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Detailed Solutions

ESE-2023 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)

Given:

Brake power of the engine, BP = 23.2 kW

BP when 1st cylinder is cut-off, $BP_{234} = 16.6$ kW

BP when 2nd cylinder is cut-off, $BP_{134} = 16.3$ kW

BP when 3rd cylinder is cut-off, $BP_{124} = 16.9$ kW

BP when 4th cylinder is cut-off, $BP_{123} = 16.5$ kW

Number of cylinder, $k = 4$

Bore, $d = 70$ mm, Stroke, $l = 100$ mm, $N = 3000$ rpm

$$(\text{I.P.})_1 = (\text{B.P.})_{1234} - (\text{B.P.})_{234} = 23.2 - 16.6 = 6.6 \text{ kW}$$
$$(\text{I.P.})_2 = (\text{B.P.})_{1234} - (\text{B.P.})_{134} = 23.2 - 16.3 = 6.9 \text{ kW}$$
$$(\text{I.P.})_3 = (\text{B.P.})_{1234} - (\text{B.P.})_{124} = 23.2 - 16.9 = 6.3 \text{ kW}$$
$$(\text{I.P.})_4 = (\text{B.P.})_{1234} - (\text{B.P.})_{123} = 23.2 - 16.5 = 6.7 \text{ kW}$$

(i) Total indicated power, $(\text{I.P.}) = (\text{I.P.})_1 + (\text{I.P.})_2 + (\text{I.P.})_3 + (\text{I.P.})_4$

$= 6.6 + 6.9 + 6.3 + 6.7 = 26.5$ kW **Ans.**

(ii) Mechanical efficiency $(\eta_m) = \dfrac{\text{B.P.}}{\text{I.P.}} = \dfrac{23.2}{26.5} = 0.8754 = 87.54\%$ **Ans.**

(iii)Brake mean effective pressure:

$$P_{bm} = \frac{\text{B.P.}}{\frac{\pi}{4}\times d^2 \times l \times \frac{N}{60\times 2}\times k} = \frac{23.2\times 1000}{\frac{\pi}{4}\times (0.07)^2 \times 0.1 \times \frac{3000}{60\times 2}\times 4}$$

$= 602.84 \times 10^3$ Pa = 6.028 bar **Ans.**

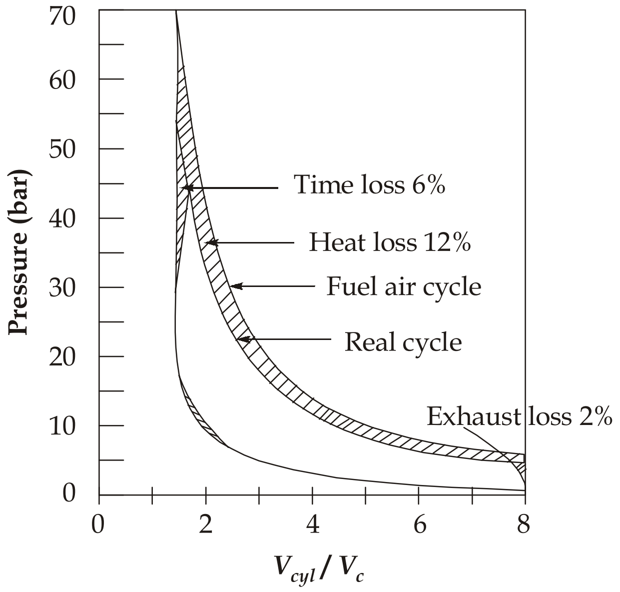
1. (b)

Time loss factor: It is the loss due to time required for mixing of fuel and air and also for combustion. In air-standard cycles, the heat addition is assumed to be an instantaneous process whereas in an actual cycle it is over a definite period of time. The time required for the combustion is such that under all circumstances some change in volume takes place while it is in progress. The crankshaft will usually turn about 30° to 40° from the initiation of the spark to the end of combustion. There will be a time loss during this period and is called time loss factor.

Heat loss factor: It is the loss of heat from gases to cylinder walls. During the combustion process and the subsequent expansion stroke the heat flows from the cylinder gases through the cylinder walls and cylinder head into the water jacket or cooling fins. Some heat enters the piston head and flows through the piston rings into the cylinder wall or is carried away by the engine lubricating oil which splashes on the underside of the piston.

Heat loss during combustion will naturally have the maximum effect on the cycle efficiency while heat loss just before the end of the expansion stroke can have very little effect because of its contribution to the useful work is very little. The heat loss factor contributes around 12%.

Exhaust blowdown factor: It is the loss of work on the expansion stroke due to early opening of the exhaust valve. The cylinder pressure at the end of exhaust stroke is about 7 bar depending on the compression ratio employed. If the exhaust valve is opened at the bottom dead centre, the piston has to do work against high cylinder pressures during the early part of the exhaust stroke. If the exhaust valve is opened too early, a part of the expansion stroke is lost. The best compromise is to open the exhaust valve 40° to 70° before BDC thereby reducing the engine pressure to halfway (3.5 bar) before the exhaust stroke begins.



Time loss, heat loss and exhaust loss in Petrol engines

1. (c)

The most effective after-treatment for reducing engine emissions is the catalytic converter found on most automobiles and other modern engines of medium or large size.

Catalytic converters are chambers mounted in the flow system through which the exhaust gases pass through. These chambers contain catalytic material, which promotes the oxidation of the emissions contained in the exhaust flow. Generally, they are called three-way converters because they are used to reduce the concentration of CO, HC and NO_x in the exhaust. It is usually a stainless steel container mounted somewhere along the exhaust pipe of the engine. Inside the container is a porous ceramic structure through which the exhaust gas flows. In most converters, the ceramic is a single honeycomb structure with many flow passages. Some converters use loose granular ceramic with the gas passing between the packed spheres. Volume of the ceramic structure of a converter is generally about half the displacement volume of the engine. This results in a volumetric flow rate of exhaust gas such that there are 5 to 30 changeovers of gas each second, through the converter. Catalytic converters for CI engines need larger flow passages because of the solid soot in the exhaust gases. The surface of the ceramic passage contains small embedded particles of catalytic material that promote the oxidation reactions in the exhaust gas as it passes. Aluminium oxide (alumina) is the base ceramic material used for most catalytic converters. Alumina can withstand the high temperatures, it remains chemically neutral, it has very low thermal expansion, and it does not thermally degrade with age. The catalyst materials mostly used are platinum, palladium and rhodium.

Palladium and platinum promote the oxidation of CO and HC with platinum especially active in the hydrocarbon reaction. Rhodium promotes the reaction of NO_x in one or more of the following reactions:

$$NO + CO \rightarrow \frac{1}{2} N_2 + CO_2$$

$$2NO + 5CO + 3H_2O \rightarrow 2NH_3 + 5CO_2$$

$$2NO + CO \rightarrow N_2O + CO_2$$

$$NO + H_2 \rightarrow \frac{1}{2} N_2 + H_2O$$

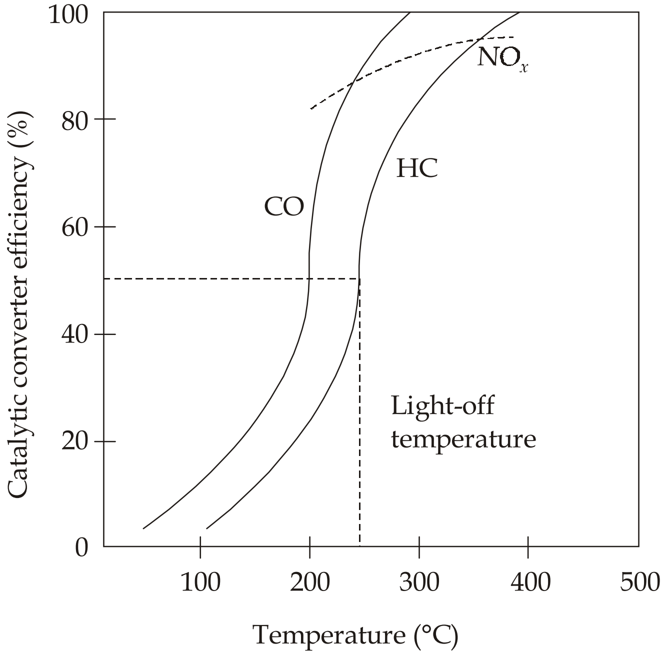
$$2NO + 5H_2 \rightarrow 2NH_3 + 2H_2O$$

$$2NO + H_2 \rightarrow N_2O + H_2O$$

Also often used in cerium oxide, which promotes the so-called water gas shift

$$CO + H_2O \rightarrow CO_2 + H_2$$

This reduces CO by using water vapor as an oxidant instead of O_2, which is very important when the engine is running rich.



