cycle.

Diesel Cycle. It consists of two isentropics, one constant volume and one constant pressure process. (Refer Fig. 1.6). Heat is supplied during constant pressure process 2—3 and is rejected during constant volume process 4—1. No heat is supplied or rejected during adiabatic processes, 3—4 and 1—2.

$$Q_{net} = W_{net} = C_p\,(T_3 - T_2) - C_v\,(T_4 - T_1)$$

$$Q_{23} = C_p\,(T_3 - T_2)$$

$$Q_{41} = C_v(T_4 - T_1),\ Q_{12} = Q_{34} = 0$$

$$W_{23} = p_2(V_3 - V_2),\ W_{41} = 0,\ W_{12} = C_v(T_2 - T_1),\ W_{34} = C_v(T_4 - T_3)$$

$$\eta = \frac{C_p(T_3 - T_2) - C_v(T_4 - T_1)}{C_p(T_3 - T_2)} = 1 - \frac{C_v(T_4 - T_1)}{C_p(T_3 - T_2)}$$

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

$$\gamma = \text{Compression ratio} = \frac{V_1}{V_2}$$

and r_c = heat additional cut off ratio $= \frac{V_3}{V_2}$.

$$\frac{T_2}{T_1} = r^{\gamma - 1},\ \frac{T_3}{T_2} = \frac{V_3}{V_2} = r_c$$

$$\therefore \quad T_3 = T_2 r_c = T_1 r^{\gamma - 1} r_c$$

and $\quad T_4 = T_1 r_c^{\gamma}$

$$\therefore \quad \eta = 1 - \frac{1}{\gamma r^{\gamma - 1}}\left[\frac{r_c^{\gamma} - 1}{r_c - 1}\right]$$

Joule or Brayton Cycle. It consists of two insentropic and two constant pressure processes for heat supply and heat rejection (Refer Fig. 1.7). It is used for gas turbines. Reversed Joule cycle is used in air refrigerators.

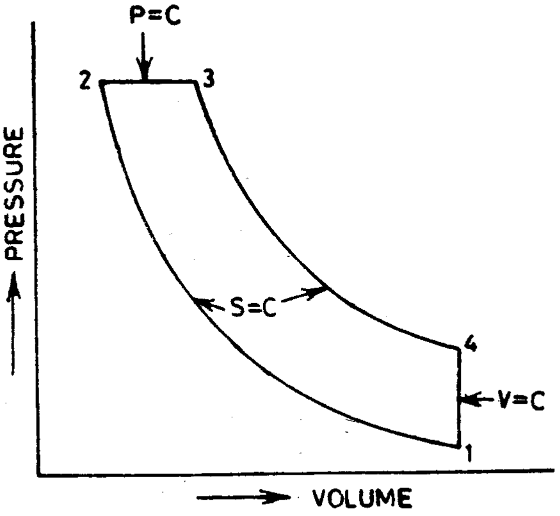


Fig. 1.6. Diesel cycle.

$$Q_{net} = W_{net} = C_p\,[T_3 - T_2) - (T_4 - T_1)]$$

$$\eta = 1 - \frac{T_4 - T_1}{T_3 - T_2} = 1 - \frac{1}{r^{\gamma - 1}}$$

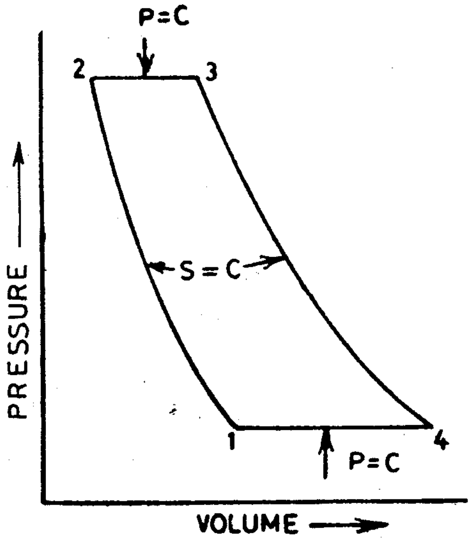


Fig. 1.7. Brayton cycle.

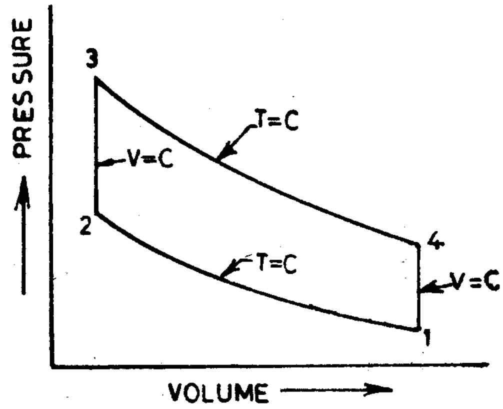


Fig. 1.8. Stirling cycle.

Atkinson Cycle. It consists of two adiabatics, a constant volume heat addition, and a constant pressure heat rejection process. This cycle is used by constant volume type gas turbines.

Stirling Cycle. It consists of two isothermal and two constant volume processes. (Refer Fig. 1.8). In order to make the cycle reversible, the constant volume processes are performed with the help of regenerator. Practical efficiency of this cycle depends on the degree of regeneration. It is used in hot air engines.

The heat rejected in process 4—1 is used to partly regenerate gas during the process 2—3.

Let percentage of regeneration from rejected heat = r.

$$Q_{41} = C_v(T_4 - T_1) \qquad \text{(rejected)}$$

$$Q_{23} = (1 - r)\, C_v\, (T_3 - T_2) \qquad \text{(supplied)}$$

$$Q_{34} = RT_3 \log_e \frac{p_3}{p_4} = RT_3 \log_e \frac{V_1}{V_2} \qquad \text{(supplied)}$$

Total heat supplied $= Q_{23} + Q_{34}$

Net work done $= W_{34} - W_{12} = RT_3 \log_e \frac{p_3}{p_4} - RT_1 \log_e \frac{p_2}{p_1}$

$$= R(T_3 - T_1) \log_e \frac{p_3}{p_4} \qquad \left(\because \frac{p_3}{p_4} = \frac{p_2}{p_1}\right)$$

$$\eta = \frac{W_{net}}{Q_{23} + Q_{34}}$$

If η of regenerator is assumed to be 100 %, then

$$Q_{23} = Q_{41}. \text{ Then } \eta = \frac{Q_{34} - Q_{12}}{Q_{34}} = \frac{T_3 - T_2}{T_3}$$

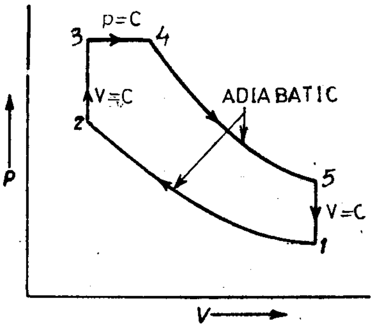
Ericsson Cycle. It consists of two isothermal processes, and two reversible constant pressure processes. It is a reversible process and its efficiency is equal to that of Carnot cycle. It is an ideal cycle for turbines using multistage compression and multistage expansion.

Dual cycle. It consists of two constant volume processes, two adiabatic processes and one constant pressure process. Heat is supplied partly at constant volume process 2—3 and partly at constant pressure process 3—4 and is rejected at constant volume process 5—1.

Air standard efficiency

$$= \frac{C_v\,[T_3 - T_2] + C_p\,[T_4 - T_3] - C_p\,(T_5 - T_1)}{C_v\,(T_3 - T_2) + C_p\,(T_4 - T_3)}$$

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



Vapour Cycles

Rankine Cycle. It is the ideal representation for the vapour power cycle. It consists of five processes, two isothermals, two isentropics, and one constant pressure. (Refer Fig. 1.10).

$$Q_{24} = H_4 - H_2,\ Q_{51} = H_1 - H_5,\ W_{45} = H_5 - H_4$$

$$W_{12} = H_1 - H_2 = V(p_1 - p_2) \text{ approx.}$$

$$\eta = \frac{(H_5 - H_4) + W_{12}}{H_4 - H_2}$$

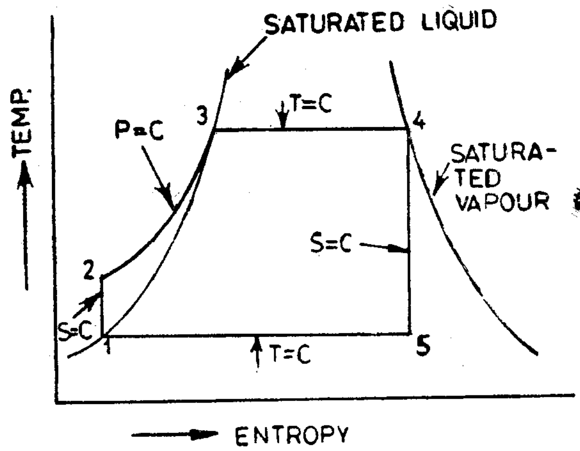


Fig. 1.10. Rankine Cycle.

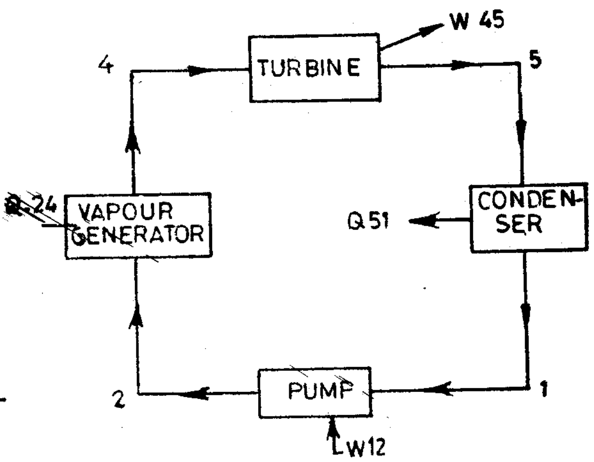


Fig. 1.11. Vapour Power System.

W_{12} is very small, usually, $\eta = \dfrac{H_5 - H_4}{H_4 - H_2}$

Compression Refrigeration Cycle. It consists of two constant pressure processes, an isentropic process, and an irreversible throttling process. (Refer Fig. 1.12).

$$Q_{12} = Q_{34} = 0, Q_{23} = H_3 - H_2$$
$$Q_{14} = H_4 - H_1,$$
$$W_{23} = W_{41} = W_{23} = 0, H_3 = H_4$$
$$\text{C.O.P.} = \frac{Q_{41}}{W_{12}} = \frac{H_1 - H_4}{H_2 - H_1}$$

Mixture of Gases and Vapours

According of Dalton's law, the total pressure of a mixture of ideal as well as real gases is equal to the sum of the partial pressures of the constituents.

Partial pressure of each constituent is defined as the pressure it would exert if it alone occupied the volume of the mixture at the same temperature as that of the mixture.

Thus considering Dalton's law for ideal gases

$$p = p_1 + p_2 + p_3 + \dots$$
$$= \frac{T}{V}(m_1R_1 + m_2R_2 + m_3R_3 + \dots)$$

or $pV = T\Sigma m_iR_i$

where R = apparent specific gas constant of mixture

$$= \frac{m_1R_1 + m_2R_2 + \dots}{m_1 + m_2 + \dots} = \frac{\Sigma m_iR_i}{\Sigma m_i}$$

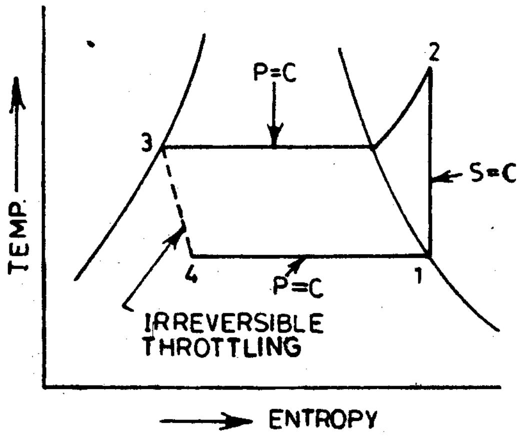


Fig. 1.12. Compression Refrigeration cycle.

