MADE EASY
India's Best Institute for IES, GATE & PSUs

Detailed Solutions

ESE-2024
Mains Test Series

Mechanical Engineering
Test No : 7

Section A : IC Engine + Power Plant [All Topics]
Section B : Renewable Sources of Energy-1 + Industrial & Maintenance Engineering-1 [Part Syllabus]
Production Engineering and Material Science-2 [Part Syllabus]

Section : A

1. (a)

The volumetric efficiency is affected by following variables:

1. **The density of fresh charge:** As the fresh charge is inducted in the hot cylinder, heat is transferred to it from the hot chamber walls and the hot residual exhaust gases, raising its temperature. This results in a decrease in the mass of fresh charge admitted and a reduction in volumetric efficiency. The volumetric efficiency is increased by low temperatures and high pressure of the fresh charge, since density is thereby increased, and more mass of charge can be inducted into a given volume.
2. **The exhaust gas in the clearance volume:** As the piston moves from TDC to BDC on the intake stroke, these products tend to expand and occupy a portion of the piston displacement greater than the clearance volume, thus reducing the space available to the incoming charge. In addition, these exhaust products tend to raise the temperature of the fresh charge, thereby decreasing its density and further reducing volumetric efficiency.
3. **The design of the intake and exhaust manifolds:** The exhaust manifold should be so shaped and designed so to enable the exhaust products to escape readily, while the intake manifold should be designed so as to bring in the maximum possible fresh charge. This implies minimum restriction is offered to the fresh charge flowing into the cylinder, as well as to the exhaust products being forced out.

4. **The timing of the intake and exhaust valves:** Valve timing is the regulation of the points in the cycle at which the valves are set to open and close. Since, the valves require a finite period of time to open or close for smooth operation, a slight "lead" time is necessary for proper opening and closing. The design of the valve operating cam provides for the smooth transition from one position to the other, while the cam setting determines the timing of the valve. For either a low speed or a high speed engine operating in its range of speed, there is some point at which the charge per cylinder per cycle becomes a maximum for a particular valve setting.

1. (b)

Disadvantages of a gas turbine power plant in a utility system are the following:

1. Large compressor work input, since the power required to drive the compressor is considerably higher than that required by a pump for the same pressure rise. The compressor thus consumes a large part of the work produced by the turbine.
2. Large exhaust loss, since the exhaust gas temperature is quite high and also the mass flow rate of gas is large due to high air-fuel ratio used.
3. Machine inefficiencies, since with the decrease in compressor efficiency (η_c) the work input to the compressor increases and with the decrease in turbine efficiency (η_T) the work output from the turbine decreases. At certain values of η_c and η_T, a situation may arise when the compressor consumes more power than what the turbine develops. So, the machine efficiencies of the compressor and the turbine have to be high enough to yield justifiable net work output.
4. Low cycle efficiency, due to the large exhaust loss, large compressor work and machine inefficiencies.
5. Costly fuel, since the cost of kerosene and other fuels used is much higher than that of coal. Its availability is also not always guaranteed.

Due to the above factors, the cost of power generated by a stationary gas turbine plant for a utility system is high. However, a gas turbine plant offers certain advantages also, as given below:

1. Less installation cost
2. Less installation time
3. Quick starting and stopping
4. Fast response to load changes

So, a gas turbine plant is often used as a peaking unit for certain hours of the day when the energy demand is high. A large steam plant designed to meet peak loads would operate at an uneconomical load factor during most of the year.

To overcome its low cycle efficiency, a gas turbine may be used in conjunction with a steam turbine plant in an utility base load station, to offer the utilities the gas turbine advantages of quick starting and stopping and permit flexible operation of the combined plant over a wide range of loads.

1. (c)

Pre-ignition in a spark ignition engine describes the event where the air/fuel mixture in the cylinder ignites before the spark plug fires. Pre-ignition is initiated by an ignition source other than the spark, such as hot spots in the combustion chamber, a spark plug that runs too hot for the application, or carbonaceous deposits in the combustion chamber heated to incandescence by previous engine combustion events. The effect is more readily achieved on carburetted engines, because the final supply to the carburettor is typically regulated by a passive mechanical float valve and fuel delivery can feasibly continue until fuel line pressure has been relived. The occurrence is rare in modern engines with throttle body or electronic fuel injection.

Causes of pre-ignition include:

1. Carbon deposits from a heat barrier can be a contributing factor to pre-ignition.

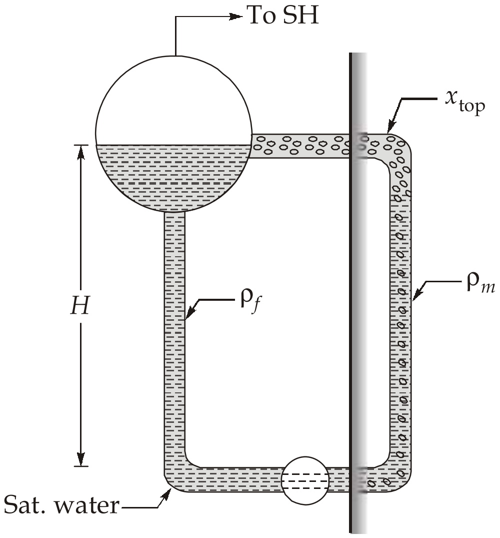
   Other causes include: An overheated spark plug, glowing carbon deposits on a hot exhaust valve.
2. Sharp edge in the combustion chamber or on top of a piston.
3. Sharp edge on valves that are reground improperly.
4. A lean fuel mixture.
5. Ignition timing too far advanced.
6. Insufficient oil in the engine.

Dangers of pre-ignition are:

1. It sharply increases the combustion chamber temperatures.
2. It causes rough engine operation or loss of performance.
3. It causes a momentary backlash as the piston tries to turn the crank in the wrong direction. This can be very damaging because of the high stresses it creates.
4. With pre-ignition, for the entire compression stroke, the engine is trying to compress a hot mass of expanded gas. That obviously puts tremendous heat into the parts and can cause substantial damage to the piston, piston rings.
5. It can cause wear in the bearings/gudgeon pin/little end, big end bearings or cause extra wear on the piston skirt or cylinder bore.

In case of highly supercharged or high compression multi-cylinder engines, pre-ignition is more dangerous. It can quickly melt or burn the piston since the power generated by other still functioning pistons will force the overheated ones along no matter how early the mix pre-ignites.

1. (d)



Given : $L = 20$ m; $D_o = 76$ mm; $D_i = D_o - 2t = 76 - 2 \times 6 = 64$ mm $= 0.064$ m; $V_w = 1.5$ m/s; $s = 1.2$; $CR = 12.5$

Properties at 80 bar :

$$v_f = 0.00138467 \text{ m}^3/\text{kg};\ v_g = 0.023526 \text{ m}^3/\text{kg}$$

$$h_f = 1317.3 \text{ kJ/kg};\ h_g = 2758.7 \text{ kJ/kg};\ h_{fg} = 1441.4 \text{ kJ/kg}$$

$$v_{fg} = v_g - v_f = 0.023526 - 0.00138467 = 0.02214133 \text{ m}^3/\text{kg}$$

$$\text{Top dryness fraction, } TDF = x_{top} = \frac{1}{CR} = \frac{1}{12.5} = 0.08$$

$$\rho_f = \frac{1}{v_f} = \frac{1}{0.00138467} = 722.19 \text{ kg/m}^3$$

$$v_{top} = v_f + x_{top} \cdot v_{fg} = 0.00138467 + 0.08 \times 0.02214133$$
$$= 0.00315597$$

$$\rho_{top} = \frac{1}{v_{top}} = \frac{1}{0.00315597} = 316.86 \text{ kg/m}^3$$

Average density of liquid-vapour mixture in the riser tube,

$$\rho_m = \frac{\rho_f + \rho_{top}}{2} = \frac{722.19 + 316.86}{2} = 519.53 \text{ kg/m}^3$$

∴ The pressure head developed due to natural circulation,

$$\Delta P = (\rho_f - \rho_m) \times g \times H = (722.19 - 519.53) \times 9.81 \times 20$$

$$= 39.76 \text{ kPa}$$ **Ans.**

$$\psi = \frac{v_f}{v_g} \times s = \frac{0.00138467}{0.023526} \times 1.2 = 0.07063$$

$$\text{Void fraction, } \alpha = \frac{1}{1+\left(\frac{1-x}{x}\right)\times\psi} = \frac{1}{1+\left(\frac{1-0.08}{0.08}\right)\times 0.07063}$$

$$= 0.5518$$ **Ans.**

Mass flow rate of saturated water entering the riser,

$$\dot{m}_w = \rho_f \cdot A_i \cdot V_w = 722.19 \times \frac{\pi}{4} \times 0.064^2 \times 1.5$$

$$= 3.485 \text{ kg/s}$$

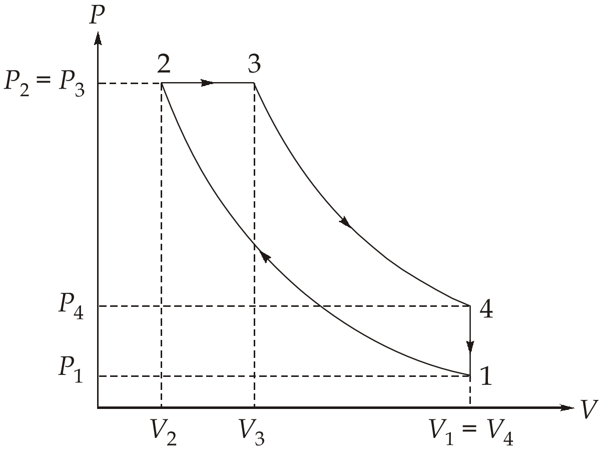
Rate of steam formation in the riser tube,

$$\dot{m}_s = x \times \dot{m}_w = 0.08 \times 3.485 = 0.279 \text{ kg/s}$$

∴ Heat transfer rate per unit projected area,

$$Q = \frac{\dot{m}_s \times h_{fg}}{D_o L} = \frac{0.279 \times 1441.4}{0.076 \times 20} = 264.57 \text{ kW/m}^2$$ **Ans.**

1. (e)



Given : $P_m = 8.4$ bar; $r = 12$; $\gamma = 1.4$; $P_1 = 1.03$ bar

$$\text{Net work done, } W = P_m \times V_s = \text{Area 1-2-3-4}$$

$$= W_{1\text{-}2} + W_{2\text{-}3} + W_{3\text{-}4} + W_{4\text{-}1}$$

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

[$W_{4\text{-}1}$ = 0, since constant volume process]

Compression ratio, $r = \frac{V_1}{V_2} = \frac{V_s}{V_c} + 1 = 12$

$\Rightarrow \quad V_s = 11 \times V_c = 11 \times V_2 \quad ...(ii)$

$V_1 = V_4 = 12 \times V_c = 12 \times V_2 \quad ...(iii)$

Cut-off ratio, $r_c = \frac{V_3}{V_2}$

$\Rightarrow \quad V_3 = r_c \times V_2 \quad ...(iv)$

$$\frac{P_2}{P_1} = \left(\frac{V_1}{V_2}\right)^{\gamma} = (r)^{\gamma} = 12^{1.4} = 32.42$$

$\Rightarrow \quad P_2 = 1.03 \times 32.42 = 33.39 \text{ bar} = P_3$

$$P_4 = P_3 \times \left(\frac{r_c}{r}\right)^{\gamma} = \frac{33.39}{32.42} \times r_c^{1.4} = 1.03 \times r_c^{1.4} \quad ...(v)$$

From equation (i),

$$W = \frac{1.03 \times 12 \times V_2 - 33.39 \times V_2}{1.4 - 1} + 33.39 \times (r_c - 1) \times V_2 + \frac{33.39 \times r_c \times V_2 - 1.03 \times r_c^{1.4} \times 12 \times V_2}{1.4 - 1}$$

$= 8.4 \times V_s$

$$\Rightarrow \quad 8.4 \times 11 \times V_2 = -52.575 \times V_2 + 33.39 \times (r_c - 1) \times V_2 + V_2 \times \left[\frac{33.39 \times r_c - 12.36 \times r_c^{1.4}}{0.4}\right]$$

$$\Rightarrow \quad 92.4 = -52.575 + 33.39 \times (r_c - 1) + \left[\frac{33.39 \times r_c - 12.36 \times r_c^{1.4}}{0.4}\right]$$

By solving above equation, we get

$r_c = 2.46$ **Ans.**

$$\therefore \quad \eta_{\text{diesel}} = 1 - \frac{(r_c^{\gamma} - 1)}{r^{\gamma - 1} \cdot \gamma \cdot (r_c - 1)} = 1 - \frac{2.46^{1.4} - 1}{12^{0.4} \times 1.4 \times (2.46 - 1)}$$

$= 0.5426 \text{ or } 54.26\%$ **Ans.**

2. (a)

Large amounts of air are needed for combustion of the fuel. The gaseous combustion products in huge quantity have also to be removed continuously from the boiler furnace. To produce the required flow of either air or combustion gas, a pressure differential is needed. The term "draught" or "draft" is used to define the static pressure in the furnace, in the various ducts, and the stack. The function of the draught system is basically two-fold:

1. To supply to the furnace the required quantity of air for complete combustion of fuel.
2. To remove the gaseous products of combustion from the furnace and throw these through chimney or stack to the atmosphere.