Conversion efficiency of Catalytic Converters as a function of Converter temperature

1. (d)

Given: Number of cylinder, $k = 6$, Bore, $d = 80$ mm, Stroke, $l = 100$ mm, Compression ratio, $r = 7.5$, $\eta_{rel} = 52\% = 0.52$, $isfc = 320$ gm/kW-h = 0.32 kg/kW-h, $P_{in} = 8.2$ bar, $N = 2400$ rpm.

$$\text{Air standard efficiency, } \eta_{otto} = 1 - \frac{1}{r^{\gamma-1}} = 1 - \frac{1}{(7.5)^{0.4}} = 0.5533 = 55.33\%$$

$$\text{Relative efficiency, } \eta_{rel} = \frac{\text{Thermal efficiency}}{\text{Air standard efficiency}}$$

$$0.52 = \frac{\eta_{ith}}{\eta_{otto}}$$

$$\eta_{ith} = 0.52 \times 0.5533 = 0.2877 = 28.77\%$$

$$\eta_{ith} = \frac{I.P.}{\dot{m}_f \times CV}$$

$$0.2877 = \frac{1 \times 3600}{isfc \times CV} = \frac{3600}{0.32 \times CV}$$

$$CV = \frac{3600}{0.32 \times 0.2877} = 39103.23 \text{ kJ/kg}$$

$$\text{Indicated power, I.P.} = P_{in} \times \frac{\pi}{4} \times d^2 \times l \times \frac{N}{2 \times 60} \times k$$

$$= \frac{8.2 \times 10^5 \times \frac{\pi}{4} \times (0.08)^2 \times 0.1 \times \frac{2400}{2 \times 60} \times 6}{1000} = 49.46 \text{ kW}$$

Fuel consumption = isfc × I.P. = 0.32 × 49.46

= 15.827 kg/hr

1. (e)

(i)

The schematic of a gas turbine cycle or Brayton cycle incorporating an heat exchanger is shown in figure below.

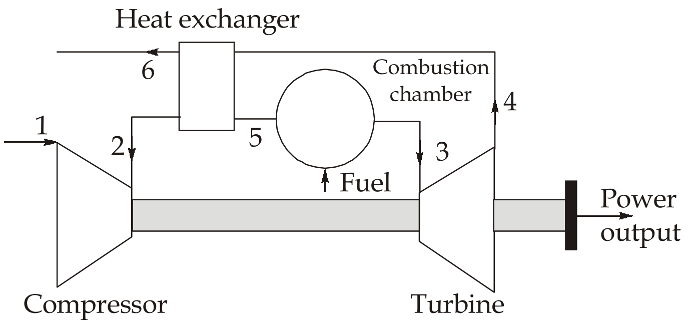
The heat exchanger helps in raising the temperature of air coming out of compressor with the help of exhaust gases.

Here, Process 1-2 : Isentropic compression in compressor

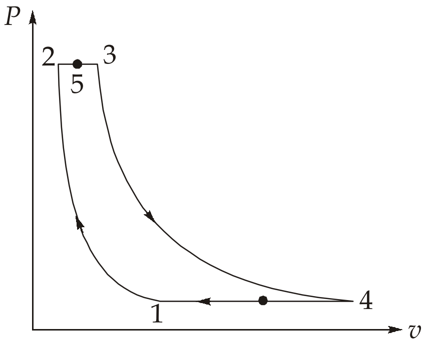
Process 2-3 : Isobaric heat addition in combustion chamber

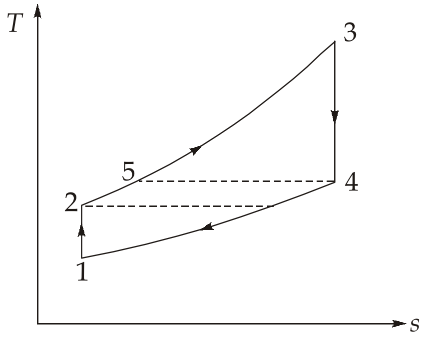
Process 3-4 : Isentropic expansion in turbine

Process 4-1 : Isobaric heat rejection

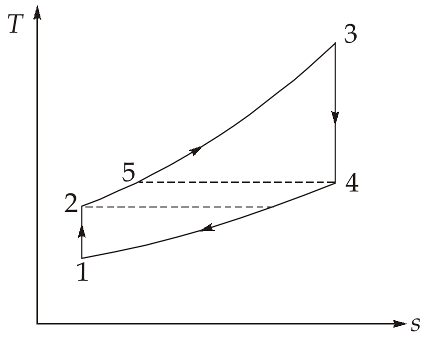


Schematic arrangement of gas turbine cycle with heat exchanger





(ii)



Compressor work (W_C),

$$W_{12} = (h_2 - h_1) = c_p\,(T_2 - T_1)$$

Heat Addition (Q),

$$Q_{53} = (h_3 - h_5) = c_p\,(T_3 - T_5)$$

Turbine work (W_T),

$$W_{34} = (h_3 - h_4) = c_p\,(T_3 - T_4)$$

So, Net work (W_N) $= W_T - W_C$

$$W_N = c_p\,(T_3 - T_4) - c_p\,(T_2 - T_1)$$

$$= c_p T_1\left[\left(\frac{T_3}{T_1} - \frac{T_4}{T_1}\right) - \left(\frac{T_2}{T_1} - 1\right)\right] \qquad \text{...(i)}$$

We know, Process 1-2 is isentropic compression,

$$\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}} = \left(r_p\right)^{\frac{\gamma-1}{\gamma}} = C \qquad \text{...(ii)}$$

Also, process 3-4 is isentropic expansion,

$$\frac{T_3}{T_4} = \left(\frac{P_3}{P_4}\right)^{\frac{\gamma-1}{\gamma}} = \left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}} = (r_p)^{\frac{\gamma-1}{\gamma}} = C \qquad \text{...(iii)}$$

From equation (ii) and (iii), we get

$$\frac{T_2}{T_1} = \frac{T_3}{T_4} \text{ or } \frac{T_4}{T_1} = \frac{T_3}{T_2}$$

From equation (i),

$$W_N = c_pT_1\left[\frac{T_3}{T_1}\left(1-\frac{T_4}{T_1}\times\frac{T_1}{T_3}\right)-(C-1)\right]$$

$$= c_pT_1\left[t\left(1-\frac{1}{C}\right)-(C-1)\right]$$

Also,

$$Q = c_p\,(T_3 - T_4) = c_p\,(T_3 - T_4) \qquad [\text{Since } T_5 = T_4]$$

$$= c_pT_1\left(\frac{T_3}{T_1}-\frac{T_4}{T_1}\right)$$

or,

$$Q = c_pT_1\left(t-\frac{T_3}{T_1}\times\frac{T_4}{T_3}\right) = c_pT_1\left(t-\frac{t}{C}\right)$$

Then,

$$\text{Efficiency } (\eta) = \frac{W_N}{Q} = \frac{c_pT_1\left[t\left(1-\frac{1}{C}\right)-(C-1)\right]}{c_pT_1\left(t-\frac{t}{C}\right)}$$

$$\eta = 1-\frac{(C-1)}{\left(t-\frac{t}{C}\right)} = 1-\frac{C}{t}$$

Proved.