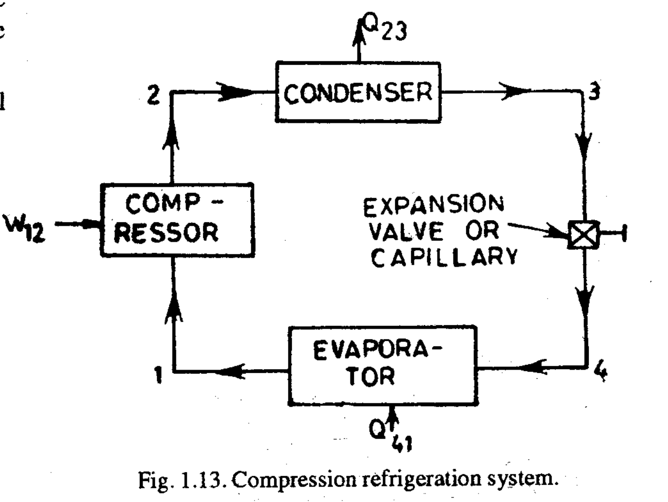


Fig. 1.13. Compression refrigeration system.

$$= \frac{\Sigma m_i R_i}{m}$$

$$\therefore \qquad pV = mRT$$

which has same form as equation of state of single ideal gas, and further it proves, that a mixture of ideal gases is itself an ideal gas.

Mole fraction x_i of a constituent of a mixture

$$x_i = \frac{n_i}{\Sigma n_i} = \frac{n_i}{n}$$

where n_i = No. of moles of any constituent

n = total No. of moles of all constituents.

Sum of mole fraction of all the constituents equals unity

$$\Sigma x_i = \frac{\Sigma n_i}{n} = \frac{n}{n} = 1$$

If M_i = molecular weight of any constituent, then mass m_i of that constituent is

$$m_i = n_i M_i = n x_i M_i$$

and total mass $m = \Sigma m_i = n \, \Sigma x_i M_i$

The apparent molecular weight M of the mixture is defined as ratio of total mass to the total number of moles,

$$M = \frac{m}{n} = \Sigma x_i M_i$$

The mole fraction of any constituent of a mixture of ideal gases is also equal to ratio of partial pressure of that gas to the total pressure of the mixture.

According to Amagat-Leduc law, the volume of a mixture of ideal gases is equal to the sum of partial volumes of the constituent gases, when the partial volumes are determined at the pressure and temperature of the mixture.

According to Gibb's law, total entropy of a mixture of ideal gases is equal to the sum of the partial entropies of its constituents.

i.e., $ms = m_1 s_1 + m_2 s_2 + \ldots = \Sigma m_i s_i.$

Similarly, $mu = m_1 u_1 + m_2 u_2 + \ldots = \Sigma m_i u_i$

$mh = m_1 h_1 + m_2 h_2 + .. \Sigma m_i h_i.$

Fuels. Fuels may be solid, liquid or gaseous type. A good fuel should have low ignition temperature, high calorific value, easy to store, produce minimum smoke and be economical.

Combustion of Fuel. The fuel is comprised of carbon and hydrogen mainly with a small amount of sulphur too. The combustion of a fuel is a chemical process in which oxygen reacts with the main constituents of fuel producing heat transfer from the reacting system. The chemical process can be represented by a chemical equation quantitatively and qualitatively. The smallest quantity which takes part in a chemical reaction is a molecule, hence a quantity of separate gas in a chemical equation must be stated as H_2, O_2 and N_2.

Combustion of Carbon. (*a*) When the combustion process is complete *i.e.* when carbon burns in air having less than minimum quantity required for complete combustion, then the process is represented by an equation

$$2C + O_2 = 2CO + 2417 \text{ kcal/kg of carbon}$$

Substituting the atomic weight of each substance in the equation

$$2 \times 12 + 32 = 2\,[28] \quad \text{or} \quad 1 + \frac{4}{3} = \frac{7}{3}$$

i.e. 1 kg of carbon + $\frac{4}{3}$ kg of oxygen = $\frac{7}{3}$ kg of CO.

(*b*) When carbon burns in plentiful supply of oxygen, the process is represented by a chemical equation.

$$C + O_2 = CO_2 + 8100 \text{ kcal per kg of carbon}$$

In other words 1 mole of carbon requires one mole of O_2 to form one mole of CO_2.

$$12 + 32 = 12 + 32 = 44 : 1 + \frac{8}{3} = \frac{11}{3}$$

i.e. 1 kg of carbon + $\frac{8}{3}$ kg of O_2 = $\frac{11}{3}$ kg of CO_2

Since air by weight has 23% oxygen, therefore air needed for combustion of

$$1 \text{ kg C to } CO_2 \text{ is } \frac{8}{3 \times 0.23} = 11.54 \text{ kg.}$$

Combustion of Hydrogen. When hydrogen combines with O_2 chemically, it forms H_2O and is represented by an equation as follows :

$$2H_2 + O_2 = 2H_2O + 34{,}200 \text{ kcal/kg of hydrogen}$$

$$2 \times 2 + 2 \times 16 = 2 \times [2 + 16] = 36 \,;\, 1 + 8 = 9$$

i.e. 1 kg of H_2 + 8 kg of O_2 = 9 kg of H_2O.

Combustion of Sulphur. When sulphur combines with oxygen chemically, it forms SO_2.

$$S + O_2 = SO_2 + 2165 \text{ kcal per kg. of sulphur}$$

$$32 + 32 = 64,\ 1 + 1 = 2$$

i.e., 1 kg. of S + 1 kg. of O_2 = 2 kg. of SO_2

All other combustion equations can be treated similarly.

Calorific value of fuel. The combustion of fuel is accompanied by a large amount of evolution of heat. The number of heat units evolved in kcal by the complete combustion of the fuel is called the calorific value of fuel. It is measured in two ways.

Higher calorific value (H.C.V.). The higher or gross calorific value of fuel as it is sometimes called is the total amount of heat liberated by the unit quantity of fuel *i.e.* 1 kg, when the products of combustion are cooled to 15°C.

Lower calorific value (L.C.V.). The lower calorific value of fuel is defined as higher calorific value minus heat taken away by water due to combustion and surface moisture.

The evaporation of water is assumed to take place at partial pressure corresponding to 15°C saturation temperature of water and therefore supposed to take latent heat at this pressure. This latent heat is 588.76 kcal/kg.

$\therefore$ L.C.V. = H.C.V. – Weight of water × Latent heat (588.76)

Calorific value can be determined by bomb calorimeter or by Boy's gas calorimeter.

Proximate Analysis. Proximate analysis is the determination of percentage of moisture, volatile matter, fixed carbon and ash in the fuel. Proximate analysis is easy; and quick to determine,, compared with ultimate analysis and is usually done for commercial purposes.

Ultimate analysis. It is the determination of percentage by weight of carbon, hydrogen, oxygen, nitrogen, sulphur and ash in the fuel.

The coal analysis may be given on either 'dry' or 'as-fired basis'

If given by dry basis, it can be changed to 'as-fired' basis by multiplying each constituent by the factor

$$1 - \left(\frac{\%\ \text{moisture}}{100}\right)$$

To change from wet or as fired basis to dry basis, divide each percentage by

$$1 - \left[\frac{\%\ \text{of moisture} + \%\ \text{ash}}{100}\right]$$

Composition of Air. Atmospheric air is a volumetric composition of 20.99% oxygen, 78.03% nitrogen and 1% argon with small quantity of several inert gases such as water vapours, carbon dioxide, helium, hydrogen, neon etc. For approximate calculations, it is sufficient enough to include all inert gases as nitrogen and to use the analysis as follows :

$$\left.\begin{array}{l}\text{Oxygen} = 21\% \\ \text{Nitrogen} = 71\%\end{array}\right\}\text{by volume ;} \quad \left.\begin{array}{l}\text{Oxygen} = 23\% \\ \text{Nitrogen} = 77\%\end{array}\right\}\text{by weight}$$

Conversion of Volumetric Analysis to Weight Analysis. If the volume analysis of any gas is known, it can be converted to weight analysis by multiplying the volume of each constituent by its molecular weight. This will give the proportional weight of the constituents, then adding up these weights and dividing each by the total weight, the analysis by weight is obtained.

Conversion of Gravimetric Analysis to Volumetric Analysis. The gravimetric analysis of any fuel can be converted to volume analysis by dividing the weight of each constituent by molecular weight. This will give the proportional volumes of the constituents and then by adding these volumes and dividing each by the total, the per cent analysis by volume is obtained.

The degree of efficiency of fuel combustion is determined by calculations involving flue gas analysis obtained by Orsat apparatus.

Minimum air required for complete combustion of a fuel. The minimum weight of air required for a solid and liquid fuel can be found from the gravimetric analysis of the fuel. For a gaseous fuel, the minimum volume of air required is generally obtained from the volumetric analysis of the gas.

Minimum air required per kg of solid or liquid fuel burnt

$$= \frac{100}{23}\left[\frac{8}{3}C + 8\left(H_2 - \frac{O_2}{8}\right) + S\right]$$

$$= 11.6\,C + 34.8\left(H_2 - \frac{O_2}{8}\right) + 4.35\ S.$$

Excess air requirement. In actual practice, for complete combustion, an excess quantity of air is required in order to permit intimate mixing of the fuel with oxygen.

Weight of dry flue gases per kg of fuel. Carbon may be present in the flue gas in the constituents CO and CO_2, and the weight of carbon per kg of flue gas can be found by conversion of volumetric analysis of CO and CO_2 to gravimetric analysis by multiplying by the molecular weight of the constituents.

Weight of dry flue gas per kg of fuel is given by the relation

$$\frac{C[11\,CO_2 + 8O_2 + 7(CO + N_2)]}{(CO_2 + CO)}$$

PROBLEMS

Provide a single word/suitable words for following statements

1. A quantity of matter of fixed mass and identity which is bounded by a closed surface.
2. An enclosure which permits thermal interaction.