Given : $h = 20$ mm; $H = 35$ m; $T_a = 300$ K; $T_g = 650$ K

Draught in mm of water column,

$$h = 353 \times H\left[\frac{1}{T_a} - \frac{m+1}{m} \times \frac{1}{T_g}\right]$$

$$20 = 353 \times 35\left[\frac{1}{300} - \frac{m+1}{m} \times \frac{1}{650}\right]$$

$$\Rightarrow \qquad m = 8.736 \text{ kg air/kg coal}$$

Let H_g be the height of the hot gas column producing the draught. Then

$$H_g = H\left[\frac{m}{m+1} \times \frac{T_g}{T_a} - 1\right]$$

$$= 35 \times \left[\frac{8.736}{8.736+1} \times \frac{650}{300} - 1\right] = 33.04 \text{ m}$$ **Ans.**

where,

$$\rho_g = 353 \times \left(\frac{m+1}{m}\right) \times \frac{1}{T_g}$$

$$= 353 \times \left(\frac{8.736+1}{8.736}\right) \times \frac{1}{650} = 0.605 \text{ kg/m}^3$$

$$\text{Mass flow of flue gas} = \text{Mass of coal + Mass of air}$$

$$= \frac{2052 \times (1+8.736)}{3600} = 5.55 \text{ kg/s}$$

$$\text{Flue gas velocity, } V_g = \sqrt{2gH_g} = \sqrt{2 \times 9.81 \times (0.1 \times 33.04)} = 8.05 \text{ m/s}$$

$$\therefore \quad \text{Volume flow of flue gas} = \frac{5.55}{0.605} = 9.17 \text{ m}^3/\text{s}$$

$$\text{Volume of flow of flue gas} = \frac{\pi}{4}\times d^2\times V_g$$

$$\Rightarrow \quad 9.17 = \frac{\pi}{4}\times d^2\times 8.05$$

$$\Rightarrow \quad d = 1.204 \text{ m}$$ **Ans.**

2. (b)

For naturally aspirated engine,

$$\text{Swept volume, } V_s = \frac{3}{1000}\times\frac{3600}{2} = 5.4 \text{ m}^3/\text{min}$$

Actual volume/ min of air inducted,

$$\dot{V}_a = \dot{V}_s\times\eta_v = 5.4\times\frac{82}{100} = 4.428 \text{ m}^3/\text{min}$$

Indicated power developed by the engine = $\dot{V}_a\times P = 4.428\times 12 = 53.136$ kW

$$\text{Brake power developed} = 0.75\times 53.136 = 39.852 \text{ kW}$$

Pressure ratio of the compressor, $r_p = \frac{P_2}{P_1} = 1.6$

Delivery pressure of the compressor,

$$P_2 = 1\times 1.6 = 1.6 \text{ bar}$$

$$\frac{T_2'}{T_1} = (r_p)^{\frac{\gamma-1}{\gamma}} = (1.6)^{\frac{0.4}{1.4}} = 1.144$$

$$T_2' = 300\times 1.144 = 343.2 \text{ K}$$

$$\eta_c = \frac{T_2'-T_1}{T_2-T_1}$$

$$\Rightarrow \quad \frac{343.2-300}{T_2-300} = 0.70$$

$$\Rightarrow \quad T_2 = 361.7 \text{ K}$$

Actual intake temperature of the engine = 361.7 – 5.7 = 356 K

At atmospheric conditions the corresponding volume (V_1) will be

$$\frac{P_1V_1}{T_1} = \frac{P_2V_2}{T_2}$$

$$\Rightarrow \quad V_1 = \frac{P_2V_2}{T_2}\times\frac{T_1}{P_1} = \frac{1.6}{1}\times 5.4\times\frac{300}{356} = 7.281 \text{ m}^3/\text{min}$$

Increased intake volume rate of air due to supercharging

$$= 7.281 - 4.428 = 2.853 \text{ m}^3/\text{min}$$

The corresponding increase in indicated power of the engine due to supercharging

$$= 2.853 \times 12 = 34.236 \text{ kW}$$

Additional indicated power developed due to positive gas exchange work because of increase in intake pressure $= \dfrac{\Delta P \times \dot{V}_s}{60 \times 1000} = \dfrac{(1.6 - 1) \times 10^5 \times 5.4}{60 \times 1000} = 5.4 \text{ kW}$

$$\text{Total increase in IP} = 34.236 + 5.4 = 39.636 \text{ kW}$$

$$\text{Total increase in BP} = \eta_m \times \text{IP} = 0.75 \times 39.636 = 29.727 \text{ kW}$$

$$\dot{m}_a = \frac{1.6 \times 100 \times 5.4}{0.287 \times 356} = 8.45 \text{ kg/min}$$

Power required to run the compressor $= \dot{m}_a c_p \Delta T$

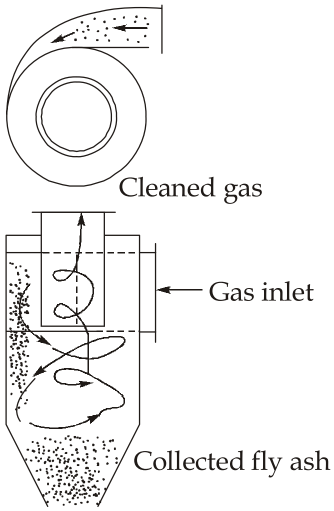
$$= \frac{8.45}{60} \times 1.005 \times (361.7 - 300) = 8.73 \text{kW}$$

$$\text{Net increase in BP} = 29.727 - 8.73 = 20.997 \text{ kW}$$

$\therefore$ The percentage increase in BP $= \dfrac{20.997}{39.852} \times 100 = 52.69\%$ **Ans.**

2. (c)

Cyclone separators: The cyclone is a separating chamber wherein high-speed gas rotation is generated for the purpose of "centrifuging" the particles from the carrying gases. Usually, there is an outer downward flowing vertex which turn into an inward flowing vertex. Involute inlets and sufficient velocity head pressure are used to produce the vortices. As multiple, small diameter vortices with high pressure drops appear to have high cleaning efficiency, that type is now being exploited. Skimming cyclones shave off the dust at the periphery of the vortex along with a small portion of the gas flow. This concentrated flow is then led to a secondary chamber for final separation.



Cyclone separator

The factors which affect the performance of this collector are gas volume, particulate loading, inlet velocity, temperature, diameter to height ratio of cyclone and dust characteristics.

The advantages and disadvantages of cyclone collectors are given below:

Advantages:

1. Rugged in construction.
2. Maintenance costs are relatively low.
3. Efficiency increases with increase in load.
4. Easy to remove bigger size particles.

Disadvantages:

1. Requires more power than other collectors.
2. Incapable to remove dust and ash particles which remain in suspension with still air.
3. Less flexible (in terms of volume handled).
4. High pressure loss comparatively.
5. Requires considerable head room and must be placed outside the boiler room.
6. As the fineness of the dust particle increases its collection efficiency decreases.

Out of m kg of particles entering the cyclone with the gas stream, if m_1 kg (fines) leave with the gas at the top and is collected, say, in a bag filter, then $(m - m_1)$ kg of particles are separated by the cyclone from the gas-solid mixture, and the expression $\left(\frac{m-m_1}{m}\times 100\right)$ is called the collection efficiency of the cyclone. The cyclone collection efficiency increases with increasing (a) particle size, (b) particle density, (c) inlet gas velocity, (d) cyclone body length, (e) number of gas revolutions, and (f) smoothness of cyclone walls. The collection efficiency decreases with increasing (a) cyclone diameter, (b) gas outlet duct diameter, and (c) gas inlet area.

For any specific cyclone whose ratio of dimensions is fixed, the collection efficiency increases as the cyclone diameter is decreased. The design of a cyclone separator represents a compromise among collection efficiency, pressure drop, and size. Higher efficiency requires higher pressure drops (i.e. inlet gas velocity) and larger sizes (i.e. body length).

3. (a) (i)

The complete mixing model is based on the following assumptions:

1. The fresh charge entering the cylinder mixes instantaneously and uniformly with the residual gases. Thus complete mixing occurs.
2. The scavenging process is considered to be a quasi-steady flow process.
3. The density of the incoming charge and the burned gases is the same.

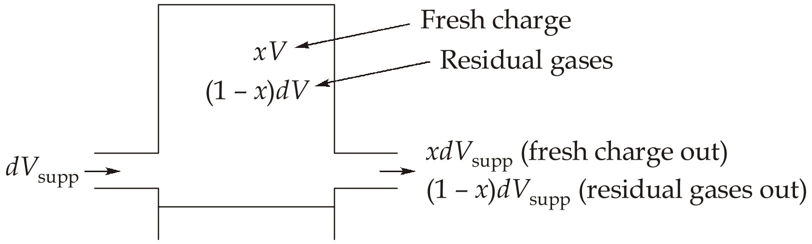
4. The residual gases are at the same temperature and have the same molar mass as the fresh mixture.
5. The piston remains at BDC during the scavenging process.
6. The cylinder pressure is assumed to be constant during scavenging.