2. (a)

Given : Compression ratio, $r_c = 8$; Brake power, $BP = 50$ kW; $N = 3600$ rpm; $\frac{A}{F} = 14:1$

$CV = 44$ MJ/kg; $\eta_v = 0.85$; $\eta_{\text{bth}} = 0.35$; $\frac{L}{d} = 1.2$; $\rho_a = 1.23$ kg/m^3

(i)

$$\eta_{\text{bth}} = \frac{BP}{\dot{m}_f \times CV}$$

$$\Rightarrow \quad 0.35 = \frac{50}{\dot{m}_f \times 44000}$$

$$\Rightarrow \quad \dot{m}_f = 3.246 \times 10^{-3} \text{ kg/s}$$

$$\because \quad \frac{\dot{m}_a}{\dot{m}_f} = \frac{14}{1}$$

$$\Rightarrow \qquad \dot{m}_a = 14 \times 3.246 \times 10^{-3} = 0.04545 \text{ kg/s}$$

Let, the ideal mass of air per cylinder per cycle be m_1,

$$\eta_v = \frac{\dot{m}_a}{m_1 \times \frac{N}{2 \times 60} \times k}$$

$$\Rightarrow \qquad m_1 = \frac{0.04545}{0.85 \times \frac{3600}{120} \times 4} = 4.4558 \times 10^{-4} \text{kg}$$

$$\text{Swept volume per cylinder, } V_s = \frac{m_1}{\rho_a} = \frac{4.4558 \times 10^{-4}}{1.23}$$

$$= 3.6226 \times 10^{-4} \text{ m}^3$$

$$\text{So, engine capacity} = 4 \times 3.6226 \times 10^{-4} \times (100)^3$$

$$= 1449.04 \text{ cm}^3$$ Ans.

(ii) Since,

$$V_s = 3.6226 \times 10^{-4} \text{ m}^3$$

$$\Rightarrow \qquad \frac{\pi}{4} \times d^2 \times L = 3.6226 \times 10^{-4} \times (100)^3 \text{ cm}^3$$

$$\Rightarrow \qquad \frac{\pi}{4} \times d^2 \times 1.2d = 362.26$$

$$\Rightarrow \qquad d = 7.27 \text{ cm}$$ Ans.

and $$L = 1.2 \times d = 1.2 \times 7.27 = 8.725 \text{ cm}$$ Ans.

$$\text{(iii) Average piston speed, } \bar{V}_P = \frac{2LN}{60} = \frac{2 \times 8.725 \times 10^{-2} \times 3600}{60}$$

$$= 10.47 \text{ m/s}$$ Ans.

(iv) Clearance volume per cylinder,

$$r_C = \frac{V_C + V_S}{V_C}$$

$$\Rightarrow \qquad r_C = 1 + \frac{V_S}{V_C}$$

$$\Rightarrow \qquad V_C = \frac{V_S}{r_C - 1} = \frac{3.6226 \times 10^{-4} \times (100)^3}{8 - 1}$$

$$= 51.75 \text{ cm}^3$$ Ans.

2. (b)

(i)

Equivalence ratio (ϕ) is defined as the ratio of the actual fuel/air ratio $(F/A)_a$ to the stoichiometric fuel/air ratio $(F/A)_s$. It may also be defined as stoichiometric air/fuel ratio $(A/F)_s$ to actual air/fuel ratio $(A/F)_a$. Thus,

$$\phi = \frac{(F/A)_a}{(F/A)_s} = \frac{(A/F)_s}{(A/F)_a}$$

If the equivalence ratio (ϕ) is greater than unity, the mixture is said to be rich and if ϕ is less than unity the mixture is said to be weak or lean. The spark-ignition engines may normally run with both rich and weak mixtures but the compression-ignition engines normally run with weak mixtures only. The inverse of equivalence ratio ϕ is called the relative air/fuel ratio (λ). Therefore,

$$\lambda = \frac{1}{\phi} = \frac{(A/F)_a}{(A/F)_s}$$

For lean mixtures, $\phi < 1, \lambda > 1$

For stoichiometric mixtures, $\phi = \lambda = 1$

For rich mixtures, $\phi > 1, \lambda < 1$

(ii)

(a) The combustion equation of an unknown hydrocarbon fuel can be written as

$$C_mH_n + xO_2 + yN_2 \rightarrow 14CO_2 + 0.6CO + 5O_2 + 80.4N_2 + zH_2O$$

On balancing the elements on both sides of equation,

C balance : $m = 14 + 0.6 = 14.6$

N_2 balance : $y = 80.4$;

Also, we know $$\frac{y}{x} = \frac{79}{21}$$

⇒ $$x = \frac{80.4 \times 21}{79} = 21.372$$

O_2 balance : $$21.372 = 14 + \frac{0.6}{2} + 5 + \frac{z}{2}$$

⇒ $$z = 4.144$$

$$\text{H}_2 \text{ balance : } \frac{n}{2} = z = 4.144$$

$$\Rightarrow \qquad n = 8.288$$

The combustion equation becomes:

$$C_{14.6}H_{8.288} + 21.372O_2 + 80.4N_2 \rightarrow 14CO_2 + 0.6CO + 5O_2 + 80.4N_2 + 4.144H_2O$$

$$\text{Air/fuel ratio} = \frac{21.372\times 32 + 80.4\times 28}{14.6\times 12 + 8.288\times 1}$$

$$= 15.996 \simeq 16$$ Ans.

(b) The stoichiometric combustion equation is

$$C_{14.6}H_{8.288} + 16.672O_2 + 16.672\times\frac{79}{21}N_2 \rightarrow 14.6CO_2 + 4.144H_2O + 16.672\times\frac{79}{21}N_2$$

$$\text{Air/fuel ratio (stoichiometric)} = \frac{16.672\times 32 + 16.672\times\frac{79}{21}\times 28}{14.6\times 12 + 8.288\times 1} = 12.478 \simeq 12.5$$

$$\therefore \quad \text{Percentage theoretical air} = \frac{16}{12.5}\times 100 = 128\%$$ Ans.

(c) Fuel composition:

$$C = \frac{14.6\times 12}{[14.6\times 12 + 8.288\times 1]}\times 100 = 95.48\%$$ Ans.

$$H = \frac{8.288\times 1}{14.6\times 12 + 8.288\times 1}\times 100 = 4.51\%$$ Ans.

2. (c)

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

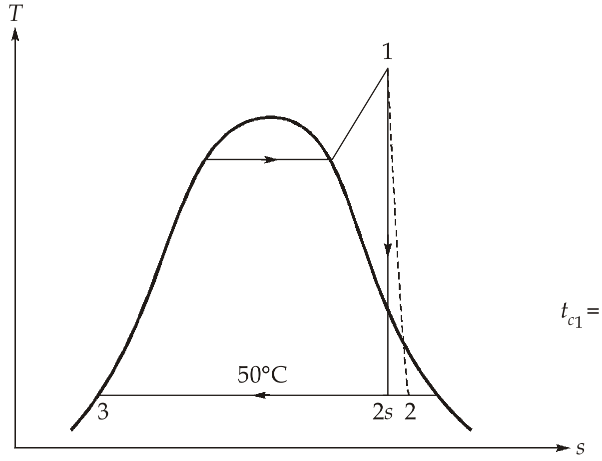
Pressure inside the condensor (P) = 0.0129 MPa = 0.129 bar

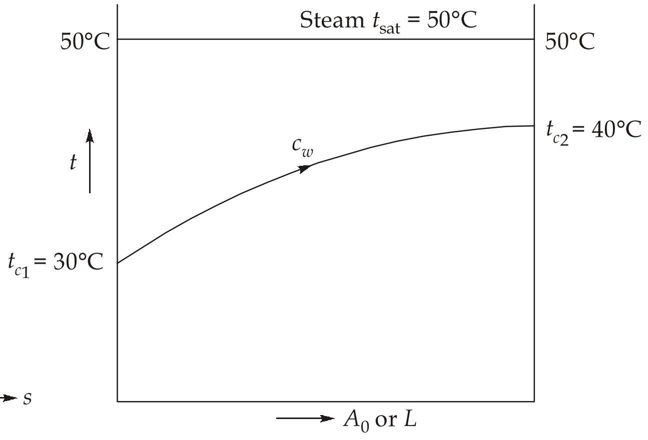
Velocity of circulating water (V) = 2 m/s

Outer tube diameter (D) = 26 mm

Inner tube diameter (d) = 23 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:

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

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

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,

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

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

$$v_2 = 10.223101 \text{ m}^3\text{/kg}$$

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

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

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

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

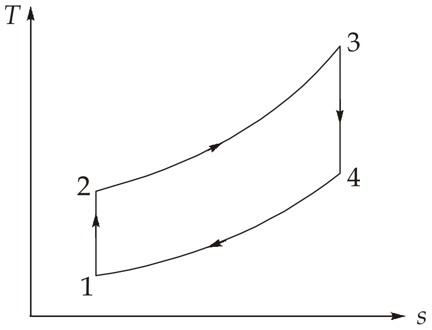
Again, $$A_0 = n\pi D l = 3898.2252$$ [where, l is the length of tube]

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

(iv) The number of tubes is 4850.