3. An enclosure which prevents thermal interaction.
4. A system in which all the measurable variables have the same value as they had inside an enclosure after a long time, irrespective of the interaction that may have taken place.
5. A region of interest, that is involved in an analysis
6. Any change of state occurring in a system.
7. A region in space or control volume or quantity of matter upon which attention is focussed for study.
8. A change of state which occurs while the system is adiabatically enclosed.
9. Any observable characteristic of the system.
10. A type of reversible process, characterised by the fact that the system is at each instant arbitrarily close to equilibrium.
11. A study of the transfer and conversion of energy.
12. If a thermodynamic system undergoes an adiabatic process, the net amount of work performed by it depends only on its initial and final states, and not on the sequence of intermediate state or path.
13. Depends solely upon the state of the system and not upon how that state was reached.
14. A change in the state of a system which occurs without any work being done.
15. It is impossible to construct a device which, working in a complete cycle, will produce no other effect than the transfer of a quantity of heat from a cooler to a hotter body.
16. Two states of two systems characterised by an absence of heat flow even when there is no adiabatic wall between them.
17. The loci of points corresponding to states of the same temperature.
18. A system going through some process whose initial and final states are the same.
19. A system which exchanges heat and work with its surroundings while operating in a cyclic process.
20. A hypothetical machine whose operation would violate the laws of thermodynamics.
21. A property of the system dependent on the mass of the system.
22. A cycle consisting of two pieces of isotherms joined by two pieces of reversible adiabatics.
23. A property of a system whose value does not depend upon the mass of the system.
24. A system in which energy may cross its boundaries, but not the mass.
25. A system envelope which permits both mass and energy to cross its boundaries.
26. A thermodynamic system which is not influenced by the surrounding.
27. An open system in which the rate of passage of mass and energy does not change with time.
28. A process in which no heat transfer takes place between the surroundings and the system but work transfer takes place.
29. A process in which fluid expands without doing any work.
30. A system in mechanical, thermal and chemical equilibrium.
31. A series of states through which a thermodynamic system passes.
32. A process in which all thermodynamic properties are the same at the start and at the end of the process.
33. A process carried out such that at every instant the system departs only infinitesimally from the thermodynamic equilibrium state.

34. If two systems are both in thermal equilibrium with a third system, they are in thermal equilibrium with each other.
35. In thermodynamics, it is defined as the sole effect external to the system that can be reduced to the rise of a weight.
36. The product of the characteristic gas constant and the molecular weight of an ideal gas.
37. The molecular weights of all the perfect gases occupy the same volume under the same conditions of pressure and temperature.
38. A property of a system, the change in whose value is the algebraic sum of the heat supply and the work done during any change in state
39. Change of state taking place without any heat transfer
40. In an isolated system, the energy of the system remains constant.
41. A machine that will give continuous work without receiving any energy from other system or surroundings.
42. A process in which the heat transfer is equal to change in enthalpy.
43. The pressure value product is a constant for a perfect gas.
44. In a process following $pv^n = C$, if $n = 0, 1$ and $\propto$ means the process is ....
45. The work done in constant volume process is ....
46. As per ...., heat transfer in a process is equal to work transfer.
47. Internal energy of an ideal gas is a function of ....
48. Internal energy change of an ideal gas is proportional to ....
49. .... cycle provides concept of maximising work output between two temperature limits.
50. Carnot cycle is independent of ....
51. All reversible engines operating between two fixed temperatures have .... efficiency.
52. A Carnot cycle operating between temperature limits of 800°K and 400°K will have efficiency of 50% when the working substance is ....
53. If a system in a given state undergoes a reversible process till its state is in thermodynamic equilibrium with the surrounding, then work done by the system is maximum.
54. Because of the diverging nature of constant pressure lines, the value of reheat factor is ....
55. The quantity H–TS is termed as ....
56. The quantity U–TS is termed as ....

ANSWERS

1. system
2. diathermic
3. adiabatic
4. equilibrium state
5. system
6. process
7. thermodynamic system
8. adiabatic process
9. property
10. quasistatic
11. thermodynamics
12. first law of thermodynamics
13. property
14. free motion
15. Clausius statement
16. thermal equilibrium
17. isotherms
18. cycle
19. thermodynamic machine
20. perpetual-motion machine
21. extensive property
22. Carnot cycle
23. intensive property
24. closed
25. open
26. isolated system
27. steady flow
28. adiabatic process
29. throttling
30. thermodynamic equilibrium

31. path
32. cyclic process
33. quasi-static process
34. zeroth law of thermodynamics
35. work
36. universal gas constant
37. Avogadro's hypothesis
38. internal energy
39. adiabatically
40. law of conservation of energy
41. perpetual motion machine
42. isobaric process
43. isothermal process
44. constant pressure, constant volume, and constant temperature
45. zero
46. Joule
47. temperature
48. C_v
49. Carnot
50. working substance
51. same
52. any
53. Availability of system
54. greater than 1
55. Gibbs function
56. Helmholtz function

2

I.C. Engines

In internal combustion engines, the combustion takes place inside the engine whereas in steam engines the combustion takes place outside the engine.

The internal combustion engine possesses certain advantages over steam engine.

(*i*) I.C. engine is more compact unit as it does not involve several cumbersome auxiliaries required in steam engine.

(*ii*) The efficiency of I.C. engine is of the order of 35% and the of steam engine is about 15%. This is because of the fact that very high temperature can be achieved in I.C. engines.

(*iii*) I.C. engines are mostly single acting, thereby avoiding the necessity of leak proof stuffing box, piston rod, D-slide valve etc.

(*iv*) As combustion takes place inside the cylinder, therefore overall size is reduced and these become portable. In steam engines, most of the area is occupied by boiler for producing steam.

Efficiency of Air Standard Otto Cycle

$$\eta = 1 - \left(\frac{1}{r}\right)^{\gamma - 1}$$

From the above expression it is obvious that greater the compression ratio, higher will be the air standard cycle efficiency.

In actual practice, petrol engine cycle is based on otto cycle. In petrol engine, the fuel is sent along with air in suction stroke. So if we try to achieve very high compression ratio, the fuel mixture will automatically ignite without getting spark. This auto ignition produces very high pressure which may burst piston. This phenomenon is called *detonation.* Also the combustion of the fuel will take place during compression stroke in case the high compression ratio is used. This is because the ignition temperature of petrol is low. But if combustion takes place during compression stroke, there will be loss of power, rather than increase in efficiency. Therefore high compression ratios can't be used in petrol engines. In case of otto engines the compression ratio is of the order of 4 to 8.

Efficiency of Ideal Diesel Cycle

$$\eta = 1 - \frac{1}{r^{\gamma - 1}}\left[\frac{\sigma^{\gamma} - 1}{\gamma(\sigma - 1)}\right]$$

where r = compression ratio $= \frac{V_1}{V_2}$

and $\sigma = \frac{\text{Compression ratio}}{\text{Expansion ratio}}$

Here for all values of σ, expression $\frac{\sigma^{\gamma}-1}{\gamma(\sigma-1)} > 1$, therefore for same compression ratio, η otto > η diesel. But in case of diesel engine high compression ratio can be achieved, as fuel is injected at the end of compression stroke.

Engines working on otto cycle use petrol as fuel and are known as spark ignition (S.I.) engines, and those working on diesel cycle use diesel oil and are known as compression ignition (C.I.) engines.

Dual combustion cycle. It is a combination of Otto and Diesel cycle and hence also known as mixed or composite cycle. Engines working on this cycle are called compression ignition engines.

Injection and ignition of fuel. Fuel in I.C. engines may be injected by (*a*) air injection or (*b*) airless or solid injection. Fuel may be ignited by (*a*) electric spark, (*b*) compression ignition, (*c*) hot tube ignition, or (*d*) hot combustion chamber.

Engine Components

1. *Cylinder.* Cylinder of an internal combustion engine is designed to withstand the high pressure and temperature conditions. It should be able to transfer the unused heat efficiently so that metal temperature does not approach the dangerous limit, and it should be economical to repair in the event of wear and tear. For this reason, it is usual to use cylinder liners or sleeves in all the big engines because of the following advantages :

(*i*) These are more economical because of ease of replacement after wear and tear.

(*ii*) Instead of making the whole of the cylinder of best grade of material, only the liner can be made of better grade, wear resistant cast iron and the jacket made of cheaper grade.

(*iii*) It's use also allows for longitudinal expansion.

In big engines the various parts, *viz.* cylinder, water jacket, frame etc. are manufactured separately, whereas in small engines these are made as one piece.

The cylinder liner should be made of such material which is strong enough to withstand high gas pressure and at the same time sufficiently hard enough to resist wear due to piston movement. It should also be corrosion resistant and produce good bearing surface to guide the piston movement. It should also be capable of resisting thermal stresses due to heat flow through the liner wall. The various materials commonly used and satisfying the above requirements in order of preference are : Grey cast iron with homogeneous and close grained structure (pearlitic cast iron) which is usually cast centrifugally ; nickel cast iron and nickel chromium cast iron ; nickel-chromium cast steel (with molybdenum in some cases). The aeroplane engine cylinders are made of forged alloy steel.The cylinders are usually made of cast steel. The inner surface of the liners is usually heat-treated properly in order to obtain hard surface to reduce wear. Sometimes it is chromium electroplated to obtain very hard and porous surface such that an oil film is formed and retained thereby reducing the wear appreciably.

Two types of liners (wet and dry type) are commonly used. The dry liner is press fit into the cylinder and the cooling water (to remove the unused heat) does not come in contact with the liner but contacts only the cylinder outer surface. This arrangement is adopted for smaller cylinders below 125 mm bore, above which wet liners are used in which case the cooling water in the jacket comes in direct contact with outside layers of the liner. In the case of wet liner, a heavy flange has to be provided at the top which means that centre distance between two cylinders in case of multicylinder engine will be more and the cooling of the top of liner will not be proper. However it permits easy supporting of heavy internal cores of cylinder bore. The dry liner is easier to replace and the wet liner is difficult. The heat flow through dry liner is poor, but is uniform throughout including the top. In the case of dry liner there is no possibility of water leakage into crank case or combustion chamber ; whereas in wet liner such a risk exists if the liner casting is defective.

2. *Cylinder head.* It closes one end of the cylinder. Air and fuel valves are also accommodated in it. A copper gasket is placed between the cylinder and cylinder head to make gas tight joint.

3. *Piston.* Piston is an important part of an I.C. engine which receives impulse from the expanding gases in the cylinder and transmits the energy to the crankshaft through the connecting rod. It also disperses a large amount of heat from the combustion chamber to the cylinder walls. I.C. engines employ trunk type pistons which are open at one end and consists of :

(*i*) head or crown to carry the cylinder pressure

(*ii*) skirt to act as a bearing for connecting rod side thrust

(*iii*) piston pin to connect the piston to the connecting rod, and

(*iv*) piston rings to seal the cylinder.

The various important design considerations for a piston are :

The piston is subjected to highly rigorous conditions and must therefore have enoumous strength and heat resistant properties to withstand high gas pressure. Its construction should be rigid enough to withstand thermal and mechanical distortion. As high speeds upto 15 mpm may be attained in high speed engines the weight of piston should be minimum possible to minimise the inertia forces. To maintain the piston temperature within limits, the heat from the crown of piston must be dissipated quickly and efficiently to the rings and bearing area and then to the cylinder walls. The profile of piston head is dependent on the design of combustion chamber. From strength considerations, it may become necessary to use different material for head, like cast steel.

The bearing area of piston should be sufficient to prevent undue wear and it should form an effective seal to avoid gases from leaking to oil side or oil to gas side. The number and type of piston rings is influences by many factors including the balancing weight of crank.

It should have least friction and have noiseless operation. Material of the piston must possess good wearing qualities, so that the piston is able to maintain the surface hardness upto the operating temperatures and there should be little or no tendency towards corrosion. The most commonly used materials for the pistons of internal combustion engines are : cast iron, cast aluminium, forged aluminium, cast steel, and forged steel. Cast iron pistons may be used for moderately rated engines with piston speeds below 6 m/s, and aluminium alloy pistons are used for highly rated engines running at higher piston speeds.

4. *Piston Rings.* These impart the necessary radial pressure to maintain the seal between the piston and the cylinder bore. The piston rings inserted at the top function as compression rings or pressure rings, and may be 3, 4, 5, 6 and 7 in number. These also transfer heat from piston to cylinder liner and absorb part of piston fluctuation due to side thrust. The rings inserted at bottom serve as oil scrapper or oil control rings. These provide proper lubrication by allowing sufficient oil to move up during upward stroke and at the same time also minimise oil flow to combustion chamber.