Let x be the volumetric fraction of the fresh charge retained in the cylinder at any time, and V_{supp} be the volume of the fresh charge supplied that enters the cylinder up to that time. Let V be the total volume of the cylinder.

$$x = \frac{V_{\text{fresh charge retained}}}{V}$$

∴ Volume of fresh charge retained, $V_{\text{fresh charge retained}} = xV$

and in differential form, $dV_{\text{fresh charge retained}} = Vdx$



Complete mixing model

Refer to the figure, let dV_{supp} be the fresh charge supplied further in the cylinder. Fresh charge and residual gases are in the ratio x: $(1-x)$ in the cylinder. In the same ratio, fresh charge and residual gases move out.

i.e. fresh charge out $= xdV_{supp}$

residual gases out $= (1-x)dV_{supp}$

Applying mass conservation equation,

Mass of fresh charge in – mass of fresh charge out = Mass of fresh charge retained

$$\rho dV_{supp} - \rho x dV_{supp} = \rho V dx$$

where, density, ρ, is assumed to be the same for fresh charge and residual gas.

$$(1-x)dV_{supp} = Vdx$$

$$\frac{dV_{supp}}{V} = \frac{dx}{1-x}$$

Integration of both sides will give

$$\frac{V_{supp}}{V} = -\ln(1-x)$$

Now,
$$\frac{V_{\text{supp}}}{V} = \frac{\rho V_{\text{supp}}}{\rho V} = \frac{M_{\text{supp}}}{M_{\text{ideal}}} = \frac{\dot{M}_{\text{supp}}}{\dot{M}_{\text{ideal}}} = R_{sc} = \text{Scavenging ratio}$$

$$x = \frac{V_{\text{fresh charge retained}}}{V} = \frac{\rho V_{\text{supp}}}{M_{\text{ideal}}}$$

$$= \frac{M_{\text{ret}}}{M_{\text{ideal}}} = \frac{\dot{M}_{\text{ret}}}{\dot{M}_{\text{ideal}}} = \eta_{sc} = \text{Scavenging efficiency}$$

So, above expression reduces to

$$R_{sc} = -\ln(1 - \eta_{sc})$$

or
$$1 - \eta_{sc} = e^{-R_{sc}}$$

$\Rightarrow$
$$\eta_{sc} = 1 - e^{-R_{sc}}$$

Hence proved

3. (a) (ii)

$$\text{Density of air, } \rho = \frac{P_e}{RT} = \frac{103}{0.287 \times 300} = 1.196 \text{ kg/m}^3$$

$$\text{Swept volume } V_s = \frac{\pi}{4} \times d^2 \times L = \frac{\pi}{4} \times 0.12^2 \times 0.15 = 1.696 \times 10^{-3} \text{m}^3$$

$$\text{Total cylinder volume } V = \left(\frac{r}{r-1}\right) \times V_s = \left(\frac{16}{16-1}\right) \times 1.696 \times 10^{-3} = 1.809 \times 10^{-3} \text{m}^3$$

Ideal mass in total cylinder volume = $\rho V = 1.196 \times 1.809 \times 10^{-3} = 2.163 \times 10^{-3}$ m^3/cycle

$$\text{Ideal mass per unit time} = 2.163 \times 10^{-3} \times 2000$$
$$= 4.326 \text{ kg/min}$$

$$\text{Actual mass of air supplied per min} = \frac{244}{60} = 4.067 \text{ kg/min}$$

$$R_{sc} = \frac{\text{Actual mass of air supplied}}{\text{Ideal mass}}$$
$$= \frac{4.067}{4.326} = 0.94$$

$\therefore$
$$\eta_{sc} = 1 - e^{-R_{sc}} = 1 - e^{-0.94} = 0.609$$

$\therefore$
$$\text{Trapping efficiency, } \eta_{tr} = \frac{\eta_{sc}}{R_{sc}} = \frac{0.609}{0.94} = 0.6478 \text{ or } 64.78\%$$

Ans.

3. (b)

Given : Mass flow rate of steam $(\dot{m}_s)$ = 300 t/h

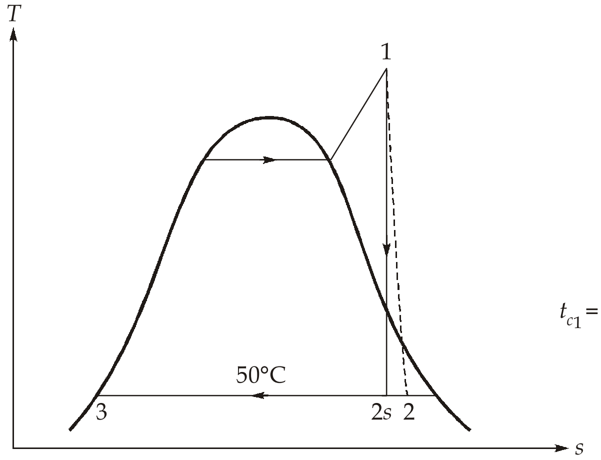
Pressure inside the condensor (P) = 0.0129 MPa = 0.129 bar

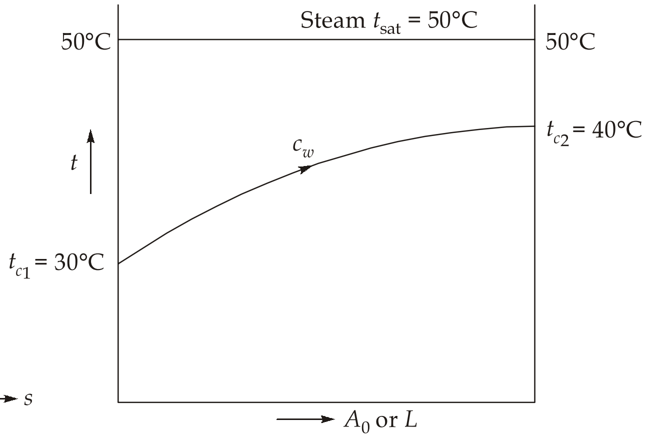
Velocity of circulating water (V) = 2 m/s

$$\text{Outer tube diameter } (D) = 26 \text{ mm}$$

$$\text{Inner tube diameter } (d) = 23 \text{ mm}$$

Overall heat transfer coefficient (U_0) = 3000 W/m^{2}K





$$\Delta t_i = 50 - 30 = 20°\text{C}$$

$$\Delta t_e = 50 - 40 = 10°\text{C}$$

From steam table, at 50°C

$$h_{fg} = 2381.9 \text{ kJ/kg}$$

Since moisture content at entry of condenser i.e. point 2 is 15%,

$$h_2 - h_3 = 0.85 h_{fg} = 0.85 \times 2381.9 = 2024.615 \text{ kJ/kg}$$

$$v_f = 0.00101215 \text{ m}^3/\text{kg}, \; v_g = 12.027 \text{ m}^3/\text{kg}$$

(i) By energy balance:

$$\dot{m}_s(h_2 - h_3) = \dot{m}_c \cdot c_w \left(t_{c_2} - t_{c_1}\right)$$

$$\frac{300 \times 1000}{3600}(2024.615) = \dot{m}_c \times 4.187 \times (40 - 30)$$

or, $\dot{m}_c = 4029.5657$ kg/s Ans.

(ii) At 50°C $P_{sat} = 0.12352$ bar

Now, pressure inside the condenser,

$$P = P_{sat} + P_{air}$$

or, $P_{air} = 0.129 - 0.12352 = 0.00548 \text{ bar} = 0.548 \text{ kN/m}^2$

Also,

$$v_2 = v_f + x_2 v_{fg}$$

$$= 0.00101215 + 0.85 \times (12.027 - 0.00101215)$$

$$v_2 = 10.2231 \text{ m}^3/\text{kg}$$

Now, assuming that air behaves as an ideal gas at such a low pressure, we have

$$P_{air}(\dot{m}_s \times v_2) = \dot{m}_{air} \times R_{\text{air}} \times T_s$$

$$0.548 \times \frac{300 \times 1000}{3600} \times 10.2231 = \dot{m}_{air} \times 0.287 \times 323$$

$$\dot{m}_{air} = 5.03613 \text{ kg/s}$$ Ans.

(iii) Since condenser acts as a heat exchanger,

$$(\Delta T)_{\text{LMTD}} = \frac{\Delta t_i - \Delta t_e}{\ln\left(\frac{\Delta t_i}{\Delta t_e}\right)} = \frac{20-10}{\ln\left(\frac{20}{10}\right)} = \frac{10}{\ln(2)}$$

or, $$(\Delta T)_{\text{LMTD}} = 14.4269°\text{C}$$

We know, $$Q = U_0 A_0 (\Delta T)_{\text{LMTD}} = \dot{m}_s (h_2 - h_3)$$

$$3 \times A_0 \times 14.4269 = \frac{300 \times 1000}{3600}(2024.615)$$

or, $$A_0 = 3898.2252 \text{ m}^2$$

Now, Mass flow rate of water

$$(\dot{m}_c) = n \times \frac{\pi}{4} d^2 \times \rho \times V$$

[where n is the number of condenser tubes]

or, $$n \times \frac{\pi}{4}(0.023)^2 \times 1000 \times 2 = 4029.5657$$

or, $$n = 4849.3406 \simeq 4850$$ Ans.

Again, $$A_0 = n\pi Dl = 3898.2252$$ [where, l is the length of tube]

$$l = \frac{3898.2252}{4850 \times \pi \times 0.026} = 9.8401 \text{ m}$$ Ans.

(iv) The number of tubes is 4850.

3. (c)

Sources of pollutants from SI engine

The following are the three main sources from which pollutants are emitted from the SI engine:

- **The crankcase:** Where piston blow-by fumes and oil mist are vented to the atmosphere.

- **The fuel system:** Where evaporative emissions from the carburettor or petrol injection air intake and fuel tank are vented to the atmosphere.
- **The exhaust system:** Where the products of incomplete combustion are expelled from the tail pipe into the atmosphere.

Crankcase Emission: The piston and its rings are designed to form a gas-tight seal between the sliding piston and cylinder walls. However, in practice there will always be some compressed charge and burnt fumes escape during compression and power stroke to crankcase. These gases are usually unburnt air-fuel mixture hydrocarbons, or burnt (or partially burnt) products of combustion, CO_2, H_2O (steam) or CO. These products also contaminate the lubricating oils.

Evaporative Emission: Evaporative emissions account for 15 to 25% of total hydrocarbon emission from a gasoline engine. The following are two main sources of evaporative emissions:

- The fuel tank
- The carburettor

Mechanism of formation of NO_x:

- NO_x includes nitric oxide (NO) and nitrogen dioxide (NO_2).
- In SI engines, the dominant component is NO.
- It forms as a result of dissociation of molecular nitrogen and oxygen.
- Since the activation energy of the critical elementary reaction is high, the reaction is very temperature dependent.
- Therefore NO is only formed at high temperature and the reaction rate is relatively slow and becomes extremely slow at temperatures below 2000 K.
- Since the cylinder temperature changes throughout the cycle, the NO reaction rate also changes.
- Each fluid element burns to its adiabatic flame temperature (AFT) based on its initial temperature, elements that burn first near the spark plug achieve a higher temperature.
- Once the element temperature reaches 2000 K, the reaction rate becomes so slow that the NO concentration effectively freezes at a value greater than the equilibrium value.

  Reactions Involved

$$N_2 + O_2 \longrightarrow 2\ NO$$

$$N_2 + 2\ H_2O \longrightarrow 2\ NO + 2\ H_2O$$

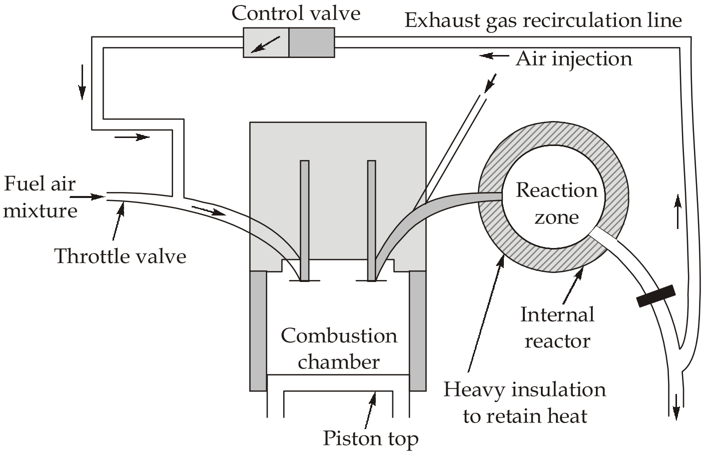
Control of emission of oxides of nitrogen: The concentration of oxides of nitrogen in the exhaust is closely related to the peak cycle temperature. The following are the three method for reducing peak cycle temperature and thereby reducing NO emission.