3. **(a)**

(i) Basic cycle



Given: $T_1 = 350$ K, $\frac{P_2}{P_1} = r_p = 9$, $T_3 = 1200$ K

Process 1-2:

$$\frac{T_2}{T_1} = (r_p)^{\frac{\gamma-1}{\gamma}}$$

$$T_2 = T_1 \times (9)^{0.2857} = 350 \times (9)^{0.2857} = 655.684 \text{ K}$$

Also, $$T_4 = \frac{T_3}{(9)^{0.2857}} = \frac{1200}{(9)^{0.2857}} = 640.551 \text{ K}$$

$$\text{Specific/Net work output} = c_p\,[(T_3 - T_4) - (T_2 - T_1)]$$

$$W_N = 1.005\,[(1200 - 640.551) - (655.684 - 350)]$$

$$= 255.03316 \text{ kJ/kg}$$

$$\text{Heat input} = c_p\,(T_3 - T_2) = 1.005\,(1200 - 655.684)$$

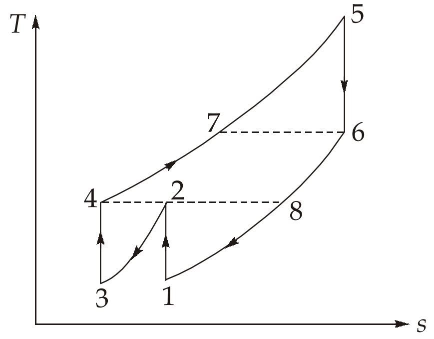
$$= 547.0375 \text{ kJ/kg}$$

$$\text{Thermal efficiency, } (\eta_{th}) = \frac{\text{Net work output}}{\text{Heat input}} = \frac{255.03316}{547.0375}$$

$$= 0.4662 \text{ or } 46.62\%$$

(ii) Basic cycle with heat exchanger and two-stage intercooled compressor

Given: $T_1 = 350$ K, $T_5 = 1200$ K



For perfect intercooling and perfect regeneration

$$T_1 = T_3; \qquad T_2 = T_4 = T_8 \text{ and } T_6 = T_7$$

$$\text{Pressure ratio for each stage} = (\text{Overall pressure ratio})^{\left[\frac{1}{\text{Number of stage}}\right]}$$

$$\frac{P_2}{P_1} = \frac{P_4}{P_3} = (9)^{1/2} = 3$$

For process 1-2: $$\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}} = (3)^{0.2857}$$

$$T_2 = 350 \times (3)^{0.2857} = 479.0508 \text{ K} = T_4 = T_8$$

For process 5-6: $$T_6 = \frac{T_5}{(9)^{0.2857}} = \frac{1200}{9^{0.2857}} = 640.551 \text{ K} = T_7$$

$$\text{Compressor work, } W_C = 2 \times c_p \times (T_2 - T_1)$$

[as it is the case of perfect intercooling]

$$= 2 \times 1.005 \times (479.0508 - 350)$$

$$= 259.39214 \text{ kJ/kg}$$

$$\text{Turbine work, } W_T = c_p \times (T_5 - T_6)$$
$$= 1.005 \times (1200 - 640.551)$$
$$= 562.2462 \text{ kJ/kg}$$

$$\text{Specific work output, } W_N' = W_T - W_C$$
$$W_N' = 562.2462 - 259.39214 = 302.854 \text{ kJ/kg}$$

$$\text{Heat input} = c_p \times (T_5 - T_7)$$
$$= 1.005 \times (1200 - 640.551) \qquad (\because \quad T_7 = T_6)$$
$$= 562.2462 \text{ kJ/kg}$$

$$\text{Thermal efficiency, } (\eta'_{th}) = \frac{\text{Net work output}}{\text{Heat input}} = \frac{302.854}{562.2462}$$
$$= 0.53865 \text{ or } 53.865\%$$

Thus, percentage change in specific work output

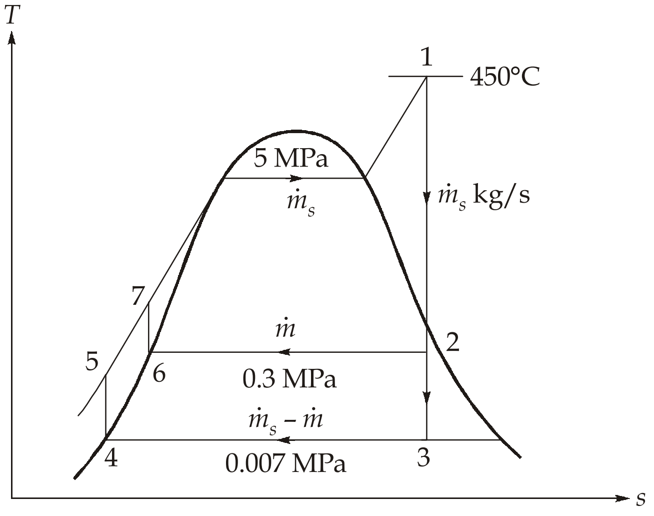
$$= \frac{W'_N - W_N}{W_N} \times 100 = \frac{302.854 - 255.03316}{255.03316} \times 100$$
$$= 18.75\%$$ **Ans.**

Percentage change in thermal efficiency,

$$= \frac{\eta'_{th} - \eta_{th}}{\eta_{th}} \times 100 = \frac{0.53865 - 0.4662}{0.4662} \times 100$$
$$= 15.54\%$$ **Ans.**

3. (b)

Given : Power load = 6.5 MW; Heating load = 1.265 MW



From steam table:

At 5 MPa and 450°C (superheated)

$$s_1 = 6.8210 \text{ kJ/kg-K};\ h_1 = 3317.2 \text{ kJ/kg}$$

At 0.3 MPa (saturated)

$$s_{2f} = 1.6717 \text{ kJ/kg-K};\ s_{2g} = 6.9916 \text{ kJ/kg-K}$$

$$h_{2f} = 561.43 \text{ kJ/kg} = h_6;\ h_{2g} = 2724.9 \text{ kJ/kg}$$

At 0.007 MPa (saturated)

$$s_{3f} = 0.55903 \text{ kJ/kg-K};\ s_{3g} = 8.2745 \text{ kJ/kg-K}$$

$$h_{3f} = 163.35 \text{ kJ/kg} = h_4;\ h_{3g} = 2571.7 \text{ kJ/kg}$$

As, $s_1 = s_2 = 6.821 = s_{2f} + x_2(s_{2g} - s_{2f})$

or, $6.821 = 1.6717 + x_2(6.9916 - 1.6717)$

or, $x_2 = 0.967931$

then, $h_2 = h_{2f} + x_2(h_{2g} - h_{2f})$

$h_2 = 561.43 + 0.967931(2724.9 - 561.43)$

or, $h_2 = 2655.5196 \text{ kJ/kg}$

Similarly, $s_1 = s_3 = 6.821 = s_{3f} + x_3(s_{3g} - s_{3f})$

or, $6.821 = 0.55903 + x_3(8.2745 - 0.55903)$

or, $x_3 = 0.811612$

then, $h_3 = h_{3f} + x_3(h_{3g} - h_{3f})$

$= 163.35 + 0.811612(2571.7 - 163.35)$

$= 2117.9963 \text{ kJ/kg}$

If $\dot{m}$ is the rate of steam extraction for process heating

$$\dot{m}(h_2 - h_6) = 1.265 \times 10^3$$

or, $$\dot{m} = \frac{1265}{(2655.5196 - 561.43)} = 0.60408 \text{ kg/s}$$

(i) From steam table:

At 0.007 MPa,

$$v_f = 0.00100750 \text{ m}^3/\text{kg} = v_4$$

At 0.3 MPa

$$v_f = 0.00107317 \text{ m}^3/\text{kg} = v_6$$

So, $h_5 = h_4 + v_4(5 - 0.007) \times 10^3$

$$h_5 = 163.35 + 0.00100750 \times 10^3(5 - 0.007)$$

or, $$h_5 = 163.35 + 5.0304475 = 168.3804 \text{ kJ/kg}$$

Similarly, $$h_7 = h_6 + v_6(5 - 0.3) \times 10^3$$

$$= 561.43 + 0.00107317 \times 10^3 \times 4.7$$

or, $$h_7 = 561.43 + 5.043899 = 566.4738 \text{ kJ/kg}$$

So, Total work output = $\dot{m}_s(h_1 - h_2) + (\dot{m}_s - \dot{m})(h_2 - h_3) - \left[(\dot{m}_s - \dot{m})(h_5 - h_4) + \dot{m}_s(h_7 - h_6)\right]$

$$6.5 \times 10^3 = \dot{m}_s \times 661.6804 + (\dot{m}_s - \dot{m}) \times 537.5233 - (\dot{m}_s - \dot{m}) \times 5.03044 - \dot{m}_s \times 5.043899$$

or, $$6.5 \times 10^3 = \dot{m}_s \times 656.6365 + (\dot{m}_s - \dot{m}) \times 532.49286$$

or, $$\dot{m}_s = \frac{6500 + 532.49286 \times 0.60408}{1189.12936}$$

or, $$\dot{m}_s = 5.736691 \text{ kg/s}$$

$$\dot{m}_s = 20652.08938 \text{ kg/hr} = 20.652 \text{ t/h}$$ Ans.

(ii) Heat input to the boiler (Q_1)= $(\dot{m}_s - \dot{m})(h_1 - h_5) + \dot{m}(h_1 - h_7)$

$$= (5.736691 - 0.60408)(3317.2 - 168.3804) + 0.60408(3317.2 - 566.4738)$$

or, $$Q_1 = 17823.3248 \text{ kJ/s} = 17.8233 \text{ MW}$$ Ans.

(iii) Boiler efficiency, $\eta_b = 0.85$ (given)

or, $$0.85 = \frac{Q_1}{\dot{m}_f \times C.V.}$$

or, $$\dot{m}_f = \frac{17.8233}{0.85 \times 30} = 0.69895 \text{ kg/s}$$

or, $$\dot{m}_f = 2516.2305 \text{ kg/hr} = 2.5162 \text{ tonne/hr}$$ Ans.

(iv)

The heat rejected in condensor (Q_2) = $(\dot{m}_s - \dot{m})(h_3 - h_4)$

$$Q_2 = (5.736691 - 0.60408)(2117.9963 - 163.35)$$

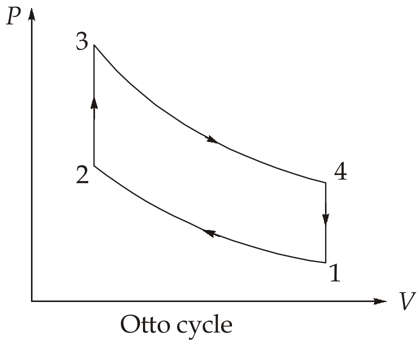
or, $$Q_2 = 10.0324 \text{ MW}$$ Ans.

3. (c)

Given: $V_s = 350$ cm^3/cylinder, $k = 4$, Power output = 45 kW, $N = 3200$ rpm, $r = 9$, $P_1 = 1$ bar, $T_1 = 30°\text{C} = 303$ K

First consider spark-ignition engine:

Air-standard efficiency, $$\eta_{otto} = 1-\frac{1}{(r)^{\gamma-1}} = 1-\frac{1}{(9)^{1.4-1}} = 0.5847 = 58.47\%$$ Ans.



Otto cycle

Also, $$\eta_{otto} = \frac{\text{Power output}}{\text{Heat supplied}}$$

$$0.5847 = \frac{45}{\text{Heat supplied}}$$

$$\text{Heat supplied} = \frac{45}{0.5847} = 76.96\ \text{kW}$$ Ans.

Mean effective pressure, $$P_m = \frac{W}{V_s} = \frac{\frac{45}{4}\times 1000}{350\times 10^{-6}\times\frac{3200}{2\times 60}}$$

$$= 1.205 \times 10^6\ \text{Pa} = 1.205\ \text{MPa} = 12.05\ \text{bar}$$ Ans.

For process 1-2,

$$\frac{T_2}{T_1} = (r)^{\gamma-1}$$

$$\Rightarrow \quad T_2 = 303 \times (9)^{0.4} = 729.69\ \text{K}$$

Heat supplied per cylinder per cycle,

$$(\delta Q)_{23} = \frac{76.96}{4\times\frac{3200}{2\times 60}} = 0.7215\ \text{kJ}$$

Using ideal gas equation,

$$P_1 v_1 = RT_1$$

$$\Rightarrow \quad v_1 = \frac{0.287\times 303}{100} = 0.8696\ \text{m}^3/\text{kg}$$

The initial volume of air in the cylinder,

$$V_1 = V_2 + V_s = \frac{V_1}{9}+V_s$$

$$\Rightarrow \quad \frac{8}{9}V_1 = V_s$$

$$\Rightarrow \quad V_1 = \frac{350\times 10^{-6}\times 9}{8} = 3.9375\times 10^{-4}\ \text{m}^3$$

$$\Rightarrow \quad \text{Mass, } m = \frac{V_1}{v_1} = \frac{3.9375\times 10^{-4}}{0.8696} = 4.5279\times 10^{-4}\ \text{kg}$$

Maximum temperature of the cycle:

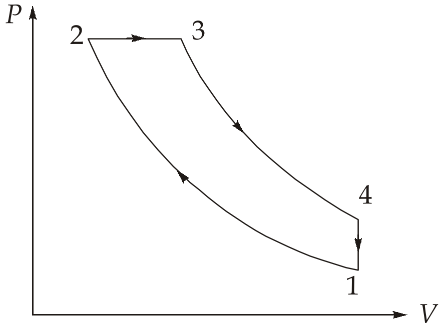
$$(\delta Q)_{23} = mC_V\,(T_3 - T_2)$$

$$0.7215 = 4.5279 \times 10^{-4} \times 0.717\,(T_3 - 729.69)$$

$\Rightarrow$ $$T_3 = 2952.08\text{ K} = 2679.08°\text{C}$$ **Ans.**

Now, consider compression-ignition:

T_2 will be the same as in the previous case i.e.; $T_2 = 729.69$ K



Diesel cycle

Heat supplied per cycle per cylinder is also same, so

$$(\delta Q)_{23} = 0.7215\text{ kJ}$$

$$= mC_P\,(T_3 - T_2)$$

$\Rightarrow$ $$T_3 - T_2 = \frac{0.7215}{4.5279 \times 10^{-4} \times 1.004}$$ [$\because$ Mass is also same]