In the oil rings, either the bottom outer edge is stepped or upper edge bevelled, or slot cut in the centre of the ring all round the periphery and lower edge of the groove of the piston is bevelled and small holes drilled towards the inside of the piston so that excess oil scrapped by the ring flows through these holes into the piston and falls into the sump.

The compression rings are usually made of rectangular cross-section and the diameter of the rings is made slightly larger than the cylinder bore. A part of the ring is cut-off in order to permit it go into cylinder against the liner wall. This also produces pressure on rings. The gap between the ends should be sufficiently large so that even at the highest temperature the ends will not touch each other, otherwise there might be buclking of the ring. The square cut ends are most commonly used. Sometimes angular cut, or square step cut ends are also used.

The ring joints of various rings should be spaced equally round the piston and should not come one below the other. The rings are sometimes, therefore, located by pins, so that all the gaps do not come in one line due to the rotation of the rings.

Piston rings are usually made of cast iron and alloy cast iron due to their god wearing qualities and also their retaining the spring characteristics even at high temperatures. To avoid wear, the rings are chrome plated.

5. *Connecting Rods*. Connecting rod is used to transmit motion from the reciprocating piston to the rotating crank. It also conveys the lubricating oil from the crank pin to the piston pin and provides splash or jet cooling of the piston crown. In the most usual form it consists of an eye at the small end for the piston pin bearing, a long shank usually I-section, and a big end opening which is usually split to take the crankpin bearing shells. Low speed large engines usually employ circular section with flattened sides or rectangular section, with the large dimension being in the plane of rotation. High speed engines employ I-section or H-section rods for lightness. I-section is most common for high speed engine connecting rods because lightness is essential in order to keep the inertia forces as small as possible. I-section also provides ample strength required to withstand the momentary high gas pressure in the cylinder. Thus I-section fulfills the most desirable conditions for connecting rod, i.e., the adequate strength and stiffness with minimum weight.

The connecting rods of internal combustion engines are mostly manufactured by drop forging with outer surfaces left unfinished.

The length of connecting rod is usually made 4 to 5 times the crank radius. The smaller length than this increases the angularity of connecting rod which increases the side thrust of piston against liner and thus the wear. More length would mean greater height of engine and thus a compromise is essential.

The lubrication of the two end bearings of the connecting rod is very important. Two methods commonly used are :

1. Splash lubrication
2. Pressure feed lubrication.

In splash lubrication, at the big end of the connecting rod is attached a spout which dips into the lubricating oil in the sump during downward motion of connecting rod, and a splash of oil is produced by the spout as the connecting rod moves up. The oil flows to big end through spout and the splashed up lubricant finds its way into the small end bearing through the widely chamfered holes provided on the upper surface of the small end.

In the pressure feed system, oil is fed under pressure to the crank pin bearing through holes drilled through the crankshaft, ~~crankwebs and~~ crankpin. From the crank pin bearing, the oil is fed to the small end bearing through the hole rifle drilled in the connecting rod shank.

6. *Crank Shafts*. Crank shafts are used in I.C. engines to convert reciprocating motion of piston into rotary motion. Crank shaft consist of the shaft parts which revolve in the main bearings, the crankpins to which the big ends of the connecting rods are connected, the crank webs (also known as cheeks) which connect the crank pins and the shaft parts.

An overhung crank has only one crank web and it requires only two bearings. It is used with medium size and large horizontal engines. A crank shaft with a centre crank has two crank webs. A crank shaft may be either single throw type or multi-throw type depending on number of cranks provided.

Its mass should be so distributed that natural frequency of vibration is very much away from the normal speed of operation.

It is generally made much heavier and stronger than necessary from the strength point of view so as to meet the requirements of rigidity and vibrations.

In industrial engines, 0.35 carbon steel and 0.45 carbon steel are commonly used. In transport engines, manganese steel is generally used. Aero-engines use cranks made of nickel chromium steel.

7. *Fuel nozzle*. The fuel in diesel engines is fed by an injection system consisting of a pump, fuel line and the injector/fuel nozzle. Fuel is fed by this nozzle in a fine spray under pressure.

8. *Intake and Exhaust valves*. These are spring loaded and operated by a cam. The valves are mounted either in the cylinder block or the cylinder head. Usually conical valves having angle of 30° or 45° are used. As the heads of the valves are subjected to high temperature of the burning gases, these should not warp under

the influence of heat and their seats should not scale or corrode ; otherwise they would start leaking. Valves are usually made of austenitic, non-hardening steels containing 25 to 35% chromium and nickel.

9. *Cam shaft.* It is driven from the crank-shaft by a timing gear on a chain. It operates the intake and exhaust valves through the cams, cam followers, push rods and rocker arms.

Valve-Timing diagrams. Theoretically the valve should open and close at the end or start of the stroke. But in actual practice it is not desirable to do so in order to obtain better results. The valves are generally opened earlier and closed later.

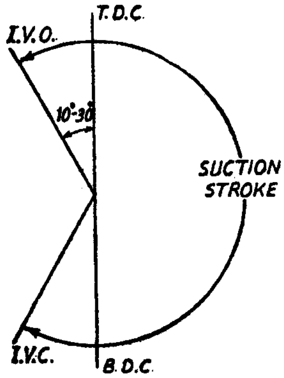


Fig. 2.1.
I.V.O. [Inlet valve opens]
I.V.C. [Inlet valve closes]

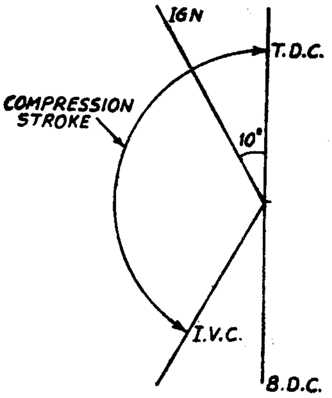


Fig. 2.2.
T.D.C. (Top Dead Centre)
B.D.C. (Bottom Dead Centre)

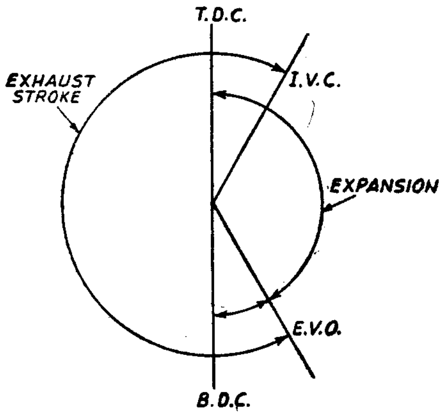
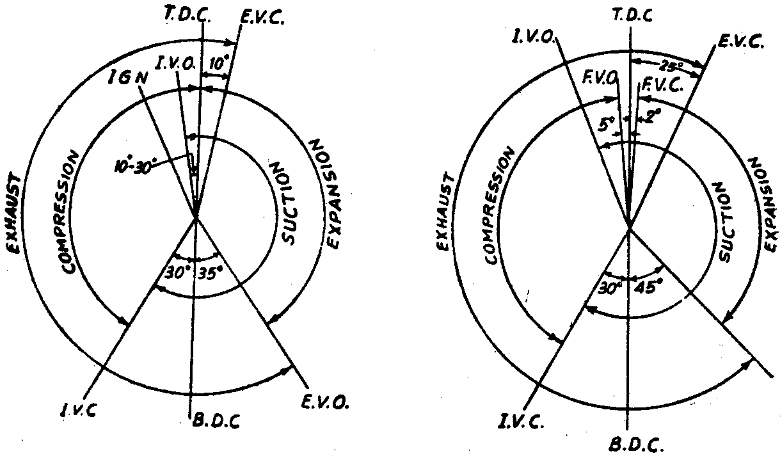


Fig. 2.3.

Starting from the suction stroke, the inlet valve is opened about 10° — 30° before the T.D.C. or (O.D.C.). At this momenet exhaust valve is also open. By opening the inlet valve earlier, more chances of fresh charge coming in are made. As fresh charge moves in, it helps in expelling the exhaust gases also.

The inlet valve does not close at B.D.C., but is closed after it. It generally closes 30° — 40° after B.D.C. By doing so, a large amount of fresh charge is ensured, as the charge during suction stroke was get going in and compression by piston has not yet been able to push out the charge.

The suction stroke is therefore as shown in Fig. 2.2 and compression stroke starts after it.



Otto

Diesel

Fig. 2.4.
EVO — Exhaust valve opens ; EVC — Exhaust valve closes

During compression, the spark is ignited before the T.D.C. in case of Otto. This is about 10° before T.D.C. Or the fuel is injected about 5 — 10° before T.D.C. in case of diesel (Fig. 2.2). This is done so, because the whole of the fuel can't burn instantaneously. Rather fuel also has some delay period, (*i.e.* period between spark and actual ignition). Also time is required for the spark to travel and spread throughout the cylinder.

In expansion stroke, the exhaust valve opens about 30 — 40° before B.D.C. and closes about 10° after T.D.C. (Fig. 2.4). Thus the period of exhaust is increased and complete and effective scavenging is ensured. If this is not done, then residual combustible mixture results in the dilution of fresh charge.

Thus combining the whole valve timings, we get complete valve timing diagram for Otto and Diesel Cycles as shown in Fig. 2.4.

Actual Indicator Diagram

Due to valves not opening and closing instantaneously the cardinal points of indicator are also rounded up instead of being flat corners. Also suction takes place below atmospheric pressure and exhaust at above atmospheric pressure. Therefore we get a sort of loop as shown in Fig. 2.5. This represents the loss due to pumping and is to be supplied by the engine. The net work done by cycle is difference of big area and loop.

Governing of I.C. Engines : Various methods are :-

(*a*) Hit and miss governing — used for small engines. No fuel is admitted during a cycle by keeping suction valve closed.

(*b*) Quantitative governing — Quantity of charge is varied.

(*c*) Qualitative governing — Quality of charge is varied.

Two stroke cycle engine. The engine is classified as two-stroke or four-stroke depending upon the number of strokes it requires to complete the basic four events of operations. The Otto, Diesel and Dual cycles are completed in four strokes, therefore engines based on these are called four stroke engines.

In two-stroke engines, the two ideal *i.e.* suction and exhaust strokes are eliminated, (In other words for suction and exhaust we do not have separate strokes). So we have one power stroke per revolution of crank in two stroke engines.

In two-stroke engine, ports are used instead of the inlet and exhaust valves operated by complicated mechanisms. The charge is collected in the oil casing which is compressed during power stroke. Since it is at high pressure, therefore it automatically enters the cylinder as ports are cleared off the piston.

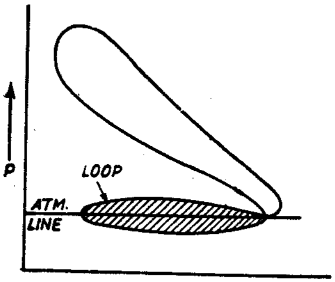


Fig. 2.5.

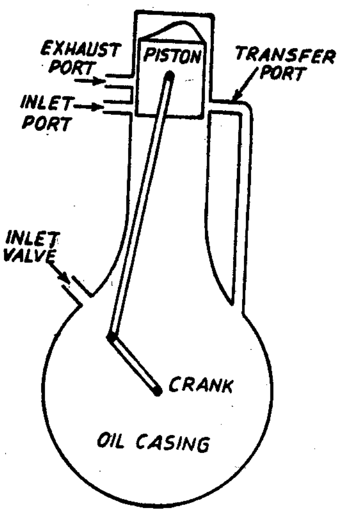


Fig. 2.6.