1. Exhaust Gas Recirculation (EGR), 2. Catalyst, 3. Water injection

1. **Exhaust Gas Recirculation:** Commonly used method to reduce NO_x in petrol as well as diesel engines. In SI engines, about 10 percent recirculation reduces NO_x emission by 50 percent.

EGR Arrangement:

EGR works by recirculating a portion of an engine's exhaust gas back to the engine cylinder. This dilutes the O_2 in the incoming air stream and provides gases inert to combustion to act as absorbents of combustion heat to reduce peak in-cylinder temperatures.



In SI engines, the inert exhaust displaces the amount of combustible matter in the cylinder.

In CI engine, the exhaust gas replaces some of the excess oxygen in the pre-combustion mixture.

This results in lower combustion chamber temperature which reduces the amount of NO_x generated during combustion.

Gas reintroduced from EGR systems contain near equilibrium concentrations of NO_x and CO, the small fraction initially within the combustion chamber inhibits the total net production of these.

In a typical SI engine, 5% to 15% of exhaust gas is routed back to the intake as EGR. A properly operating EGR can theoretically increase the efficiency of petrol engines via reduced throttling losses, reduced heat injection and reduced chemical dissociation.

In diesel engines, the lower oxygen exhaust gas into the intake, makes combustion less efficient, compromising economy and power.

In general, the poor combustion directly increases HC emission and calls for mixture enrichment to restore combustion regularity which a further indirect increase of both HC and CO.

2. **Catalyst:** Emission control catalysts enlisted below are being used to reduce NO_x emission.
   - **(a) Lean NO_x catalyst:** does selective catalytic reduction by hydrocarbons (HC–SCR) which targets CO and HC in addition to NO_x.
   - **(b) NO_x absorber catalyst:** absorbs (traps) NO_x from lean exhaust, followed by release and catalytic reduction under rich conditions. It is commercially used on lean burn petrol engines and some light-duty diesel engines.

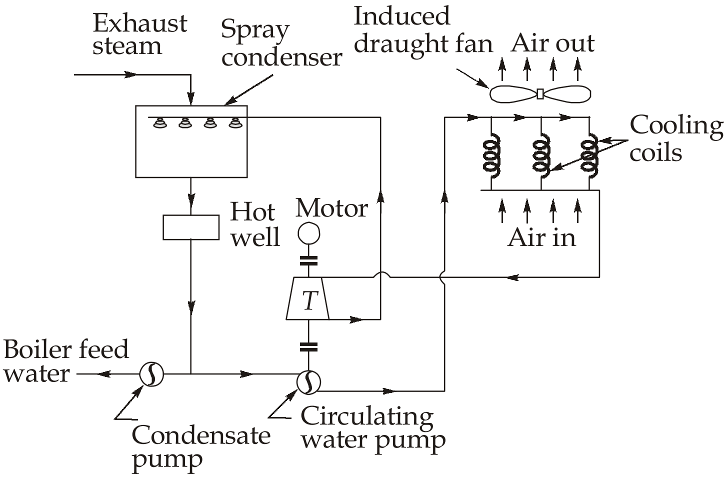
4. (a) (i)

The necessity of using dry cooling towers has been felt due to the following reasons:

(i) Natural water resources can be used for dissipating heat in power plants but there are some limitations to do so. Moreover there are potential thermal pollution problems in this system.

(ii) In evaporative cooling system (cooling towers) due to continuous evaporation of water, the concentration of impurities goes on increasing and so the disposal of tower blow down may become a serious problem at some sites. Besides this make up water for tower use is limited in some areas.

Thus the use of dry cooling towers in power plants in the only alternative. The dry system rejects the heat directly to the atmosphere which is the largest heat sink available.



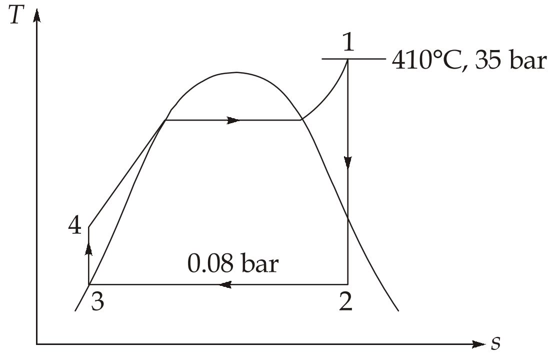
Indirect system

Indirect System. Refer to figure. In this case, the exhaust steam is condensed in a spray condenser by means of circulating water. The major part of the water from the condenser flows back to the cooling coils and an amount equal to the exhaust steam from the turbine is directed back to the boiler feed water circuit. Some energy recovery is possible by using hydraulic turbine (T) to drive the circulating water pumps. This system is applicable to all large unit sizes.

4. (a) (ii)

From steam table:

At 0.08 bar : $h_f = 173.84$ kJ/kg; $h_{fg} = 2402.4$ kJ/kg; $s_f = 0.59249$ kJ/kgK; $s_{fg} = 7.6348$ kJ/kgK



At 35 bar and 410°; $h = 3246.3$ kJ/kg; $s = 6.8769$ kJ/kgK

$$\therefore \quad s_1 = s_2$$

$$\Rightarrow \quad 6.8769 = 0.59249 + x_2 \times 7.6348$$

$$\Rightarrow \quad x_2 = 0.823$$ **Ans.**

$$h_2 = (h_f + x_2 h_{fg})_{@0.08\text{ bar}} = 173.84 + 0.823 \times 2402.4$$

$$= 2151.02 \text{ kJ/kg}$$

Since pump work is neglected,

$$h_3 = h_4 = h_f = 173.84 \text{ kJ/kg}$$

$$\text{Net work} = \text{Turbine work} = (h_1 - h_2) = 3246.3 - 2151.02$$

$$= 1095.28 \text{ kJ/kg}$$

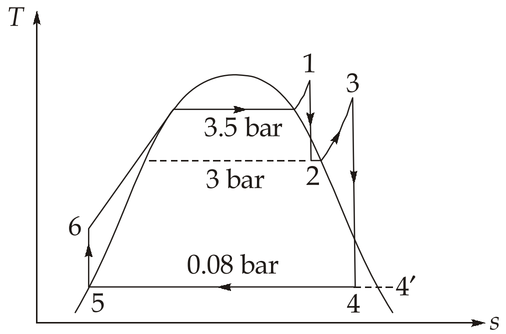
$$\text{Heat supplied} = h_1 - h_4 = 3246.3 - 173.84 = 3072.46 \text{ kJ/kg}$$

$$\text{Thermal efficiency} = \frac{\text{Net work}}{\text{Heat supplied}} = \frac{1095.28}{3072.46} = 0.3565 \text{ or } 35.65\%$$ **Ans.**

At 3 bar: $h_f = 561.43$ kJ/kg; $h_{fg} = 2163.5$ kJ/kg;

$s_f = 1.6717$ kJ/kgK; $s_{fg} = 5.3199$ kJ/kgK

Reheating case



For isentropic expansion process 1 - 2 :

$$\therefore \quad s_1 = s_2$$

$$\Rightarrow \quad s_1 = (s_f + x_2 s_{fg})_{@3\text{ bar}}$$

$$\Rightarrow \quad 6.8769 = 1.6717 + x_2 \times 5.3199$$

$$\Rightarrow \quad x_2 = 0.978$$

$$h_2 = (h_f + x_2 h_{fg})_{@3\text{ bar}}$$

$$= 561.43 + 0.978 \times 2163.5$$

$$= 2677.33 \text{ kJ/kg}$$

At 3 bar and 400°C : $s_3 = 8.0347$ kJ/kgK; $h_3 = 3275.5$ kJ/kg

For isentropic expansion process 3 - 4:

$$s_3 = s_4$$

$$\Rightarrow \quad s_3 = (s_f + x_4 s_{fg})_{@0.08\text{ bar}}$$

$$\Rightarrow \quad 8.0347 = 0.59249 + x_4 \times 7.6348$$

$$x_4 = 0.975$$

$$h_4 = (h_f + x_4 h_{fg})_{@0.08\text{ bar}}$$

$$= 173.84 + 0.975 \times 2402.4 = 2516.18 \text{ kJ/kg}$$

$$\text{Net work} = (h_1 - h_2) + (h_3 - h_4)$$

$$= (3246.3 - 2677.33) + (3275.5 - 2516.18)$$

$$= 1328.29 \text{ kJ/kg}$$

$$\text{Heat supplied} = (h_1 - h_6) + (h_3 - h_2)$$

$$= (3246.3 - 173.84) + (3275.5 - 2677.33)$$

$$= 3670.63 \text{ kJ/kg}$$

$$\text{Thermal efficiency} = \frac{\text{Net work}}{\text{Heat supplied}} = \frac{1328.29}{3670.63} = 36.18\%$$

4. (b)

At full load, the net imep, p_{mi} = 6.5 – 0.4 = 6.1 bar

At no-load, the number of working cycles per minute = 55

∴ At no-load, dead cycles per minute = $\frac{510}{2} - 55 = 200$

In hit and miss governing the working cycle has the same indicated diagram at any load. Since at no load, *bp* is zero.

$$FP = IP_{\text{working cycle}} - \text{Pumping power of dead cycles}$$

$$V_s = \frac{\pi}{4} \times D^2 \times L = \frac{\pi}{4} \times 0.2^2 \times 0.36 = 0.0113 \text{ m}^3$$

$$\therefore \quad FP = \frac{P_{mi} \times V_s \times n}{60} - \frac{P_{mid} \times V_s \times n}{60}$$

$$= \frac{6.1 \times 100 \times 0.0113 \times 55}{60} - \frac{0.65 \times 100 \times 0.0113 \times 200}{60}$$

$$= 3.87 \text{ kW}$$

At full load, with regular firing $\left(n = \frac{510}{2}\right)$ per minute

$$IP = \frac{P_{mi} V_s n}{60} = \frac{6.1 \times 100 \times 0.0113 \times \left(\frac{510}{2}\right)}{60} = 29.295 \text{ kW}$$

$$\therefore \quad BP = IP - FP = 29.295 - 3.87 = 25.425 \text{ kW}$$ **Ans.**

$$\therefore \quad \eta_{\text{mech}} = \frac{BP}{IP} = \frac{25.425}{29.295} = 0.8879 \text{ or } 86.79\%$$ **Ans.**

Q.4 (c) Solution:

Given: Power input to fan = 5 kW,

Power, $P = \frac{\Delta p \times \dot{V}}{\eta_{\text{mech}}}$

where, Δp is change in pressure,

$\dot{V}$ is volume flow rate.

η_{mech} is mechanical efficiency of fan

$$\dot{V} = \frac{5 \times 10^3 \times 0.8}{\Delta p} = \frac{5 \times 10^3 \times 0.8}{\rho_w \times g \times \Delta h}$$

$$\dot{V} = \frac{5000 \times 0.8}{1000 \times 9.81 \times 0.180} = 2.265 \text{ m}^3/\text{s}$$

$$\text{Density of air, } \rho_a = \frac{P}{RT} = \frac{1.02 \times 10^5}{287 \times (273 + 16)} = 1.23 \text{ kg/m}^3$$

$$\text{Mass flow rate of air, } \dot{m}_a = \rho_a \times \dot{V} = 1.23 \times 2.265$$

$$\dot{m}_a = 2.786 \text{ kg/s}$$ Ans.(i)

Assuming complete combustion of fuel.