$\Rightarrow$ $$T_3 = 2316.795\text{ K}$$ **Ans.**

$$\text{Cut-off ratio, } \rho = \frac{V_3}{V_2} = \frac{T_3}{T_2} = \frac{2316.795}{729.69} = 3.175$$

$$\text{Air-standard efficiency, } \eta_{\text{diesel}} = 1 - \frac{1}{(r)^{\gamma-1}} \times \left[\frac{\rho^{\gamma} - 1}{\gamma(\rho - 1)}\right] = 1 - \frac{1}{(9)^{0.4}} \times \left[\frac{(3.175)^{1.4} - 1}{1.4(3.175 - 1)}\right]$$

$$= 0.44905 = 44.905\%$$ **Ans.**

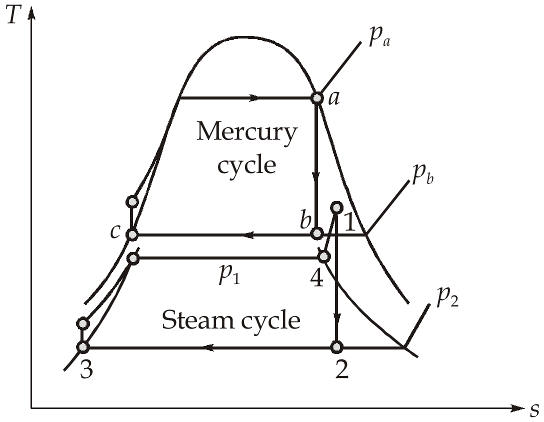
$$\text{Power output} = \eta_{\text{diesel}} \times \text{Total rate of heat added}$$

$$= 0.44905 \times 76.96 = 34.56\text{ kW}$$ **Ans.**

$$\text{Mean effective pressure, } P_m = \frac{\frac{34.56}{4} \times 1000}{350 \times 10^{-6} \times \frac{3200}{2 \times 60}} = 925.689 \times 10^3\text{ Pa}$$

$$= 9.25\text{ bar}$$ **Ans.**

4. (a)



Given:

Mercury cycle condensor pressure (P_a) = 10 bar

Mercury cycle evaporator pressure (P_b) = 0.1 bar

Steam cycle condensor pressure (P_1) = 35 bar

Steam cycle evaporator pressure (P_2) = 0.06 bar

Mercury cycle:

$$s_a = s_b = 0.5158 = s_{fm} + x(s_g - s_{fm})$$

From mercury table, putting the value of s_f and s_g at 0.1 bar

$$0.5158 = 0.089 + x(0.6604 - 0.089)$$

or, $x = 0.746937$

$$\text{Enthalpy at } b = h_{fm} + x(h_g - h_{fm})$$

$$h_b = 34.485 + 0.746937\,(332.975 - 34.485)$$

$$= 257.4382 \text{ kJ/kg of mercury}$$

From mercury table, $h_a = 362.406$ kJ/kg of mercury

Isentropic work done by mercury turbine

$$h_a - h_b = 362.406 - 257.4382$$

$$= 104.9677 \text{ kJ/kg of mercury}$$

Heat rejected by mercury in mercury condensor = $(h_b - h_c)$

$$= 257.4382 - 34.485 = 222.9532 \text{ kJ/kg of mercury}$$

Heat supplied in mercury boiler = $h_a - h_c$ = 362.406 – 34.485

$$= 327.921 \text{ kJ/kg of mercury}$$

For steam cycle:

From steam table:

At 35 bar and 320°C, $h_1 = 3030.5$ kJ/kg of steam

$s_1 = 6.5377$ kJ/K-kg of steam

At 0.06 bar, $h_f = h_3 = 151.48$ kJ/kg of steam

$h_g = 2566.6$ kJ/kg of steam

$s_f = 0.52082$ kJ/kg-K of steam

$s_g = 8.3290$ kJ/kg-K of steam

At 3.5 bar, $h_4 = 2802.6$ kJ/kg of steam

As, $s_1 = s_2 = 6.5377 = s_f + x'(s_g - s_f)$

or, $6.5377 = 0.52082 + x'(8.329 - 0.52082)$

or, $x' = 0.770586$

$$h_2 = h_f + x'(h_g - h_f)$$

$$= 151.48 + 0.770586\,(2566.6 - 151.48)$$

or, $h_2 = 2012.5394$ kJ/kg of steam

Isentropic work done by steam turbine $= h_1 - h_2$

$= 3030.5 - 2012.5394$

$= 1017.9605$ kJ/kg of steam

Heat to be supplied in steam boiler i.e. super heater

$= h_1 - h_4 = 3030.5 - 2802.6$

$= 227.9$ kJ/kg of steam

Heat rejected by mercury/kg of steam

= Heat received by water/kg of steam

$$m_m\,(h_b - h_c) = (h_4 - h_3) \times 1$$

or, $$m_m = \frac{2802.6 - 151.48}{257.4382 - 34.485} = 11.8909 \text{ kg of mercury/kg of steam}$$

Total work done in the cycle per kg of steam

= Work done in the steam turbine/kg of steam + Work done in mercury turbine/kg of steam

$= 1017.9605 + 104.9677 \times 11.8909$

$= 2266.1236$ kJ/kg of steam

Heat supplied in the cycle = Heat supplied in mercury boiler/kg of steam + Heat supplied in superheater/kg of steam

$= (h_a - h_c) \times m_m + (h_1 - h_4)$

$= 327.921 \times 11.8909 + (227.9) = 4127.1758$ kJ/kg of steam

Thus, the efficiency of combined cycle (η),

$$\eta = \frac{2266.1236}{4127.1758} = 0.54907 = 54.907\%$$ **Ans.**

4. (b)

Given: Number of cylinders, $k = 6$, $d = 190$ mm $= 0.19$ m, $L = 200$ mm $= 0.2$ m

$$\text{Heat supplied by the fuel} = \dot{m}_f \times CV = \frac{72}{3600} \times 44000 = 880 \text{ kW}$$

$$\text{Indicated power, I.P.} = P_{in} \times \frac{\pi}{4} \times d^2 \times L \times \frac{N}{2 \times 60} \times k$$

$$= \frac{8.2 \times 10^5 \times \frac{\pi}{4} \times (0.19)^2 \times 0.2 \times \frac{1520}{2 \times 60} \times 6}{1000} = 353.39 \text{ kW}$$

Brake power = 280 kW (Given)

- Mechanical efficiency, $\eta_m = \frac{\text{BP}}{\text{IP}} = \frac{280}{353.39} = 0.7923 = 79.23\%$ **Ans.**

$$\text{Heat carried away by cooling water} = \dot{m}_W \times (c_p)_W \times (\Delta T)_W = \frac{80}{60} \times 4.187 \times 44$$

$= 245.637$ kW

$$\text{Heat carried away by cooling oil} = \dot{m}_O \times (c_p)_O \times (\Delta T)_O = \frac{50}{60} \times 2.1 \times 25$$

$= 43.75$ kW

$$\text{Mass flow rate of the exhaust gas} = \dot{m}_f + \dot{m}_a = \frac{72}{60} + 30 = 31.2 \text{ kg/min}$$

∵ 1 kg of H_2 produces 9 kg of H_2O $[\because\ 2H_2 + O_2 \rightleftharpoons 2H_2O]$

∴ Mass of the vapour with exhaust gas = 9 × %H_2 × Mass of fuel/min

$$= 9 \times 0.1 \times \frac{72}{60} = 1.08 \text{ kg/min}$$

$$= \frac{1.08}{60} = 0.018 \text{ kg/s}$$

So, Mass of dry exhaust gas $= \dfrac{31.2 - 1.08}{60} = 0.502$ kg/s

It is given that enthalpy of steam at the exhaust conditions is 3070 kJ/kg.