Carburettor

The carburettor is a device used in petrol engines for atomising and vaporising the fuel and mixing it with air in varying proportions to suit the charging mixture in the induction manifold of the engine. The carburettor meters the required quantity of fuel and atomises or breaks it into 'minute globules for being mixed with a correct quantity of air. The main object of the carburettor is to supply the required petrol and air mixture of the correct strength as dictated by the load conditions of the engine.

Theoretically 15 : 1 is the correct mixture of air and petrol which would result in burning without leaving excess of air or fuel. Combustion will take place for ratio between 7 : 1 to 10 : 1 on lower side and upto 20 : 1 on higher side. For average cruising speed, the air fuel ratio is approximately 15 : 1 to 17 : 1. Richer mixture of 12 : 1 is desirable for accelerating the engine quickly. When starting engine from cold, even richer mixture may be desired. For maximum economy, *i.e.*, less fuel consumption per unit power, the fuel air ratio should be 16 : 1 or 17 : 1. Thus carburettor has to be designed to provide varying requirements of fuel air ratios.

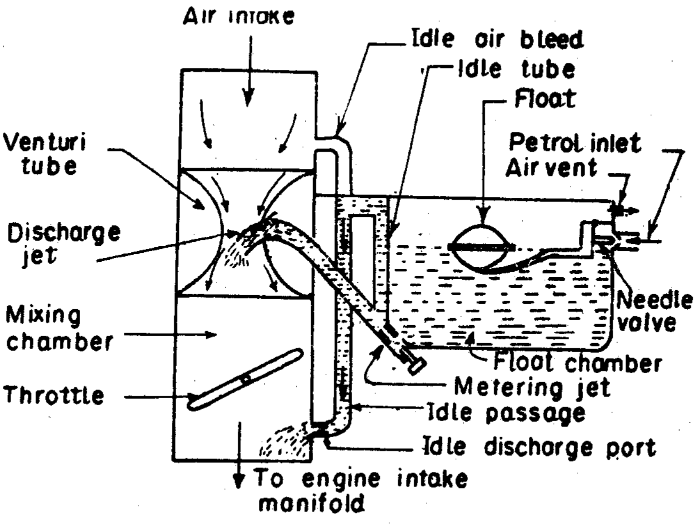


Fig. 2.7

Petrol from the petrol tank enters the float chamber through a needle valve. The float maintains the constant level in the chamber. The petrol in float chamber is made to stand at about 1.5 mm below the orifice at the top of the jet. The petrol is sent to the discharge jet, located in between venturi tube, through a metering jet which controls the rate of flow of petrol. The air is drawm in by the suction in the cylinder during suction stroke. Venturi tube converts some of the static head of the air into velocity head thus causing suction (proportional to velocity of air at venturi tube) at the discharge jet. The fuel air mixture formed in the mixing chamber passes on to the intake mainfold. Vaporisation of fuel gets completed near the end of comnpression in the cylinder. The throttle is used to control the speed and power of the engine.

To achieve richer mixtures, special idling arrangement comprising idling fuel passage and idling ports is incorporated in carburettors. When the throttle is closed for slow speeds or idling, the suction below the throttle raises the fuel in the idle tube and the fuel is sent directly to the intake pipe.

Ignition System in Petrol Engines

In a petrol-engine, the combustible mixture is ignited by an electric spark produced between the points of a spark-plug. There are two systems of electric ignition. (1) Battery ignition (also called battery or coil ignition) and (2) magneto ignition. Either of the two systems can be used in petrol engines.

Battery or Coil Ignition System

It has two circuits, the primary circuit and the secondary circuit. Fig. 2.8 shows the various elements of a battery ignition system. It relates to four cylinder petrol engine.

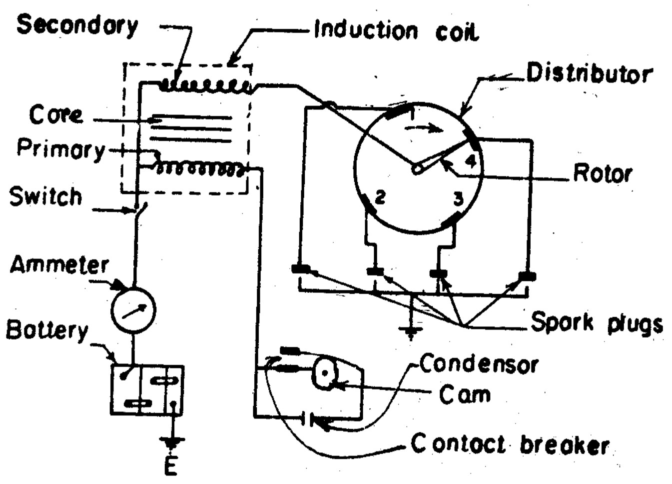


Fig. 2.8

On closing the switch, the current from the battery passes through the ammeter, the primary of the induction coil and contact breaker point, the contact points being closed. The secondary of the induction coil is connected to the distributor-arm. The primary winding has a small number (between one hundred and two hundred) turns of coarse-wire whereas a secondary-winding has a large number (of the order of 10,000) of turns of very fine wire. When a spark is required in a particular cylinder, the cam opens the contact breaker points and this induces high voltage in secondary. The high voltage is of the order of 2400 volts. At the same time the distributor arm comes opposite to the point from where the wire leads to the spark-plug of the particular cylinder and so the high voltage induced in the secondary gives a spark at the spark-plug. The function of the ignition coil is to step-up 6 or 2 volts from the battery to the high tension voltage of about 24,000 volts.

Magnet Ignition System

This type of ignition system does not require a battery. It generates its own voltage for the primary. Here an armature having wound upon it in the primary coil of a few hundred turns of enamelled copper wire and secondary coil of several thousand turns of fine insulated wire, rotates in a permanent magnetic field. The modern trend is to keep the armature stationary and the magnets rotating. By this action, the primary voltage is generated in accordance with the laws of electric generator, which is then transformed into a very high secondary voltage exactly on the lines described in the Battery Ignition System.

The magneto system is used in high speed engines like scooter, motor cycles, racing cars, aeroplanes etc.

Fuel Pump and Injector

Refer Fig. 2.9.

P is rack which is connected to the governor mechanism or the accelerator through various linkages. It meshes with quadrant of the gear *Q* and the motion of the rack rotates the quadrant *Q*.

Q is quadrant of the gear to which hollow cylindrical portion with slot at the bottom is attached. The slot engages with the bottom of the plunger *R*. Thus plunger will also rotate as a result of the movement of the quadrant.

R is plunger which is operated by the cam mounted on the cam shaft. It will reciprocate up and down with constant stroke.

S is the barrel in which fuel enters at the fuel inlet and overflows from fuel overflow passage.

V is the valve and seat. It is a non return valve and is kept in position by the spring *T*. When the pressure in the barrel exceeds a predetermined value, the valve opens against the compression of the spring and pressure above the valve due to fluid in the delivery pipe. Thus the pressure developed in the barrel depends upon the stiffness of spring *T* and the fluid pressure above the valve.

T is the spring housed in the body which can be screwed in or out and vary the compression of the spring, resulting in the pressures to be developed in the barrel to open the valve.

W is the delivery pipe from the pump connected in the injector or atomiser assembly.

Injector

A is the nozzle body.

B is the nozzle valve resting on the nozzle body seat.

C is valve cap nut holding the nozzle and the body with the nozzle valve in between.

D is spindle, one end of which is resting on the nozzle valve and the other on a seat for the spring.

E is spring. The compression of this spring controls the pressure at which the nozzle valve can lift up due to fuel pressure. Thus this spring controls the injection pressure. The fuel must be injected at a pressure much higher than the pressure in the engine cylinder developed due to combustion of fuel-air charge. The fuel continues to be injected at the maximum pressure reached in the cylinder. And the fuel to be injected must be atomised and possess high velocity so that the atomised particles go deep in the combustion space. Thus pressure as high as 120 to 150 kgf/cm^2 or even more might

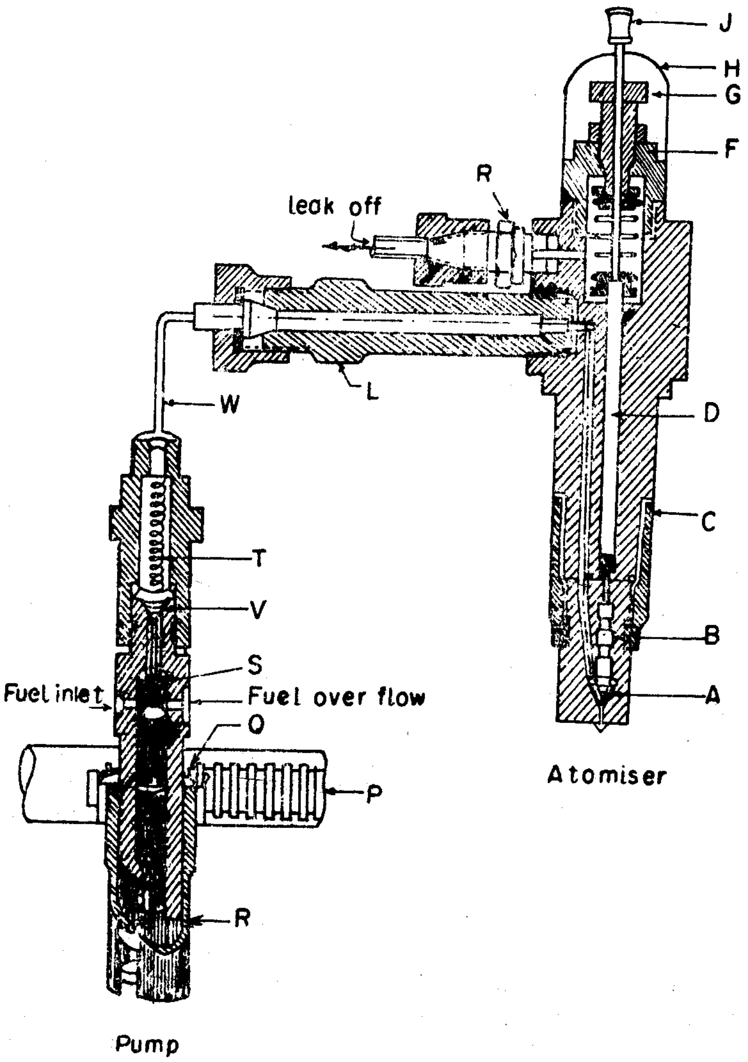


Fig. 2.9

have to be developed to ensure high velocities, suitable degree of atomising and introduction of the fuel.

F is spring cap nut.

G is compression screw to adjust the compression of the spring.

H is protecting cap for the compression screw so that the nut which is vital for the operation of the injector is not mishandled.

J is feeling pin. When the fuel is injected the spindle will jump up and the feeling pin will also jump up. This jerky motion of the feeling pin ensures injection of fuel.

K is nipple connecting the leak off from the sides of the spindle to the overflow container.

L is fuel delivery connection.

When the fuel under pressure is led to the injector, the valve lifts from the seat against the compression of the spring and fuel is sprayed through nozzle hole or hoses.