The mass flow rate of flue gases, $\dot{m}_g = \dot{m}_a + \dot{m}_f = 2.786 + \frac{500}{3600} = 2.925 \text{ kg/s}$

By energy conservation,

Heat lost by flue gas = Energy gained by air in air preheater

$$\dot{m}_g \times (c_p)_g \times (\Delta T)_g = \dot{m}_a \times (c_p)_a \times (\Delta T)_{air}$$

$$2.925 \times 1.07 \times (\Delta T)_g = 2.786 \times 1.005 \times 75$$

$$(\Delta T)_g = 67.096°\text{C}$$

Temperature of flue gases leaving the plant = Temperature of flue gas entering the air preheater – Temperature drop of gas

$$= (225 - 67.096)°\text{C} = 157.904°\text{C}$$

Temperature of flue gases leaving the plant = 157.904°C **Ans.(ii)**

By energy conservation in economizer,

$$\dot{m}_w \times c_w \times (\Delta T)_w = \dot{m}_g \times (c_p)_g \times (\Delta T)_{eg}$$

$$\dot{m}_w \times 4.182 \times (125 - 40) = 2.925 \times 1.07 \times (395 - 225)$$

$$\dot{m}_w = \frac{2.925 \times 1.07 \times (395 - 225)}{4.182 \times 85}$$

Mass flow rate of steam, $\dot{m}_w = 1.4968$ kg/s **Ans.(iii)**

Enthalpy of feed water entering the boiler at 40°C, h_1 = 168 kJ/kg

Enthalpy of steam leaving the boiler i.e. at 40 bar and 300°C (h_2) = 2962.7 kJ/kg

$$\text{Boiler efficiency, } \eta_b = \frac{(h_2 - h_1) \times \dot{m}_w}{\dot{m}_f \times C.V.} = \frac{(2962.7 - 168) \times 1.4968}{35000 \times \left(\frac{500}{3600}\right)}$$

$$\eta_b = 0.8605 = 86.05\%$$ **Ans.(iv)**

Section : B

5. (a)

For 15 holes, at 300 rpm,

$$\text{Time, } T_1 = \frac{15 \times 30}{0.2 \times 300} = 7.5 \text{ min}$$

For 50 holes, at 200 rpm, $$T_2 = \frac{50 \times 30}{0.2 \times 200} = 37.5 \text{ min}$$

According to Taylor's tool life equation,

$$VT^n = \text{Constant}$$

$$N_1 T_1^n = N_2 T_2^n$$

$$\therefore \quad \ln N_1 + n \ln T_1 = \ln N_2 + n \ln T_2$$

$$\text{or} \quad n = \frac{\ln N_1 - \ln N_2}{\ln T_2 - \ln T_1}$$

$$n = \frac{\ln 300 - \ln 200}{\ln 37.5 - \ln 7.5} = 0.252$$

$$\text{Tool life we get } N_3 = 150 \text{ rpm}$$

$$N_1 T_1^n = N_3 T_3^n$$

$$300 \times 7.5^{0.252} = 150 \times T_3^{0.252}$$

$$\therefore \quad T_3 = 117.39 \text{ min}$$

Time required to drill one hole,

$$T = \frac{30}{0.2 \times 150} = 1 \text{ min}$$

∴ Number of holes can be produced at 150 rpm

$$n = \frac{117.39}{1} = 117.39 \simeq 117 \text{ holes}$$ **Ans.**

5. (b)

$$\text{B.E.P} = \frac{F}{1 - \frac{v}{s}} = \frac{1000000}{1 - \frac{40}{180}}$$

$$\therefore \quad \text{B.E.P} = ₹1285714.29/-$$ **Ans.(i)**

$$\text{Sales} = \frac{F + P}{1 - \frac{v}{s}}$$

or
$$1800000 = \frac{1000000 + P}{1 - \frac{40}{180}}$$

$$\therefore \quad P = ₹400000/- \qquad \textbf{Ans.(ii)}$$

Now, estimated contribution,

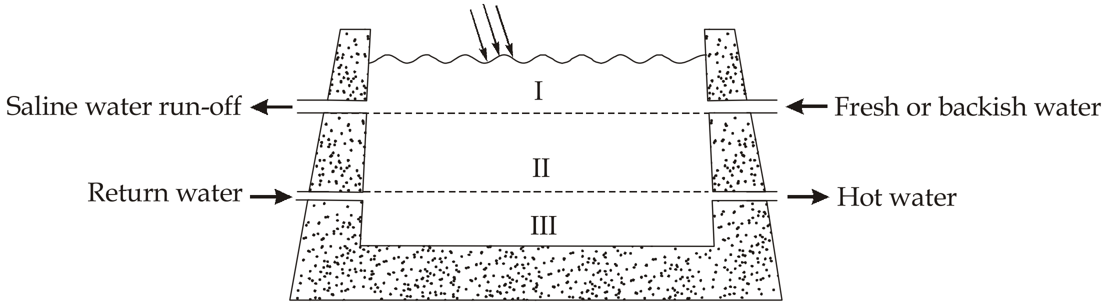
$$C = F + P = 1000000 + 400000$$
$$= ₹1400000/- \qquad \textbf{Ans.(ii)}$$

If profit is ₹1250000, then sales =
$$\frac{F + P}{1 - \frac{v}{s}} = \frac{1000000 + 1250000}{1 - \frac{40}{180}}$$
$$= ₹2892857.14/- \qquad \textbf{Ans.(iii)}$$

5. (c)

The concept of solar pond was derived from the natural lakes where the temperature rises (of the order of 45°C) towards the bottom. It happens due to natural salt gradient in these lakes where water at the bottom is denser. In salt concentration lakes, convection does not occur and heat loss from hot water takes place only by conduction.

This technique is utilised for collecting and storing solar energy. An artificially designed pond filled with salty water maintaining a definite concentration gradient is called a 'Solar Pond'. A schematic diagram of a solar pond is shown in figure below. The top layers remain at ambient temperature while the bottom layer attains a maximum steady-state temperature of about 60°C-85°C.



I = Surface convective zone (SCZ)
II = Concentration gradient zone (CGZ)
III = Lower convective zone (LCZ)

Fig. Schematic diagram of a solar pond

For extracting heat energy from the pond, hot water is taken out continuously from the bottom and returned after passing through a heat exchanger. Alternatively, heat is extracted by water flowing through a submerged heat exchanger coil. As a result of continuous movement and mixing of salty water at the top and bottom, the solar pond can have three zones.

(i) Surface Convective Zone (SCZ) having a thickness of about 10 cm-20 cm with a low uniform concentration at nearly the ambient air temperature.

(ii) Non-Convective Zone (NCZ) occupying more than half the depth of the pond. It serves as an insulting layer from heat losses in the upward direction.

(iii) Lower Convective Zone (LCZ) having thickness nearly equal to NCZ. This zone is characterized by constant temperature and concentration. It operates as the major heat collector and also as the thermal storage medium.

5. (d)

MRP do not provide a link with other areas of business, such as finance and marketing. MRP II has been developed in recent years to have an integrated system encompassing business functions other than manufacturing.

MRP II is a total company system, in which functional groups interact commonly and formally and make joint decision. MRP II is essentially a closed loop MRP with linkages to business and financial planning, reporting facilities and "What if" simulation capabilities.

In MRP II system there are three levels of planning and control.

(a) Strategic planning and control which includes (i) sales and operation planning and (ii) Long term capacity planning.

(b) Tactical planning and control which is concerned with preparing MRP taking into consideration (i) MPS (ii) Actual and forecast demand and (iii) Demand management.

(c) Execution planning and control: At this level MRP is linked with (i) planed and open order and (ii) shop floor control.

Benefits of MRP II:

(i) Improved customer service.

(ii) Improved productivity.

(iii) Reduction in purchase cost.

(iv) Higher inventory turn over.

The major Limitations of MRP II are:

(i) Complexity in manufacturing, planning and control:

(ii) Lack in expertise needed to implement effective manufacturing planning and control system.

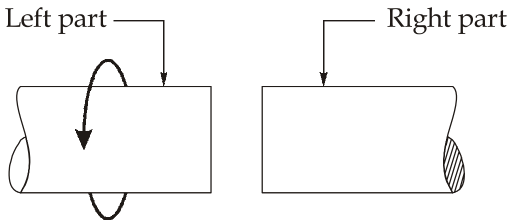
(iii) Non-availability of basic and accurate data.

(iv) Chances of by-passing MRP II system.

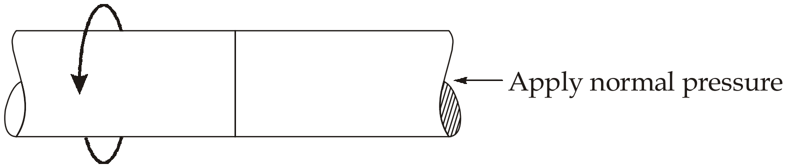
5. (e)

Friction Welding

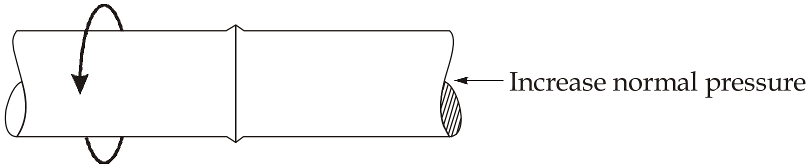
In this welding process, often termed as “inertia welding”, (shown in figure below) the two surfaces to be welded are rotated relative to each other under light normal pressure. When the interface temperature increases due to frictional rubbing and when it reaches the required welding temperature, sufficient normal pressure is applied and maintained until the two pieces get welded.



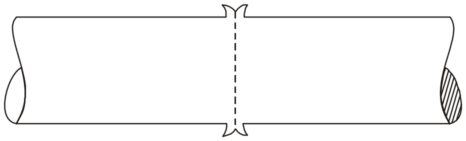
(i) Rotate left part at high speed



(ii) Bring right part in contact and apply axial force



(iii) Flash begins to form when axial force is increased



(iv) Stop rotating left part when flash is formed

Fig. Friction welding

- The shape of the welded joint depends on the rotational speed and the axial force applied; these factors must be controlled to obtain a uniformly strong joint. The radially outward movement of the hot metal at the interface pushes oxides and other contaminants out of the interface.

- A wide variety of metals and metal combinations can be welded by this process. Filler metals, fluxes, or shielding gases are not required, and welds can be made with a minimum of joint preparation.
- The method is most suitable for circular parts, that is, butt welding of round bars or tubes.

Advantages:

1. High quality welds.
2. The process is clean.
3. Low initial capital cost.
4. Low-cost power requirements.
5. Very little loss of material through exclusions.
6. Annealing of weld zone is not necessary.
7. The heating zone being very thin, therefore, dissimilar metals are easily joined.

Limitations:

- The method is limited to smaller components.
- The parts to be welded must be essentially round and must be able to withstand the high torque developed during welding.

Applications:

- H.S.S. twist drills;
- Gas turbine shafts;
- Aero-engine drive shafts and valves;
- Refrigerator tubes of dissimilar metals;
- Steering columns;
- Welding of sintered products, etc.

6. (a) (i)

Fresnel lens collector

Fresnel lens refraction type focusing collector is made of an acrylic plastic sheet, flat on one side, with fine longitudinal grooves on the other as shown in Figure (a). The angles of grooves are designed to bring radiation to a line focus. The CR ranges between 10 and 80 with temperature varying between 150°C and 400°C.

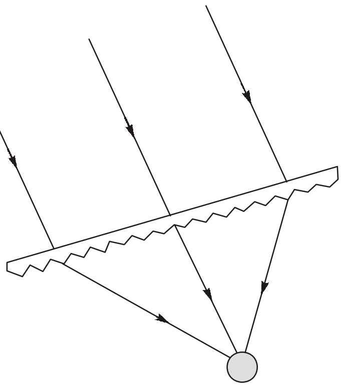


Fig. (a) : Fresnel lens collector

Paraboloid dish collector

To achieve high CR and temperature, it is required to build a point-focusing collector. A paraboloid dish collector is of point-focusing type as the receiver is placed at the focus of the paraboloid reflector (Figure (b)).