So,Heat carried away by steam $= 0.018 \times (3070 - 4.187 \times 30) = 53$ kW

Heat carried away by dry exhaust gas

$$= 0.502 \times 1.045 \times (420 - 30) = 204.59 \text{ kW}$$

Hence, the heat balance sheet is as follows:

Heat Input	**KW**	**Heat expenditure**	**KW**	**%**
Heat supplied by fuel	880	1. Equivalent to BP	280	31.81
		2. Heat carried away by cooling water	245.637	27.91
		3. Heat carried away be cooling oil	43.75	4.97
		4. Heat carried away be steam	53	6.023
		5. Heat carried away by dry exhaust gas	204.59	23.248
		6. Unaccounted heat transfer	53.024	6.025
		Total	**880**	**100**

4. (c)

Given: Bore diameter, $d = 8.5$ cm, Stroke, $L = 12$ cm, Compression ratio, $r_c = 10$, A/F ratio = 16:1

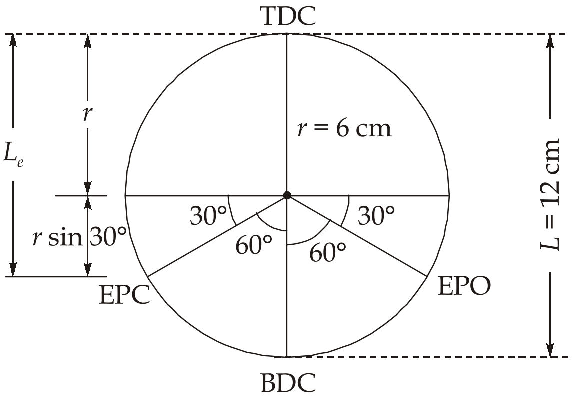
Temperature of the mixture at inlet, $T_1 = 320$ K

Pressure at the time of closing the exhaust port,

$$P_e = 1.07 \text{ bar},$$

$$\dot{m}_a = 160 \text{ kg/h},\ N = 4200 \text{ rpm},\ R = 290 \text{ J/kgK}$$

Considering effective stroke, L_e:



$$r = \frac{L}{2} = \frac{12}{2} = 6 \text{ cm}$$

Effective stroke, $L_e = r + r\sin30° = 6 + 6\sin30° = 9\text{ cm} = 0.09\text{ m}$

Swept volume corresponding to L_e:

$$V_{se} = \frac{\pi}{4}\times d^2\times L_e = \frac{\pi}{4}\times(0.085)^2\times 0.09$$

$$= 5.107\times10^{-4}\text{ m}^3$$

Total cylinder volume corresponding to L_e:

$$V = \frac{r_c}{(r_c-1)}V_{se} = \frac{10}{(10-1)}\times5.107\times10^{-4}$$

$$= 5.6745\times10^{-4}\text{ m}^3$$

Density of the fresh mixture, $\rho = \dfrac{P_e}{RT_1} = \dfrac{1.07\times10^5}{290\times320} = 1.153\text{ kg/m}^3$

Mass of the fresh mixture per cycle,

$$m = 5.6745\times10^{-4}\times1.153 = 6.5428\times10^{-4}\text{ kg/cycle}$$

∴ Ideal mass flow rate, $\dot{m}_{\text{ideal}} = m\times N = 6.5428\times10^{-4}\times4200$

$$= 2.7479\text{ kg/min} = 164.875\text{ kg/h}$$

(i) Scavenging ratio, $R_{sc} = \dfrac{\dot{m}_{\text{supplied}}}{\dot{m}_{\text{ideal}}}$

where, $\dot{m}_{\text{supplied}}$ = Mass flow rate of the fresh charge supplied to the engine

$\dot{m}_{\text{ideal}}$ = Mass flow rate of the fresh charge supplied during the ideal scavenging process which would just fill the cylinder at BDC at inlet temperature and exhaust pressure.

A/F = 16 : 1

∴ $\dfrac{\dot{m}_f}{\dot{m}_a} = \dfrac{1}{16}$

⇒ $\dot{m}_f = \dfrac{160}{16} = 10\text{ kg/h}$

∴ $\dot{m}_{\text{supplied}} = \dot{m}_a + \dot{m}_f = 160 + 10 = 170\text{ kg/h}$

∴ $R_{sc} = \dfrac{170}{164.875} = 1.031$ **Ans.**

(ii) Scavenging efficiency, $\eta_{sc} = 1 - e^{-R_{sc}} = 1 - e^{-1.031} = 0.6433\text{ or }64.33\%$ **Ans.**

(iii) Trapping efficiency, $\eta_{tr} = \dfrac{\eta_{sc}}{R_{sc}} = \dfrac{64.33}{1.031} = 62.39\%$ **Ans.**

Section : B

5. (a)

Given : Initial diameter of specimen, d_0 = 13.2 mm; Final diameter of specimen, d_f = 11.1 mm; Engineering fracture strength, σ_f = 480 MPa

Original cross-sectional area,

$$A_0 = \frac{\pi}{4} \times (13.2)^2 = 136.847 \text{ mm}^2$$

Area of cross-section at fracture,

$$A_f = \frac{\pi}{4} \times (11.1)^2 = 96.7689 \text{ mm}^2$$

(i)

$$\text{Percentage reduction in area} = \frac{A_o - A_f}{A_o} = \frac{136.847 - 96.7689}{136.847} = 0.2928 = 29.28\%$$

(ii) True fracture stress,

$$\sigma_{Tf} = \frac{\sigma_f A_o}{A_f} = \frac{480 \times 136.847}{96.7689}$$

$$= 678.798 \text{ MPa}$$

(iii) True fracture strain,

$$\varepsilon_{Tf} = 2\ln\left(\frac{d_o}{d_f}\right) = 2\ln\left(\frac{13.2}{11.1}\right)$$

$$= 0.346$$

5. (b)

Given : Depth of cut, d = 25 mm; Cutter diameter, D = 140 mm; Cutting speed, V = 54 m/min; Feed, f_t = 0.24 mm per tooth; Number of teeth, n = 12; Length of workpiece, l = 220 mm

Compulsory approach,

$$X = \sqrt{d(D-d)} = \sqrt{25(140-25)}$$

$$= 53.62 \text{ mm}$$

$\because$ Cutting speed,

$$V = \frac{\pi D N}{1000}$$

$$\Rightarrow \quad 54 = \frac{\pi \times 140 \times N}{1000}$$

$$\Rightarrow \quad N = 122.776 \text{ rpm}$$

(i) Table feed,

$$f_m = f_t \times n \times N$$

$$= 0.24 \times 12 \times 122.776$$

$$= 353.597 \text{ mm/min}$$

(ii) Total cutter travel = Length of workpiece + Compulsory approach

$$= (220 + 53.62)\text{ mm} = 273.62\text{ mm}$$

(iii) Slot machining time, $t_m = \dfrac{\text{Effective length}}{\text{Table feed}}$

$$= \frac{273.62}{353.597} = 0.7738\text{ min} = 46.43\text{ seconds}$$

5. **(c)**

The voltage-current relationship of an arc determines the required characteristics of the power source. The important points are open-circuit voltage and short-circuit current. For efficient striking of arc, open circuit voltage of power supply source should be high above the operating voltage. Since the arc length in welding process (particularly in manual process) keeps on changing, and this should not cause a large change in welding current. This is achieved by a sharply drooping characteristic. The supply source should have quick response because of unsteady nature of welding process. Further the power source should not get damaged due to flow of short circuit current for appreciable length of time. The characteristic curves will be different for different settings of short circuit currents.

With a flat characteristic, for a big change in an arc length, there may not be any point of intersection between the arc and the source characteristics and the arc may blow out. For an efficient striking of the arc, it is necessary that the open circuit voltage of the source be high above the operating voltage. Moreover, it is necessary to have a quick response of the source (low time constant) since the welding process itself is unsteady.

The different zones in an electric arc for electric arc welding are as follows:

(i) **Cathode spot :** This is a relatively very small area on the cathode surface, emitting the electrons.

(ii) **Cathode space :** This region is very close to the cathode and a very sharp drop of voltage takes place in this zone due to cooling effect of cathode. Voltage drop in this region directly affects the heat generation near the cathode which in turn governs melting rate of the electrode in case of the consumable arc welding process with straight polarity (electrode is cathode).

(iii) **Arc column :** This is the visible portion of the arc consisting of plasma (hot ionized gas) where the voltage drop is not sharp.

(iv) **Anode space :** This, again, is a gaseous region (thickness ; 10^{-3} cm) and is adjacent to the anode surface where a sharp drop in the voltage takes place. This is because the electrons have to penetrate the anode surface after overcoming the repulsion of the thermonically-emitted electrons from the anode surface.

(v) **Anode spot :** This is the area on the anode surface where the electrons are absorbed. This area is larger than the cathode spot.

5. (d)

As per Johnson's rule for '*n*' jobs on two machines, the resulting sequence will be

4	1	3	2	5	6

Now we can calculate the elapsed time corresponding to the optimal sequence, using the individual processing times given in the problem. The details are shown in table below.

	Drilling		Boring	
Job	**In**	**Out**	**In**	**Out**
1	0	2	2	8
2	2	5	8	16
3	5	10	16	25
4	10	22	25	35
5	22	31	35	38
6	31	42	42	43

Thus, the minimum elapsed time is 43 minutes. Idle time for drilling operation is 1 minute (from 42^{nd} minute to 43^{rd} minute) and for boring operation is 2 + 4= 6 minutes (from 0 - 2 and 38 - 42 minutes).