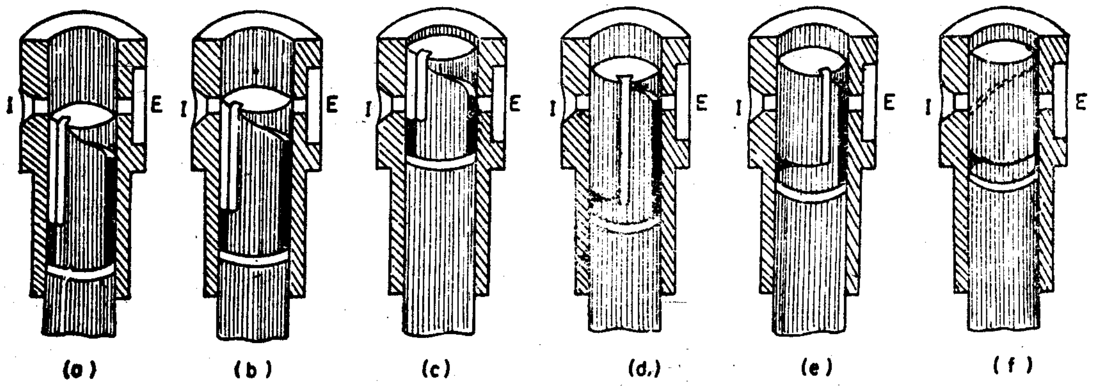


Fig. 2.10.

The system of operation of the pump element which comprises the plunger and barrel is shown in Fig. 2.10. When the plunger is at the bottom dead centre as at (*a*), oil enters through the ports. In the primed system, the barrel and the delivery pipe *W* are full of oil. As the pump plunger rises, a certain amount of fuel is pushed back through the ports until the plunger reaches the position as at (*b*), where the top land of the plunger has closed both the ports. The fuel above the plunger is then trapped and its only outlet is *via* the delivery valve on the top of the pump barrel. The pressure exerted by the rising plunger upon the oil causes this to lift the valve and to enter the pipe which connects the pump to the injector. As this is already full of oil, the extra oil, which is being pumped in at the pump end, causes a rise in pressure throughout the line and the nozzle valve. This permits oil to be sprayed into the engine conbustion chamber. This continues until the plunger reaches the position as at (*c*). Here the lower edge of control helix has uncovered the port, thus allowing the fuel to be bypassed to the suction chamber by way of vertical slot. This causes the delivery valve to shut under the action of its spring and with consequent collapse of pressure in the pipe line, the nozzle valve also shuts.

The plunger stroke is always constant, but that part of it during which it is actually pumping is variable. By means of the helical edge which runs around the plunger, which itself can be rotated within the barrel, it is possible to make this point of cut-off occur earlier, or late, in the stroke. Compare drawings (*c*), (*d*) and (*e*) which show approximately the positions at full load, half load and idling respectively. To stop the engine the plunger is turned so that vertical slot coincides with the port as at (*f*) during the whole of the stroke ; thus no fuel is delivered. The position of the plunger stroke at which the helical edge will uncover the port is adjustable by rotating the plunger axially by means of toothed quadrant mating with the rack rod which controls simultaneously the pump element.

Comparison of Two Stroke and Four Stroke Engines

Advantages of Two Stroke Engines

(1) In two stroke engine, one power stroke is obtained per revolution of crank. Thus for same capacity and speed, nearly double power is developed in comparison to four stroke engine.

(2) Since there is one working stroke per crank revolution, therefore turning moment is quite uniform and lighter flywheel is sufficient. This is whv, this type of engine is very suitable for light vehicles, like scooters.

(3) Weight/power ratio is less for two stroke engine.

(4) The complicated valve mechanism is got rid of. Lubrication difficulties and noise due to moving parts in four stroke are overcome in two stroke engine. Mechanically efficiency is higher due to absence of valve rockers, cams and camshafts.

(5) Two stroke engine can be run in either direction. Therefore no reversing gears are needed.

(6) Overall cost is less.

Disadvantages

(1) Scavenging (removing of exhaust gases from the cylinder) is very poor. Therefore dilution of charge takes place and though there is one power stroke per revolution, thermal efficiency is less. Overall efficiency is low at high speeds due to poor volumetric efficiency.

(2) High compression ratios can't be achieved due to ports, therefore efficiency is less.

(3) In petrol type two stroke engine, the fuel mixture in dispelling exhaust gases out of cylinder also moves along with that. Therefore there is loss of fresh charge.

(4) At high loads, running is not very smooth due to dilution of charge.

(5) Consumption of lubricating oil is too much as it also moves along with the charge in form of vapours. This is because lub oil gets heated up and its vapours mix with the fresh charge.

Combustion takes place more rapidly if the fuel air mixture is in a state of turbulence.

Air fuel ratio. Theoretically, 15 : 1 ratio is required for petrol but in actual practice higher ratio 17 : 1 is used. Richer mixture is used for maximum power. Diesel engines can work on low air fuel ratio also.

Detonation. It is caused due to a pressure wave occurring as a result of rapid auto-ignition of a portion of a part of the fuel. The auto-ignition propagates a high pressure wave through fuel air mixture, giving a violent blow (knock) to walls of cylinder. While iso-octane has little tendency towards detonation, *n*-heptane detonates readily. A fuel having higher self ignition temperature detonates less.

Detonation in petrol engines can be reduced by the addition of a small amount of lead ethide or ethyl fluid to the fuel. This is known as doping.

The knocking tendency in petrol engines can be prevented by ensuring that the charge away from the spark plug has low density, low temperature, long ignition delay, and rich mixture. It is also decreased by reducing compression ratio, and increasing the engine speed with fixed octane rating fuel. However knocking in petrol engines is increased by increase in cooling water temperature, supercharging.

The knocking tendency in diesel engines can be prevented by reducing the delay period, increasing the compression ratio, inlet pressure of air and injection pressure. However it is increased by high self ignition temperature, low volatality, high viscosity, long ignition delay and reduced compression ratio.

Auto-ignition is the phenomenon of fuel catching fire without external source of ignition energy.

It is accelerated by normal heptane and resisted by iso-octane.

Carburetion is the process of breaking up the petrol into fine particles and mixing it with air in desired proportion. This is achieved by a device called carburettor.

Ignition system. In petrol engine, the charge is ignited by a spark plug. A high voltage (20,000 volts) is produced by an ignitor coil and applied to spark plug by a distributor. The gap between two electrodes of spark plug is of the order of 0.3 to 0.7 mm.

Supercharging is the process of supplying greater mass of air to engine cylinder by compressing intake air initially with a view to obtain high power. This is essential at high altitudes where density of atmospheric air is low.

Scavenging is process of removing the burnt gases from engine cylinder.

Pre-Ignition. It is caused by the spontaneous combustion of the mixture before the end of the compression stroke in spark-ignition engine, *i.e.* even before the spark occurs in the spark plug. It may occur due to the cylinder walls being too hot, or red hot carbon deposited, or overheated sparking plugs, or the pressure wave due to detonation. It may also be due to faulty timings.

Ignition delay. If occurs with a weak mixture, which causes retarded ignition.

Indicated HP is the power produced inside the cylinder and is equal to $\frac{p_m LAN}{4500}$, where p_m = mean effective pressure in kg/cm^2, L = stroke length in m, A = area in m^2 and N = No. of power strokes per mt.

Brake HP is the power available at shaft

BHP = IHP + FHP (FHP = Friction horse power)

Octane Number. It is defined as the percentage by the volume of iso-octane in a mixture of iso-octane and n-heptane which shows the same tendency to knock as the fuel in question under same conditions. Ignition quality of petrol is expressed by octane number.

Cetane Number. It is defined as the percentage by the volume of cetane in a mixture of cetane and α-methyl-napthalane which has the same ignition delay as the fuel in question under same conditions.

Ignition quality of diesel oil is expressed by cetane number.

Engine Efficiencies

Volumetric efficiency

$$= \frac{\text{Mass of air admitted to cylinder during suction stroke}}{\text{Mass of free air equivalent to piston displacement}}$$

Air standard efficiency $= \frac{\text{heat supplied} - \text{heat rejected}}{\text{Heat supplied}}$

It is the hypothetical efficiency used to compare the efficiencies of various cycles.

Mechanical $\eta = \frac{\text{B.H.P.}}{\text{I.H.P.}}$, For single cylinder, IHP is measured from an indicator diagram and for multi cylinder by Morse test.

Thermal efficiency based on I.H.P. (Indicated thermal efficiency).

$$= \frac{\text{I.H.P.} \times 4500}{\text{Total heat in fuel/mt.} \times 427}$$

Thermal η based on B.H.P. (Brake thermal efficiency)

$$= \frac{\text{B.H.P.} \times 4500}{\text{Total heat in fuel/mt.} \times 427}$$

(This is also called overall η),

Relative efficiency $= \frac{\text{Thermal } \eta}{\text{Air Standard } \eta}$

Isentropic efficinecy $= \frac{\text{Actual work done}}{\text{Isentropic work done}}$

Specific fuel consumption $= \frac{\text{Fuel consumption/hr}}{\text{Horse Power}}$

(H.P. may be I.H.P. or B.H.P.).

Performance curves. Performance curves for I.C. engines are plotted at variable speed. Most economical speed for an engine is one at which specific fuel consumption is the minimum and thermal efficiency is maximum. Maximum power is developed at speed somewhat above the speed corresponding to maximum efficiency.

PROBLEMS

Provide single word (suitable words) for the following :

1. The constant volume process in I.C. engines is characteristic of the ....
2. Compression-ignition engines use liquid fuels of .... volatility.

3. Compression ratio may be of the order of 11.5 : 1 to 22 : 1 in case of ....
4. Low CO and hydrocarbon emission occurs at low and moderate loads in case of ....
5. A triangular rotor rotates on an eccentric shaft inside an epitrochoidal housing, the rotor tips being in constant contact with the housing and form three working chambers.
6. In case of aircraft engines, the power at 6100 *m* altitude is about ....% of the sea level wide-open throttle output for any given speed.
7. The stroke-bore ratio in case of aircraft engines in normally ....
8. The spontaneous combustion or autoignition of an appreciable portion of the charge
9. A divided chamber construction, a combination of the precombustion chamber and the turbulence chamber design
10. Early or late injection of fuel in the diesel engine results in ....
11. Injection system which forces fuel through spray nozzle by hydraulic pressure.
12. It times, meters and forces the fuel at high pressure through the spray nozzle.
13. A restriction in the outer end of the carburettor to provide an extra rich air-fuel mixture for starting.
14. Used to produce gas-tight seal between the piston and the cylinder liners.
15. It takes care of the fluctuations or the cyclic variations in speed.
16. Closes one end of the cylinder and contains the inlet and exhaust valves
17. A .... is a device used to diminish noise of the intake or exhaust
18. The finished part of a shaft which rotates in or against a bearing is called ....
19. An item made of thin layers.
20. The most effective knock suppressor
21. Optimum spark advance is the timing which develops maximum ....
22. Higher concentrations of NO_x are found in I.C. engines with .... compression ratio
23. The principal source of exhaust carbon monoxide is ....
24. Masses used for balancing purposes.
25. A device for atomising and vaporising the fuel and mixing it with air in varying proportions.
26. Used to step up 6 or 12 volts to high tension voltage of about 20 Kvolts.
27. The closed area formed by suction and exhaust operatoin in I.C. engines.
28. Ratio of brake power to indicated power.
29. The ratio of brake power output to the fuel energy input per unit time
30. The ratio of the mass of the charge admitted during the suction stroke of the engine to the mass at normal pressure and temperature of the volume of the charge equal to piston displacement.
31. Ratio of the indicated thermal efficiency to the corresponding ideal air standard efficiency
32. The ratio of actual fuel air ratio and chemicall correct fuel air ratio.
33. Specific fuel consumption is minimum for fuel air ratio ....
34. Mean effective pressure is maximum for fuel air ratio ....
35. The mechanical efficiency of a multicylinder engine is determined by .... test

36. The four stroke cycle is complete in .... revolutions of crankshaft.

37. For completion of four strokes, the cam shaft makes .... revolution.

38. Only air is sucked in during suction stroke.

39. .... operation in 4 stroke cycle petrol engine continues from 50° before bottom dead centre to 10° after top dead centre

40. The thermal efficiency of diesel engine in comparison to petrol engine is ....

41. .... is used for obtaining required firing order in spark ignition engines.