As a typical case, a dish of 6 m in diameter is constructed from 200 curved mirror segments forming a paraboloidal surface. The absorber has a cavity shape made of zirconium-copper alloy, with a selective coating of black chrome. The CR ranges from 100 to a few thousands with maximum temperature up to 2000°C. For this, two-axis tracking is required so that the sun may remain in line with the focus and vertex of the paraboloid.

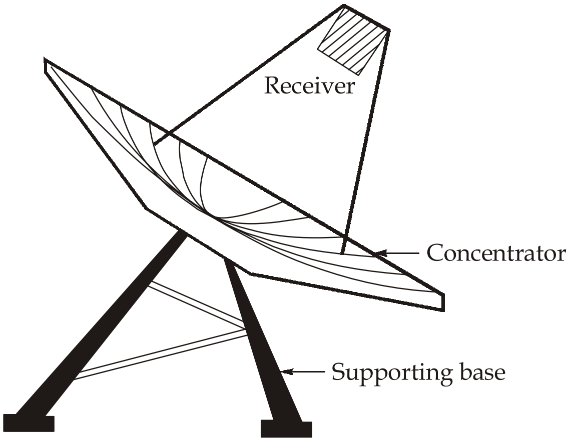


Fig. (b): Paraboloid dish collector

Central receiver with heliostat

To collect large amounts of heat energy at one point, the 'Central Receiver Concept' is followed. Solar radiation is reflected from a field of heliostats (an array of mirrors) to a centrally located receiver on a tower (Figure (c)).

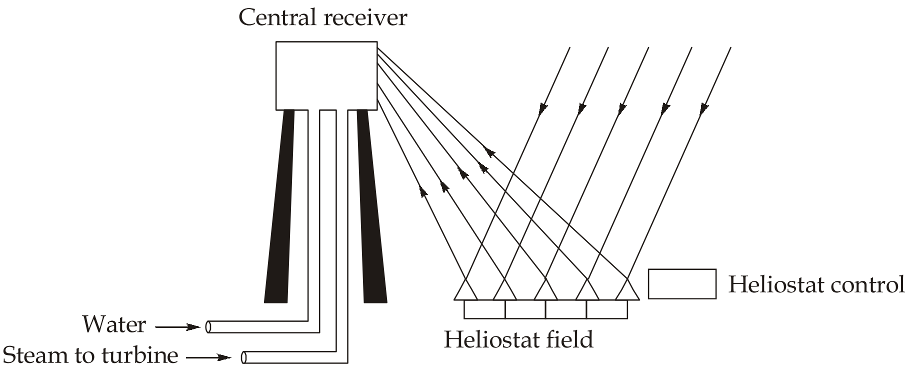


Fig. (c) : Central receiver tower with a field of heliostats

Heliostats follow the sun to harness maximum solar heat. Water flowing through the receiver absorbs heat to produce steam which operates a Rankine cycle turbo generator to generate electrical energy.

With a central receiver optical system, a large number of small mirrors are installed, each steerable to have an image at the absorber on the central receiver. A curvature is provided to the mirrors so as to focus the sunlight in addition to directing it to the tower.

6. (a) (ii)

$$\text{Concentration ratio, } C = \frac{1}{\sin\theta_A}$$

$$C = \frac{1}{\sin 10°} = 5.76 \qquad \textbf{Ans.}$$

$$\text{Aperture, } W = 5.76 \times 20 = 115.2 \text{ cm} = 1.152 \text{ m}$$

The ratio of height to aperture can be expressed as

$$\frac{H}{W} = \frac{1}{2}\left[1 + \frac{1}{\sin\theta_A}\right]\cos\theta_A$$

$$\frac{H}{W} = \frac{1}{2}\left[1 + \frac{1}{\sin 10°}\right]\cos 10° = 3.328$$

or $$H = 3.328 \times 115.2 = 383.39 \text{ cm} \qquad \textbf{Ans.}$$

Now, $$\frac{A_{conc.}}{WL} = 1 + C = 1 + 5.76$$

$$\therefore \quad A_{\text{conc.}} = 6.76 \times 1.152 \times 2.5$$

$$\therefore \quad A_{\text{conc.}} = 19.47 \text{ m}^2 \qquad \textbf{Ans.}$$

6. (b)

Nanomaterials

Nanoscale is usually defined as a one tenth of micrometer (100 nm), in at least one dimension, although this term is sometimes also used for materials smaller than 1 μm. Nanolayers such as thin films, surface coatings, and computer chips have one dimension in the nanoscale and are extended in the other two dimensions. Materials having a nanoscale in two dimensions and extended into the third one include nanowires and nanotubes. Those of a nanoscale in three dimensions are called nanoparticles, such as precipitates, colloids, quantum dots, and tiny particles of semiconducting materials. Table below shows typical nanomaterials together with their corresponding size. The outstanding characteristics of nanomaterials also include strength, hardness, ductility, wear resistance, and corrosion resistance, which are basically required for structural and non-structural applications. Moreover, nanomaterials should possess unique electrical, magnetic, and optical characteristics.

Typical Nanomaterials

Nanotype	Size	Material
Nanoparticles	1-100 nm, diameter	Ceramic oxide
Nanocrystals and quantum dots.	1-10 nm, diameter	Metals, semiconductors, magnetic materials
Nanowires	1-100 nm, diameter	Metals, semiconductors, oxides, sulfides, nitrides
Nanotubes	1-10 nm, diameter	Carbon, metal
2-D arrays of nanoparticles	Several nm^2 to μm^2	Metals, semiconductors, magnetic materials
Surface and thin films	1-1000 nm thick	Various materials
3D structures (superlattices)	Several nm	Metals, semiconductors, magnetic materials

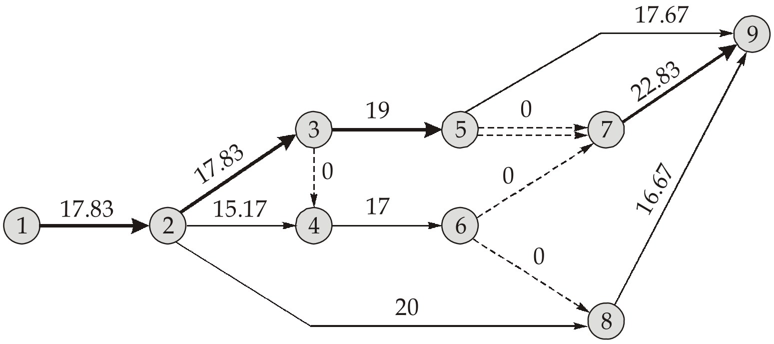
Materials reduced to nanoscale can suddenly show very different properties, enabling specific applications. For instance, opaque substances such as copper become transparent, inert materials such as platinum and gold attain catalyst properties, stable materials such as aluminium turn into combustibles, solids such as gold turn into liquids at room temperature, and insulators such as silicon become conductors. The composition of nono-materials can be any combination of the following elements or compounds: oxides, carbides, nitrides, metals and alloys, polymers, and composites. The preparation follows different techniques, such as inert-gas condensation, electro-deposition, plasma synthesis, sol-gel synthesis, and mechanical alloying or ball milling.

Nanoparticles Applications.

Particle Type	Application
Palladium	Chemical vapor sensors to detect hydrogen gas
Quantum dots	To identify the location of cancer cells in the body
Iron	Clean up carbon tetrachloride pollution in ground water
Silicate	Provide a barrier to gases (oxygen), or moisture in a plastic film used for packaging.
Zinc oxide	Industrial coatings to protect wood, plastic, and textiles from exposure to UV rays
Silicon dioxide	Filling gaps between carbon fibers, strengthening tennis racquets
Silver	To kill bacteria, making clothing odor-resistant
Titanium oxide	To remove germs and other pollutants from air
Manganese oxide	For removal of volatile organic compounds in industrial air emissions

6. (c)

The network is drawn in figure. The expected durations and variances of critical activities are calculated below:



Activity	Duration			$t_e = \dfrac{t_o + t_p + 4t_m}{6}$	$V = \left(\dfrac{t_p + t_o}{6}\right)^2$
	Optimistic (t_0)	Pessimistic (t_p)	Most likely (t_m)		
1 - 2	14	25	17	17.83	3.36
2 - 3	14	21	18	17.83	1.36
2 - 4	13	18	15	15.17	
2 - 8	16	28	19	20	
3 - 4	0	0	0	0	
3 - 5	15	27	18	19	4
4 - 6	13	21	17	17	
5 - 7	0	0	0	0	
5 - 9	14	20	18	17.67	
6 - 7	0	0	0	0	
6 - 8	0	0	0	0	
7 - 9	16	41	20	22.83	17.36
8 - 9	14	22	16	16.67	
					26.08

Hence 1-2-3-5-7-9 is the critical path with project duration of 77.49 days. Variances of the critical activities have been calculated.

i.e. $V = 26.08$

$\therefore$ $\sigma = \sqrt{26.08} = 5.107$ days

Now, we are to determine the time within which the project should be completed so as to provide 95% probability of breakeven.

Now, $P = 0.95,\ z = 1.65$ (Given)

$$\therefore \quad 1.65 = \frac{T - 77.49}{5.106}$$

$\therefore$ $T = 85.92$ days

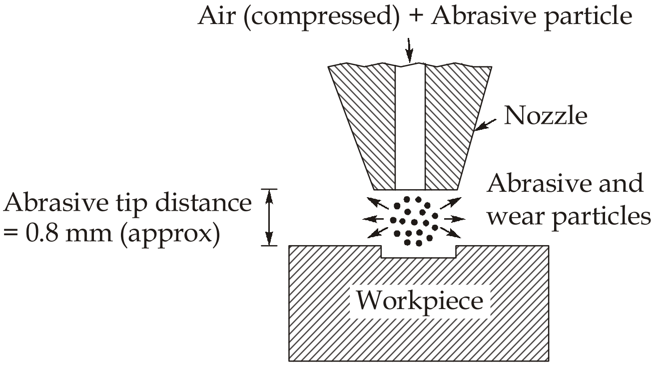
∴ The amount to bid = ₹(1000000 + 8000 × 85.92)

= ₹1687360/- **Ans.**

7. (a)(i)

ABRASIVE JET MACHINING (AJM)

Principle and Working: Refer to Figure



Abrasive Jet Machining (AJM)

This process consists of directing a stream of fine abrasive grains, mixed with compressed air or some other gas at high pressure through a nozzle on to the surface of the workpiece to be machined. These particles impinge on the work surface at high speed and the erosion caused by their impact enables the removal of metal. The metal removal rate depends upon the flow rate and size of abrasive particles.

The abrasives may be Al_2O_3, SiC, sodium bicarbonate, dolomite, glass beads etc. The abrasive particles should have irregular shape consisting of short edges. Their size is 10 to 50 microns. The carrier is usually air, CO_2 or N_2.

Advantages:

1. Low capital investment required.
2. Brittle materials of thin sections can be easily machined.
3. Intricate cavities and holes of any shape can be machined in materials of any hardness.
4. There is no direct contact between the tool and workpiece.
5. Normally inaccessible portions can be machined with fairly good accuracy.

Disadvantages:

1. Low metal removal rate.
2. Unsuitable for machining of ductile materials.
3. The abrasive powder used in the process cannot be reclaimed or reused.

4. Machining accuracy is relatively poorer.
5. There is always a danger of abrasive particles getting embedded in the work material. Hence cleaning needs to be necessarily done after the operation.

Applications:

1. Machining of intricate profiles on hard and fragile materials.
2. Fine drilling and micro-welding.
3. Frosting and abrading of glass articles.
4. Aperture drilling for electronic microscopes.
5. Machining of semiconductors.