42. Petrol engines employ .... governing.

43. Standard firing order for 4 cylinder petrol engine is ....

44. Standard firing order for 6 cylinder petrol engine is ....

45. Morse test is used for multicylinder spark ignition engines to determine ....

46. Auto-ignition reaction time for petrol-air mixture is minimum for relative fuel air ratio of ....

47. The tendency to knock in C.I. engines increases with .... the cooling water water temperature.

48. Iso-octane in a fuel for spark ignition engines .... auto ignition.

49. Normal heptane in fuel for spark ignition engines .... auto ignition.

50. The knocking in S.I. engines increases with .... in compression ratio.

51. Advancing the spark timing in S.I. engines .... the tendency for knocking

52. Tendency to knock in S.I. engines and the cooling water temperature are .... related.

53. Ignition quality of fuel for S.I. engines is determined by .... number rating.

54. The petrol available commercially in the country has octane number of ....

55. The diesel available commercially in the country has cetane number of ....

56. The knocking tendency in C.I. engines increases with .... of compression ratio.

ANSWERS

1. spark ignition
2. low
3. C.I. engines
4. diesel engines
5. Wankel or rotary engine
6. 50
7. below 1.0
8. combustion knock
9. energy cell
10. loss of power
11. mechanical injection
12. injection pump
13. choke
14. piston rings
15. fly wheel
16. cylinder head
17. muffler
18. journal
19. laminated
20. tetraethyl lead
21. torque
22. higher
23. rich mixture combustion
24. crank webs
25. carburettor
26. ingintion coil
27. negative loop
28. mechanical efficiency
29. thermal efficiency
30. charge efficiency
31. relative efficiency
32. relative fuel air ratio
33. less than one
34. greater than one
35. Morse
36. two
37. one
38. diesel engines
39. exhaust
40. higher
41. distributor
42. quantity
43. 1–3–4–2
44. 1–4–2–6–3–5
45. mechanical efficiency
46. unity
47. lowering
48. retards
49. accelerates
50. increase
51. increases
52. directly
53. octane
54. 80–85
55. 40–45
56. decrease

3

Nuclear Power Plants

Basic Atomic Structure. Most of the mass of an atom resisdes in a very dense, small nucleus (consisting of protons and neutrons). Protons carry positive electrical charge and neutron is electrically neutral. A number of electrons rotate about the nucleus in their own orbits. Mass of electron is $\frac{1}{1840}$ of the mass of proton. Charge on electron is negative equal to charge on proton and as such atom becomes electrically neutral. If one or more planetary electrons are lost, then atom is said to be ionised. Number of electrons is same as number of protons. Chemical nature of an atom is determined by the electrons around an atom.

Atom consists mainly of an empty space. Atomic number is equal to the number of protons.

One atomic mass unit a.m.u. (measure of mass of particles)

$$= 1.66 \times 10^{-24} \text{ gm.}$$

The nucleus of an element is specified completely by giving the atomic number and atomic mass.

Isotopes are varying forms of an element having different numbers of neutrons in the nucleus.

Energy liberated in annihilating a mass m is equal to mc^2, where c =velocity of light = 3×10^{10} cm/sec.

Radioactivity is the process of disintegration of an unstable nucleus. α-particles, β-particles, γ-radiation, and neutrons are emitted during the process of radioactive decay. These four radiations (known as ionising radiation) are capable of ionising the atoms of matter through which they pass. The quantity of radioactive material in any sample is measured in curies and one curie corresponds to 3.7×10^{10} nuclear disintegrations per second.

In a **nuclear reaction,** the impact of a particle with the nucleus alters it and produces an emergent particle. When the incident particle is neutron in a nuclear reaction, it may be absorbed, or scattered, or may cause fission reaction. Power is generated by the nuclear reaction in the fission of a heavy element and it releases energy and further neutrons.

Nuclear reactions are also caused (in addition to neutrons) by γ-rays, protons, deuterons and α-particles.

In **fusion reaction** (as in the case of sun), various isotopes of hydrogen are combined to form helium, with a consequential reduction in total mass and liberation of tremendous quantities of energy.

Energies involved in nuclear reactions are expressed in terms of electron volts.

1 electron volt $= 1.6 \times 10^{-19}$ watt sec.

$= 1.6 \times 10^{-12}$ ergs

Properties of U^{235} and U^{238}

(*i*) U^{235} will undergo fission on capturing a neutron of any energy. Since its capture cross-section is larger at lower energies, it is more likely to capture slow (low-energy) neutrons than fast (high-energy) neutrons (*ii*) U^{238} will undergo fission with neutrons of energy greater than 1.1 MeV.

(*iii*) U^{238} will capture neutrons of intermediate energy to form plutonium.

(*iv*) On fissioning any uranium atom, on an average about 2.5 neutrons, having high kinetic energy of the order of 2 MeV are produced.

(*v*) Energy obtained by fission is of the order of 200 MeV per atom fissioned.

Chain Reactions in Uranium

For power generation, it is essential to establish controlled chain reaction, *i.e.*, the number of neutrons causing fission in one generation exactly equals the number of neutrons causing fission in the next. Such a reactor is called critical reactor. Power production is then proportional to the number of fissions per sec. or number of neutrons present at any one time.

Most practical reactors are fuelled with uranium.

Reactors are classified as (*i*) fast, (*ii*) intermediates, or (*iii*) thermal, depending on the type of neutrons which cause fission in the chain reaction.

In fast reactor, the chain reaction is sustained by fast neutrons, *i.e.*, high energy neutrons (2 MeV energy) as produced in fission and having velocity of 2×10^9 cm/sec. Such reactors need to be fuelled on either pure U^{235} or Pu^{239}.

In intermediate reactors, the fission neutrons are slowed down to intermediate energies before they are reacted to cause fission. These are experimental type and require highly enriched fuel.

In thermal reactors, the fission neutrons are slowed down to thermal energies (*i.e.*, neutrons are in thermal equilibrium with their surroundings, energy of 0.025 eV and velocity of 2.2×10^5 cm/sec. at room temperature) before being allowed to cause fission. In actual practice the fission neutrons leave the fuel with high energies and are slowed down outside the fuel in a non-absorbing medium called moderator. This minimises the risk of wasteful neutron absorption in U^{238}. Thermal reactor may be fuelled with natural uranium.

Reactors are generally heterogeneous *i.e.*, the moderater and fuel are not uniformly dispersed through one another.

Nuclear Power Reactors. A big advantage of nuclear power reactors is that fission of uranium or plutonium nuclei requires no oxygen. A gas or liquid is used as the heat transport medium (primary coolant), and it is recirculated in a closed cycle after having transported fission heat from the reactor to the water-steam in a secondary circuit. An exception to this arrangement is the direct-cycle boiling-water reactor (BWR), where the turbine is part of the primary circuit. Fig. 3.1 shows a typical gas cooled reactor (magnox or AGR).

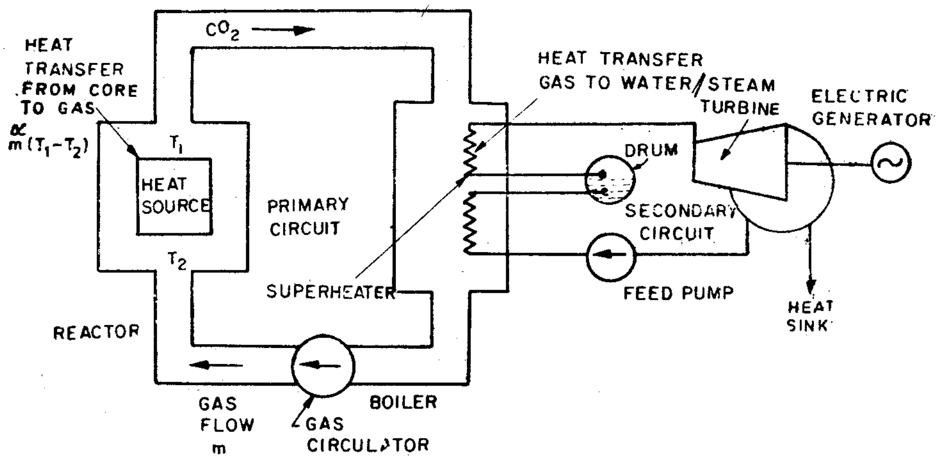


Fig. 3.1.

For natural uranium metal fuel, the power output

$$= 5.9 \times 10^{-12} \text{ W/cm}^3 \text{per unit flux.}$$

In order to get reasonable power rating, or power per unit mass of fuel, the flux must be of the order of 10^{13} neutrons/cm ^{2}/sec. In actual practice flux distribution radially and axially is of sine wave form, being minimum at boundaries and maximum at the centre due to leakage of neutrons at the core boundaries. The flux distribution in the reactor can be flattened by several methods.

Much of the engineering of nuclear reactors is concerned with the process of extracting heat from the reactor core and striking a balance between many conflicting factors in order to reach the most economical selection.

Thermal reactors owe their name to the fact that they make use of slow neutrons having energies of the order of 0.1 eV (corresponding to the temperature of the moderator) as the main source of fission. Such reactors can be classified according to the type of fuel, the moderator and the coolant.

Reactors Types

(1) **Magnox.** It uses graphite as moderator, metallic natural uranium fuel clad in magnesium alloy cans, and CO_2 as coolant. Reactor pressure vessel is surrounded by a thick concrete biological shield, which attenuates the gamma and neutron radiation from the core.

(2) **Advanced Gas Cooled Reactors (AGR).** It uses uranium oxide fuel clad in stainless steel, thus permitting higher coolant temperature and pressure. The core temperatures are much higher and thus CO_2 is also passed through the core and in the spaces between graphite bricks (moderator).

(3) **Boiling Water Reactor (BWR).** It uses ordinary water as moderator, coolant and working fluid. Its core consists of an almost uniform array of, say 12.5 mm diameter fuel pins (UO_2 canned in zirconium alloy) on a square lattice of about 17.5 mm pitch. Fuel is assembled into zirconium alloy boxes, each about 150 mm square section and containing 49 pins on a 7 × 7 square lattice. The spaces between fuel boxes are wide enough to accommodate control rods inserted from bottom by hydraulic actuators.

(4) **Perssurised Water Reactor (PWR).** In it the coolant-moderator is maintained at a pressure high enough to prevent bulk boiling. The system pressure is regulated by means of a pressuriser, which is a closed vessel equipped with electric heaters and water sprays, and connected to the reactor vessel. The primary coolant water passes up through the core and then through the heat exchanger tubes. Steam is generated on the secondary side of these heat exchangers. The coolant is then recirculated through the reactor by means of pumps. Fuel is assembled into large clusters. Since the secondary circuit is separated from the primary, steam is not activated or contaminated by radioactive isotopes.

(5) **CANDU** (CANadian Deuterium Uranium). It uses heavy water as moderator and coolant, and UO_2 as fuel.

(6) **(SGHW) Steam Generating Heavy Water Reactor.** It is an attempt to combine as many as possible of the virtues of CANDU and BWR. It is a heavy water, moderated pressure tube reactor using ordinary water as coolant in the boiling regime. The steam is used in a direct cycle.

(7) **Fast Breeder Reactor.** It uses high-energy neutrons. In it the average neutron yield of a fission is greater than in thermal reactors and accordingly all absorption cross-sections are much reduced. Plutonium is the fissile material for fast reactors. Liquid metal coolants are used.

Solar Thermal Generation. The sun is a gigantic thermonuclear reactor. The total solar radiation energy emission is estimated to be 3.86×10^{23} kW. Considering the mean distance from the sun to the semi-major axis of the earth orbit as 149.4×10^6 km, by applying the Stefan-Boltmann law the effective temperature of the sun's surface is 5750°K. The solar energy which would be intercepted by plane surface oriented at right angle to the sun rays outside the earth atmosphere is 1.36 kW/m^2.

For silicon cells the maximum useable sunlight concentration is about 10 times.

There are many other methods of solar heat collection by focussing and non-focussing devices such as flat plate collectors, parabolic dishes or troughs, Fresnel's lenses, electromagnetic collector, thermo-electric collectors, etc. Suitably designed gallium-arsenide/gallium-aluminium hetero-structure function semi-conductor solar cells can be operated at light intensities of 2000 times full sunlight to produce specific output between 20 W/cm^3 and 40 W/cm^3 at an efficiency of 24%.

In remote areas, central receiver power plant concept employing heliostat array made of surfaced aluminium or plastic sheet with protective coating can be employed. The heliostats can continuously track the sun by optical guides and automated computer controlled system and focussed to the tower top vacuum windows where heat transport fluid is heated and piped to ground for turbo generator drive. Solar concentration ratio of about 1000 can be achieved with a temperature range of 480°C–540°C which suits the turbine characteristics.

Wind Energy. The wind power is proportional to the cube power of its velocity. Wind power is likely to produce a cheap source of energy for pumping water in rural areas.

Ocean Wave Energy. Wave energy is derived from wind energy which in turn is derived from solar energy. Wind energy is caused by uneven solar heating and subsequent cooling of the earth's crust and rotation of the earth. Wave energy can be much more concentrated than the solar energy.

Waves of 2 to 3 m high (Crest to trough) with a capacity of 5 kW/m to 10 kW/m during normal trade wind periods are available. Water waves are basically characterized by height, length, period and speed. Wave height is proportional to square of wind speed.

Oscillating water column (cavity resonator type) technique is popular in which RCC column is installed with turbine and generator mounted on its top utilizing pressure induced by waves.

Biomass Energy (Wood and Animal Dung). Photosynthesis process plants convert solar energy into biomass which can be used as a source of fuel. The specific production of biomass is one of the alternative fuel source which has several advantages over depleting fossil resources. It is renewable environmentally clean and easily adaptable.

Plants serve as solar energy storage device from which accumulated energy can be released.

By pyrolysis which is an irreversible chemical change caused by action of heat in absence of oxygen, the biomass leaves the energy stored in it. Pyrolysis needs simple equipment, low pressure operation, negligible waste product and high conversion efficiency of the order of 83%.

Wood waste, agriculture waste and roots of various crops are gasified in gasifiers which have the value of the order of 950–1200 kcal/m^3. Large size gasifiers with output of 300 kW and above may be employed for power generation.

Mini/Micro Hydro Power. Mini-hydro refers to schemes of around 1–5 MW rating while micro-hydro refers to schemes of less than 1 MW rating. These schemes operate under heads of few meters.

In these plants civil work is simple and can be built by using local labour in a short time. The standard packaged units which include an intake valve, hydraulic turbine, alternator, electronic governor system, automatic control unit and switchgears are used for generation of power. These are particularly useful for a small isolated group of consumers.

PROBLEMS

Provide a single word (group of words) for following :

1. Energy derived from the fission of the nuclei of heavy elements (uranium or thorium), or from the fusion of the nuclei of light elements (deuterium or tritium)
2. Reaction caused by changes in the electron structure surrounding the nucleus
3. Reaction which occurs when the particles making up the nucleus of an atom are rearranged.
4. Theoretically, the irreducible constituents of the material world

5. Except for the electron and proton, all the fundamental particles are ....
6. Electrons emitted by radio-active atoms
7. It is identical to the nucleus of the hydrogen atom
8. It has a mass approximately equal to that of the proton
9. It can't be detected by subjecting it to electric or magnetic fields, nor can its presence be shown by its passage through cloud chambers.
10. The basic unit of any chemical element
11. The number of electrons associated with an atom determines its ....
12. Elements which have identical chemical characteristics but different atomic weights
13. .... has three isotopes
14. The work required to disintegrate an atom completely into protons and neutrons
15. An unstable nucleus undergoes atomic disintegration by emitting α, β, β^+, γ or X-ray electromagnetic radiation
16. The alpha particle is identical with nucleus of a .... atom.
17. A particle whose mass is the same as that of an electron and whose charge is equal in magnitude but opposite in sign
18. A technique used to determine the molecular and crystalline structure of materials.
19. A heat source which requires no oxygen.
20. Those isotopes of uranium and plutonium which fission upon interaction with thermal neutrons.
21. Those isotopes of uranium and plutonium which have even atomic weights.
22. Materials capable of reducing neutron energy very rapidly.
23. A technique used to determine the molecular and crystalline structure of materials
24. Most widely used and planned power reactor
25. A nuclear reactor that produces more fissionable material than it consumes.
26. Unmoderated liquid-metal-cooled reactors operating at extremely high power density
27. Those isotopes of uranium and plutonium which fission on integration with thermal neutrons.
28. Those isotopes of uranium and plutonium which fission upon interaction with thermal neutrons.
29. Materials capable of reducing neutron energy very rapidly
30. Materials having high cross section for absorption of neutrons.
31. The main objective of reactor design during reactor operation
32. The ratio (of number of fissile nuclides produced by the capture of neutrons by the fertile nuclides to the number of fissile nuclides) being greater than unity.
33. Tolerance radiation level
34. Device for direct conversion of solar radiation into electricity

ANSWERS

1. nuclear energy
2. chemical reaction
3. nuclear reaction
4. fundamental particles
5. unstable
6. beta rays
7. proton
8. neutron

9. neutron
10. atom
11. chemical characteristics
12. isotopes
13. hydrogen
14. binding energy
15. radioactivity
16. helium
17. positron
18. neutron diffratrometry
19. nuclear reactor
20. fissionable materials
21. fertile materials
22. moderating materials
23. neutron diffractrometry
24. water cooled reactor
25. breeder reactor
26. fast breeder reactor
27. fissionable materials
28. fertile materials
29. moderating materials
30. control materials
31. to achieve neutron balance
32. breeding ratio
33. 10^3 particles/cm^2/s
34. photo voltaic cell

4

Steam Boilers, Engines, Nozzles and Turbines

Conversion Factors for Pressure

	bar	*dyne/cm²*	*kgf/cm²*	*N/m²*	*mm Hg (21°C)*	*mm H_2O (21°C)*	*at m*
1 bar =	1	10^6	1.01972	10^5	750.06	10197.2	0.986923
1dyne/cm² =	10^{-6}	1	101.972×10^8	0.1	750.062×10^{-6}	10197×10^{-6}	986.923×10^{-5}
1kgf/cm² =	0.980665	980.665×10^3	1	98066.5	735.559	10000	967.861×10^{-3}
1 N/m² =	10^{-5}	10	0.03453	1	750.06×10^{-5}	10197.2×10^{-5}	0.986923×10^{-5}
1 mm Hg = (21°C)	1.333223×10^{-3}	1333.223	1.3595×10^{-3}	133.322	1	13.5951	1.315×10^{-3}
1 mm H_2O = (21°C)	98.0655×10^6	98.0669	10^4	9.80665	0.073556	1	96.7837×10^{-6}
1 atm=	1.0132	101.325×10^4	1.03323	133.322	760	10332.276	1

Properties of Liquids (Water and Steam)

For understanding the various properties of steam, let us start heating 1 kg of water at 0°C in closed vessel closed by a piston and continue till it becomes superheated steam. Let this 1 kg of water be subjected to continuous constant pressure P kg/cm². The volume occupied by water is nearly independent of the pressure. As heat is applied, the speed of movement of molecules in water increases and temperature starts rising. If we assume there are no other losses, then this heat energy is being stored in water and internal energy of water is increased. This is shown visibly by rise of temperature in thermometer. Change of volume will be very small, therefore work done will be negligible as long as it is in state of water.

So heat supplied to water

$$Q = U_2 - U_1 + \frac{W}{J}$$

U_2 = final internal energy

U_1 = initial internal energy

However H (Enthalpy), is defined as sum of internal energy and work.

$$\therefore \quad H = U + \frac{pV}{J}$$

But for water, $\frac{pV}{J}$ = negligible.

Hence $H = U$ (as long as water remains water)

As we keep on increasing the application of heat, a stage is reached when pressure exerted by the molecules of water equals the external pressure and boiling starts. The temperature corresponding to this stage is called *saturation temperature.* By still further addition of heat, the molecules of water start shooting off, thus push the piston away which is causing pressure. The temperature remains same. In other words for any particular value of pressure there is a definite temperature at which water will start boiling and change into steam. This temperature is called saturation temperature and the temperature remains same during complete formation of steam. The saturation temperature increases as the pressure of water is increased.

When water is boiling and steam is being formed at constant temperature, steam is said to be *saturated.* Its physical condition is such that slight disturbance in pressure or temperature will change it into water.

Wet steam is a mixture of steam and water which exist in equilibrium at saturation temperature.

When no water particles are present and temperature of steam corresponds to saturation temperature then steam is said to be dry saturated.

Sensible heat (*h*). It is the heat required to raise the temperature of 1 kg of liquid from 0°C to the boiling point.

Latent heat (*L*). It is the quantity of heat required to convert 1 kg of liquid at boiling point into dry saturated vapour at the same temperature.

Total heat (*H*). It is the quantity of heat required to convert 1 kg of liquid from the 0°C to dry saturated vapour at constant pressure.

During steam formation stage, the volume of the working substance goes on increasing. Therefore, work done is given by

$$\frac{p\,(V_s - V_w)}{J} \qquad \begin{bmatrix} V_s = \text{volume of steam} \\ V_w = \text{volume of water} \end{bmatrix}$$

V_w is very small in comparison with V_s, therefore, it is neglected. Term $\frac{pV_s}{J}$ is known as external work of evaporation.

Heat supplied or enthalpy of steam

$$= h + L + \frac{pV_s}{J}$$

As the term pV_s/J is spent in doing external work and not stored in the form of energy, therefore the expression $h - \frac{pV_s}{J}$ is called true or internal latent heat.

Total increase in internal energy of water changed into dry saturated steam $= h + L - \frac{pV_s}{J}$.

= heat of water from zero °C to saturation temperature, and $h + L$ is defined as enthalpy (H).

$$\therefore \qquad U_2 - U_1 = H - \frac{pV_s}{J}.$$

Dryness Fraction is the term used to define the wetness of steam. This is equal to ratio of weight of steam to total weight of mixture.

This is also defined as the ratio of actual heat supplied to total latent heat of evaporation.

i.e. $x = \frac{H_w - h}{L}$; H_w = total heat of steam at any stage