7. (a)(ii)

Given : $l_c = 95$ mm; $l = 250$ mm; $\alpha = 20°$, $t = 0.6$ mm; $F_c = 2400$ N; $F_t = 250$ N

$$\text{Chip thickness ratio, } r = \frac{l_c}{l} = \frac{95}{250} = 0.38$$

$$\text{Shear plane angle, } \phi = \tan^{-1}\left(\frac{r\cos\alpha}{1 - r\sin\alpha}\right)$$

$$\phi = \tan^{-1}\left(\frac{0.38\cos 20°}{1 - 0.38\sin 20°}\right)$$

$$\phi = 22.31° \qquad \textbf{Ans.}$$

$$\text{Chip thickness, } t_c = \frac{t}{r} = \frac{0.6}{0.38} = 1.58 \text{ mm} \qquad \textbf{Ans.}$$

$$\text{Friction angle, } \mu = \tan\beta = \frac{F_c\tan\alpha + F_t}{F_c - F_t\tan\alpha}$$

$$\tan\beta = \frac{2400\tan 20° + 250}{2400 - 250\tan 20°} = 0.4866$$

or $$\beta = 25.95° \qquad \textbf{Ans.}$$

$$\text{Resultant cutting force, } R = \sqrt{F_c^2 + F_t^2} = \sqrt{2400^2 + 250^2}$$

$$= 2412.98 \text{ N} \qquad \textbf{Ans.}$$

7. (b)

Basically, there are two approaches for application of solar energy to buildings, namely active systems and passive systems. In an active system, solar collecting panels, the storage unit and the energy distribution system are installed with one or more working fluids. Energy is distributed by the circulation of working fluids using electrically-operated pumps and fans.

In a passive system all the functions of collection, storage and distribution are carried out by the building materials themselves. The term 'passive' refers to the solar-related architectural concept which describes the methods to utilise solar heat that is available to buildings by natural means. Generally, no electrical, mechanical or power electronic controls are used.

Indirect Gain Systems (Thermal Storage Wall)

In direct heat gain passive-heated rooms, there are large variations in the room air temperature. To reduce variations in the room air temperature, a thermal storage wall is provided between the living space and the glazing. A diagram of such a system, designed by Professor Trombe, is shown in figure below.

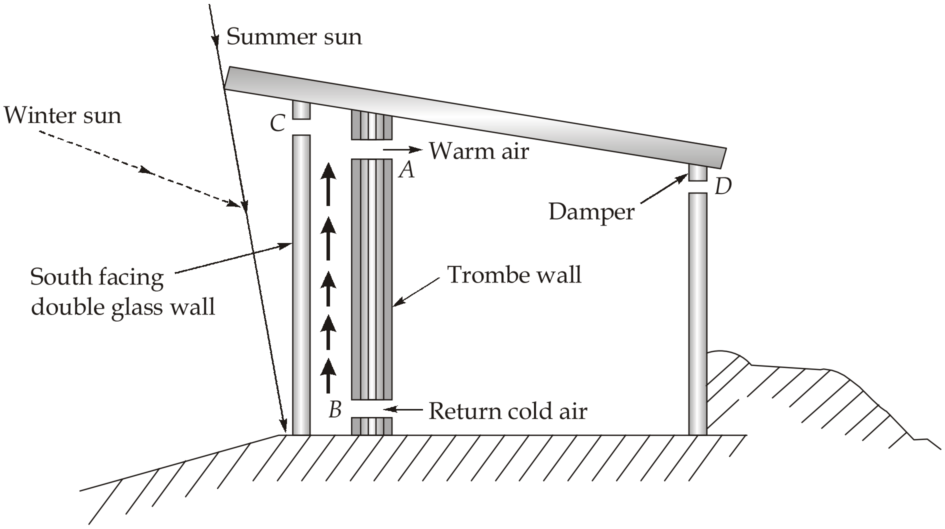


Fig. : Trombe wall passive solar heating system

In the Trombe wall passive system:

(i) The entire south-facing wall is double glazed by two sheets of glass or plastic with air gap between the wall and the inner glazing. Hot air flows from bottom to top through this air-gap owing to natural convection.

(ii) A large blackened concrete thermal storage wall of 40 cm or more in thickness is constructed with the outer side facing the sun. The sunlight after penetration through the glazing is absorbed by the wall and thus the wall is heated.

Accordingly, the air between the glazing and the wall gets heated and flows into the room through the top vent. This circulation process continues and the cool air from the room enters into this gap through the bottom vent. In addition, the room is also heated by radiation and convection from the inner surface of the wall facing the room. During night, both vents are closed and heat transfer takes place only by radiation.

During summer the vent A at the top of the south-facing wall is kept closed while the vents B, C and D are opened. The hot air between the glazing and the wall then flows out through the vent C and the air from the room flows in to fill this space. Simultaneously, the air is pulled into the room through the vent D which is located in a shaded cool area. The construction of the building is done in such a way that the overhanging roof prevents direct sun rays to heat glazing during summer.

7. (c) (i)

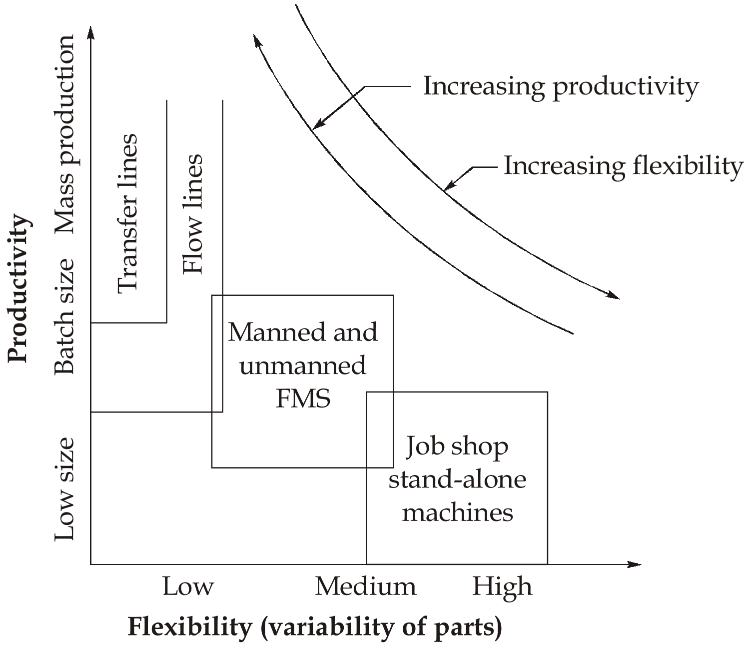
Flexible Manufacturing Systems

Flexible manufacturing system (FMS) is a high automated manufacturing system comprising a collection of production devices, logically organized under a host computer and physically connected by a central transporting system. It has been developed to provide some of the economics of mass production to small batch manufacturing.

Features and characteristics of FMS are summarized as follows:

- FMS offers immerging cost and quality benefits for most engineering sectors requiring batch production.
- In FMS, there is no batch size limitation in case of FMS; consequently there is no need to lock up money in extensive stocks of finished parts. The work-in-progress is reduced considerably and the inventory cost is, therefore, eliminated.
- It is possible to produce at random all varieties of products planned by a firm. FMS has the capability to quickly respond to any design changes or market demands in the product.
- FMS are usually equipped with robots and/or handling equipment. Software is developed to integrate CNC and the handling systems. All necessary tools can be stored in a magazine.
- All part programs of different models are stored in the system memory. The system identifies the model program to be produced.
- Extensive use of touch triggers is made to minimize the operator intervention in the line. Industrial robots are used for material handling (loading and unloading), inspection activities, and assembly operations.

The main advantage of a FMS is the high flexibility in terms of the small effort and short time required to manufacture a new product and is therefore denoted as a flexible manufacturing system. It is an alternative that fits in between the manual job shop and hard automated transfer lines as shown in figure.



FMS is best suited for applications that involve an intermediate level of flexibility and productivity. FMS can be regarded as a system that combines the benefits of two other systems: (1) the highly productive, but inflexible, transfer lines, and (2) the shop production that fabricates a large variety of products stand-alone machines but is inefficient. In FMS, the time required for changeover to a different part is very short (1 min) thus making the quick response to product and market demand variations a major benefit of FMS.

Elements of FMS

The basic elements of a FMS are

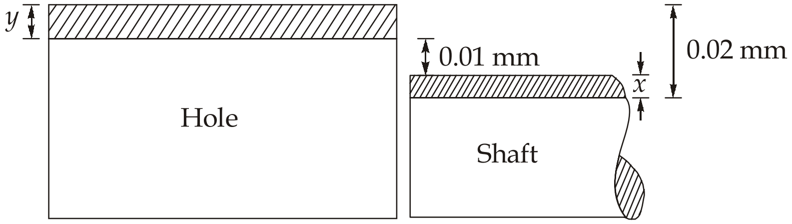
- Workstations
- Automated handling and transport of materials and parts
- Control systems

The use of FMSs is hampered by the following limitations:

- High programming cost
- Smaller degree of sophistication of fabrication and assembly processes
- Availability of reliable feedback devices for tool wear and breakage

7. (c) (ii)

Refer to figure below:



If x is the shaft tolerance and y is the hole tolerance, then

$$\begin{aligned} y + 0.01 + x &= 0.02 \\ \text{or} \qquad 1.5x + 0.01 + x &= 0.02 \\ \Rightarrow \qquad x &= 0.004 \text{ mm} \\ \therefore \qquad y &= 0.006 \text{ mm} \end{aligned}$$

(a) Hole basis system : The lower deviation of hole is zero.

$$\begin{aligned} (LL)_{\text{hole}} &= 30 \text{ mm (Basic size)} \\ (UL)_{\text{hole}} &= 30 + y = 30 + 0.006 = 30.006 \text{ mm} \\ (UL)_{\text{shaft}} &= (LL)_{\text{hole}} - \text{Minimum clearance} \\ &= 30 - 0.01 = 29.99 \text{ mm} \\ (LL)_{\text{shaft}} &= 24.99 - x = 24.99 - 0.004 \\ &= 29.986 \text{ mm} \end{aligned}$$

(b) Shaft basis system : The upper deviation of shaft is zero.

$$\begin{aligned} (UL)_{\text{shaft}} &= 30 \text{ mm (Basic size)} \\ (LL)_{\text{shaft}} &= 30 - 0.004 = 29.996 \text{ mm} \\ (LL)_{\text{hole}} &= 30 + 0.01 = 30.01 \text{ mm} \\ (UL)_{\text{hole}} &= 30.01 + 0.006 = 30.016 \text{ mm} \end{aligned}$$

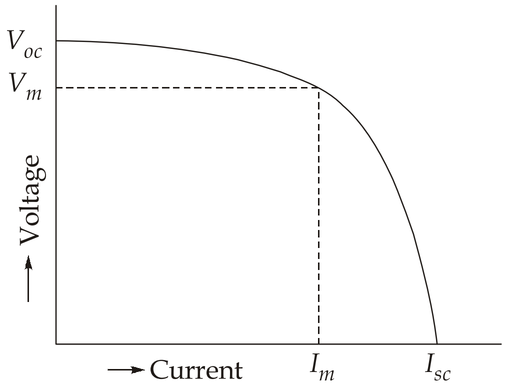
8. (a) (i)

Efficiency of Solar Cells

Electrical characteristics of a solar cell are expressed by the current-voltage curves plotted under a given illumination and temperature conditions as shown in figure below.

The significant points of the curve are short-circuit current I_{sc} and open circuit voltage V_{oc}. Maximum useful power of the cell is represented by the rectangle with the largest area. When the cell yields maximum power, the current and voltage are represented by the symbols I_m and V_m respectively. Leakage across the cell increases with temperature which reduces voltage and maximum power. Cell quality is maximum when the value of 'fill factor' approaches unity where the Fill Factor (FF) is expressed as

$$FF = \frac{I_m V_m}{I_{sc} V_{oc}}$$



Maximum efficiency of a solar cell is defined as the ratio of maximum electric power output to the incident solar radiation. So,

$$\eta_{\max} = \frac{I_m V_m}{I_s A_c}$$

where, I_s = incident solar flux; A_c = cell's area

Photovoltaic cells have low efficiency of 15%-only about 1/6th of the sunlight striking the cell generates electricity. The low efficiency of photovoltaic cell is due to the following major losses:

(i) When photons of light energy from the sun strike the cell, some of them (30%) are reflected (since reflectance from semiconductors is high). However, reflectance can be reduced to nearly 3% by surface texturing and anti-reflection coating.

(ii) Photons of quantum energy $h\nu < E_g$, cannot contribute to photoelectric current production (h is the Planck's constant and ν the frequency). This energy is converted into thermal energy and lost.

(iii) Excess energy of active photons ($h\nu > E_g$) given to the electrons beyond the required amount to cross the band gap cannot be recovered as useful electric power. It appears as heat (about 33%) and is lost.

(iv) Photovoltaic cells are exposed directly to the sun. As the temperature rises, leakage across the cell increases. Consequently, there is reduction in power output relative to input of solar energy. For silicon, the output decrease by 0.5% per°C.

(v) Incident active photons produce electron-hole pairs with high quantum efficiency. Better cell design is required to ensure 95% absorption.

(vi) Generated electric current flows out of the top surface by a mesh of metal contacts provided to reduce series resistance losses. These contacts cover a definite area which reduces the active surface and prove an obstacle to incident solar radiation.

(vii) For higher efficiency, the p-n junction should be located near to the top surface (within 0.15 μm).

(viii) The semiconductor with optimum band gap should be used (for maximum efficiency.

8. **(a) (ii)**

Maximum efficiency of a solar cell is

$$\eta_{max} = \frac{V_{max} I_{max}}{I_s \cdot A_c}$$

or

$$V_{max} = \frac{I_s \cdot A_c \cdot \eta_{max}}{I_{max}}$$

$$= \frac{0.8 \times 10^{-3} \times 1.5 \times 0.3}{7.5 \times 10^{-3}}$$

$$V_{max} = 0.048 \text{ V/cm}^2$$ **Ans.**

$$\text{Fill factor, } FF = \frac{I_{max} V_{max}}{V_{oc} \cdot I_{sc}} = \frac{7.5 \times 10^{-3} \times 0.048}{0.6 \times 15 \times 10^{-3}}$$

$$FF = 0.04$$ **Ans.**

8. **(b)**

Here, annual demand, D = 1500 units; inventory rate, C_h = 40% of C = 0.4 × C

Ordering cost, C_o = ₹400 per order

The cost per unit is shown in the table below:

Supplier	Quantity	Cost per unit
First	Any quantity	₹ 160
Second	160 and above	₹ 125
Third	250 and more	₹ 100

Total annual costs are calculated below the three suppliers:

$$\text{First supplier, } Q_1^* = \sqrt{\frac{2C_0 D}{C_h}} = \sqrt{\frac{2 \times 1500 \times 400}{160 \times 0.4}} = 136.93 \text{ units (Feasible)}$$

$$T.C_1 = D \cdot C + \sqrt{2C_0 \cdot D \cdot C_h}$$

$$= 1500 \times 160 + \sqrt{2 \times 1500 \times 400 \times 160 \times 0.4}$$

$$T.C_1 = ₹248763.56/-$$

$$\text{Second supplier, } Q_2^* = \sqrt{\frac{2 \times 1500 \times 400}{125 \times 0.4}} = 154.92 \text{ units (Not feasible)}$$

$$\text{Total annual cost at } Q_2 = 160 \text{ units}$$

$$\therefore \quad T.C_2 = D \cdot C + \frac{Q_2}{2} \times C_h + \frac{D}{Q_2} \times C_0$$

$$= 1500 \times 125 + \frac{160}{2} \times 125 \times 0.4 + \frac{1500}{160} \times 400$$

$$= ₹195250/-$$

$$\text{Third supplier, } Q_3^* = \sqrt{\frac{2 \times 1500 \times 400}{0.4 \times 100}} = 173.2 \text{ unit (Not Feasible)}$$

$$\text{Total annual cost at } Q_3 = 250 \text{ units}$$

$$\text{T.C}_3 = D \cdot C + \frac{Q_3}{2} \times C_h + \frac{D}{Q_3} \times C_0$$

$$\text{T.C}_3 = 1500 \times 100 + \frac{250}{2} \times 0.4 \times 100 + \frac{1500}{250} \times 400$$

$$\text{T.C}_3 = ₹157400/-$$

Thus, the order should be placed with the third supplier as it involves the lowest annual cost.

8. (c) (i)

Crevice

A local attack in a crevice between metal and metal surfaces or between metal and non-metal surfaces is known as ‘crevice’. One side of the crevice must be exposed to corrodent or the corrodent must be in the crevice. This type of corrosion generally occurs in poorly gasketed pipe flanges, under bolt heads and attachments immersed in liquids.

It is generally believed that the chemistry of corrodent changes in the stagnant area of crevice as shown in figure below. If the solution chemistry differs between the crevice and the bulk solution around the crevice, the area within the crevice becomes anodic. A decrease in pH has been measured in crevices in metals immersed in sea water.

Because of localized damage, crevice corrosion is very destructive. Good gasketing must be done to avoid crevice corrosion.

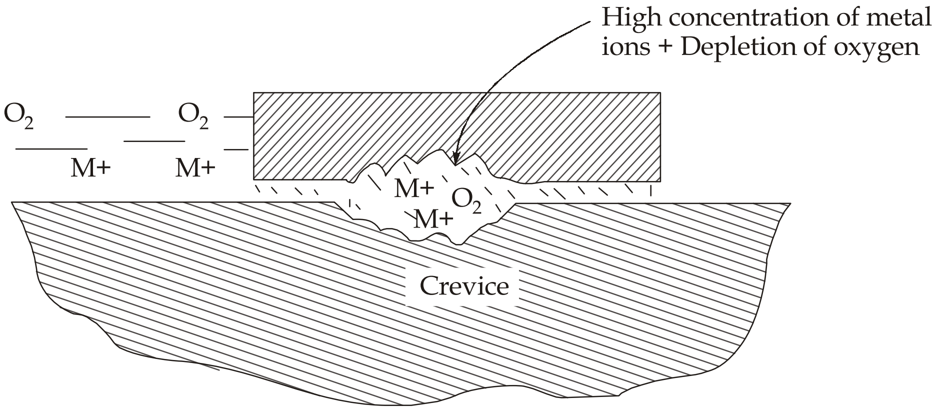


Figure : Crevice Corrosion

Factors affecting corrosion are as follows:

1. Redox Potential

Redox potential measured is a function of the metal and there is a definite relationship between the nature of material and its possible corrosion.

$$E_{\text{cell}} = E_{\text{redox}} = E_{\text{reduction}} - E_{\text{oxidation}}$$

2. Metallurgical Effects

Electrochemical corrosion requires one anode and one cathode. In pure metals, usually grain boundaries are anodic. In alloys and other materials, impurities such as chemical segregations, presence of multiphases, inclusions, degree of cold work and non-uniform stresses in components affect corrosion, as these impurities create anodic areas. For examples:

1. In a bolted assembly, plates are in compression, area under bolt is in compression, bolt are in tension, metals react differently to corrodent and cell corrosion can occur.
2. Shot peening is a cause of corrosion.

3. Passivity

Some metals form a passive film and this film imparts corrosion resistance by acting as a barrier in between the metal surface and the corrodent. If an environment is not attacking a particular metal, even though it is capable of attacking, it is known as passivity of the surface of the metal. Some metals have a tendency to form passive surface, for example, chromium, nickel, cobalt, iron and molybdenum.

For example, dilute solution of nitric acid causes rapid attack on steel while concentrated nitric acid causes a surface film to form, which imparts passivity. Passivity is the formation of a protective film.

Any operational conditions such as surface abrasion and impingement on a high-velocity solution contact will tend to break the film by a mechanical action, which can lead to corrosion.

4. Chemical Nature

Different materials react differently with different environments. Different types of environments are acids (oxidizing and reducing), bases, salts (acidic, alkaline or neutral), gases and solvents. Some materials like oxidizing, some like reducing and many like alkaline environments. Some gases are strength of acids or base (Table). pH stands for positive hydrogen ion.

Table pH Concentration of Different Environments

pH value	Environment
< 7	Acid
7	Neutral
7-12	Alkaline

Presence of halogen ions (e.g. chlorine and iodine) in a solution can lead to corrosion in solutions that would not normally cause corrosion.

Operating Conditions

Some essential operating conditions that must be considered while selecting a material are velocity, temperature, concentration, impurities and aeration. Some important observations are as follows:

(i) Increasing the temperature of most chemical reactions increases the rate of corrosion.

(ii) Increasing fluid velocity increases the rate of corrosion due to erosive effect.

(iii) Increasing the concentration of corrosive species (H^+ ions in acids) in some situation produces more rapid rate of corrosion.

(iv) If the impurity is abrasive particles, it may accelerate corrosion by the removal of passive film.

(v) If the impurity is a trace chemical such as water in an organic solvent, pitting may occur.

(vi) Metals that do not depend on passive surface films for corrosion resistance usually show increased corrosion rates in aerated solutions.

6. Polarization

If corrosion reactions are studied under controlled conditions and corrosion current and corrosion potential are noted, then change in potential with increasing or decreasing corrosion current flow is called polarization. Different types of polarization are:

(i) activation polarization, (ii) concentration polarization and (iii) IR potential drop.

(i) Activation Polarization

In a corrosion cell, this type of polarization can be seen at cathode where hydrogen is being reduced.

$$2H^+ + 2^-e \rightarrow H_2\uparrow$$

Hydrogen goes off as gas bubbles. Sometimes this reaction can be sluggish and thus polarization is said to occur.

The gas bubbles at cathode keep other hydrogen ions from reaching the surface and corrosion rate is decreased.

(ii) Concentration Polarization

This occurs when reacting species are not enough at an active electrode, i.e. enough hydrogen ions are not available at cathode, and hence corrosion potential will decrease.

(iii) IR Drop

IR drop simply means the drop of IR or potential drop in the electrochemical cell due to resistance in electrolyte. The flow of corrodent to the metal surface is impeded by the surface film and corrosion decreases.

8. **(c) (ii)**

Let a_1 and a_2 denote the lattice parameters of FCC and BCC structures, respectively.

For FCC structure,

$$4R = a_1\sqrt{2}$$

or

$$a_1 = 2.828R$$

$$a_1^3 = (2.828R)^3 = 22.617R^3$$

In FCC structure, there are four atoms per unit cell volume per atom,

$$\therefore \quad V_1 = \frac{22.617R^3}{4} = 5.654R^3$$

Similarly, for BCC structure

$$4R = a_2\sqrt{3}$$

$$\therefore \quad a_2 = 2.309\text{R}$$

$$\Rightarrow \quad a_2^3 = 12.31\text{R}^3$$

There are only two atoms per unit lattice of BCC structure,

$$V_2 = \frac{12.31R^3}{2} = 6.155R^3$$

∴ Percentage change in volume,

$$\Delta V = \left(\frac{V_2 - V_1}{V_1}\right) \times 100 = \left(\frac{6.155 - 5.656}{5.654R^3}\right) \times 100$$

$$= 8.86\%$$

Ans.

* * *