5. (e)

Thermal energy can be stored in chemical bonds by means of reversible thermochemical reactions. A reversible chemical reaction is one that proceeds simultaneously in both directions. In this class of energy storage, a type of reversible reaction $AB + \Delta H \leftrightarrow A + B$ takes place that occurs predominantly in one (forward) direction at higher temperature with absorption of heat, and predominantly in the opposite (reverse) direction at a lower temperature with emission of heat. The temperature above which the equilibrium shifts to the forward direction and below which it shifts to the reverse direction is known as the turning temperature. Such types of chemical reactions can be used for energy storage. The products of the forward reaction (endothermic decomposition), which store thermal energy (heat) as chemical energy, can be stored separately for a long duration at ambient temperature. The thermal energy may be recovered when the products are brought together and the conditions are changed to permit the reverse reaction (exothermic recombination) to occur.

Reversible thermochemical reactions of the type $A + B + \Delta H \leftrightarrow C + D$ may also be used for the same purpose. Some of the possible reactions suitable for thermochemical energy storage are given in table below.

S.No.	Reaction	ΔH(kJ/g-mole of reactants or products)	Turning temp. °C
1.	$Mg(OH)_2 \leftrightarrow MgO + H_2O$	81.6	258
2.	$NH_4HSO_4 \leftrightarrow NH_2 + H_2O + SO_3$	337	467
3.	$2NH_3 \leftrightarrow N_2 + 3H_2$	92.26	466
4.	$CH_4 + CO_2 \leftrightarrow 2CO + 2H_2$	247.4	960
5.	$CH_4 + H_2O \leftrightarrow CO + 3H_2$	250.31	677

To be suitable for heat storage, the reaction system should involve the materials that are inexpensive and not too difficult to handle. Also, the forward and reversible reactions should occur at reasonable temperatures. One or more catalyst may be needed to speed up the desired reaction, especially at lower temperature.

Some of the advantages of reversible chemical reaction storage systems are

1. High energy density (much higher than sensible or latent heat storage)
2. Storage at ambient temperature.
3. Low storage-related investment cost.
4. Suitable for both long-duration thermal storage and for long-distance thermal energy transport at ambient temperature.

The main disadvantage is that the technology is still immature.

These methods are suitable for solar thermal power generation.

6. (a)

The electrolysis process is governed by the following two laws proposed by faraday:

(i) The amount of chemical change produced by an electric current, that is, the amount of any material dissolved or deposited, is proportional to the quantity of electricity passed.

(ii) The amounts of different substances dissolved or deposited by the same quantity of electricity are proportional to their chemical equivalent weights.

We know that volumetric material removal rate $(\text{MRR})_V = \dfrac{eI}{F\rho}$

e = Gram equivalent of the alloy.

F = Faraday's constant = 96500 gm/mol

I = Current

ρ = Density of the alloy

For alloy:

$$\frac{1}{e} = \frac{2}{58.71}\times\frac{68.5}{100}+\frac{2}{51.99}\times\frac{21.2}{100}+\frac{2}{55.85}\times\frac{4.8}{100}+\frac{3}{47.9}\times\frac{1.5}{100}+\frac{4}{28.09}\times\frac{25}{100}+\frac{2}{54.94}\times\frac{1}{100}+\frac{1}{63.57}\times\frac{0.5}{100}$$

$$\Rightarrow \qquad e = 26.211$$

Density:

$$\frac{1}{\rho} = \frac{1}{8.90}\times\frac{68.5}{100}+\frac{1}{7.19}\times\frac{21.2}{100}+\frac{1}{7.86}\times\frac{4.8}{100}+\frac{1}{4.51}\times\frac{1.5}{100}+\frac{1}{2.33}\times\frac{2.5}{100}+\frac{1}{7.43}\times\frac{1}{100}+\frac{1}{8.96}\times\frac{0.5}{100}$$

$$\Rightarrow \qquad \rho = 7.781\ \text{g/cm}^3$$

$$\therefore \qquad (\text{MRR})_V = \frac{eI}{F\rho} = \frac{26.211\times 1200}{96500\times 7.781}$$

$$= 0.04188\ \text{cm}^3/\text{s}$$

$$= 2513.352\ \text{mm}^3/\text{min} \qquad \text{(Ans)}$$

6. (b)

Given : D = 20000 units/year, P = 4000 × 12 = 48000 units per year, C_0 = Rs. 500 per setup, C_h = 0.25 × 12 = Rs. 3 per unit/year, C_b = Rs. 20 per year, C = Rs. 5 per unit

Optimum lot size,

$$Q^* = \sqrt{\frac{2C_0D}{C_h}}\sqrt{\frac{C_b+C_h}{C_b}}\sqrt{\frac{P}{P-D}}$$

$$Q^* = \sqrt{\frac{2\times 500\times 20000}{3}}\times\sqrt{\frac{20+3}{20}}\times\sqrt{\frac{48000}{48000-20000}}$$

$$Q^* = 3625.3\ \text{units} \qquad \text{Ans.}$$

Total cost per year,

$$\text{T.C.} = D.C. + \sqrt{2C_0C_hD}\times\sqrt{\frac{C_b}{C_b+C_h}}\times\sqrt{\frac{P-D}{P}}$$

$$= 20000\times 5+\sqrt{2\times 500\times 3\times 20000}\times\sqrt{\frac{20}{23}}\times\sqrt{\frac{28000}{48000}}$$

$$= \text{Rs. } 105516.77 \text{ per year} \qquad \text{Ans.}$$

Maximum inventory,

$$Q_{\max} = \sqrt{\frac{2C_0D}{C_h}}\times\sqrt{\frac{C_h}{C_b+C_h}}\times\sqrt{\frac{P-D}{P}}$$

$$Q_{\max} = \sqrt{\frac{2\times 500\times 20000}{3}}\times\sqrt{\frac{20}{23}}\times\sqrt{\frac{28000}{48000}}$$

$$= 1838.92 \simeq 1839\ \text{units} \qquad \text{Ans.}$$

Manufacturing time interval,

$$t_p = \frac{Q^*}{p} = \frac{3625.3}{4000} = 0.9063 \text{ months} \qquad \text{Ans.}$$

Total time interval, $$T = \frac{Q^*}{D} = \frac{3625.3}{20000/12} = 2.175 \text{ months} \qquad \text{Ans.}$$

6. (c)

Given : $\phi = 11.02°$, $\overline{t}_d = 10.5h$

For 17 January, $n = 17$, the corresponding angle δ

$$\delta = 23.45 \times \sin\left[\frac{360(17+284)}{365}\right]$$

$$\delta = -20.917°$$

The hour angle at sunrise/sunset,

$$\omega_s = \pm\cos^{-1}(-\tan\phi\tan\delta)$$

$$= \pm\cos^{-1}(-\tan(11.02°)\tan(-20.917°))$$

$$= 85.73° \text{ or } 1.496 \text{ (rad)}$$

∴ Maximum day length, $$\overline{t}_{d\max} = \frac{2}{15} \times 85.73 = 11.43h$$

Total monthly average of daily extraterrestrial radiation on horizontal surface is,

$$H_0 = 3600 \times \frac{24}{\pi} \times 1.367\left[1 + 0.033\cos\frac{360n}{365}\right](\cos\phi\cos\delta\sin\omega_s + \omega_s\sin\delta\sin\phi)$$

$$= 3600 \times \frac{24}{\pi} \times 1.367\left[1 + 0.033\cos\frac{360 \times 17}{365}\right](\cos(11.02)$$
$$\times\cos(-20.917)\sin(85.73) + 1.496 \times \sin(-20.917) \times \sin(11.02))$$

∴ $$H_0 = 37595.2 \times 1.0316 \times (0.914 - 0.102)$$

$$= 31492 \text{ kJ/m}^2\text{-day}$$

or $$\overline{H}_0 = H_0 = 31492 \text{ kJ/m}^2\text{-day}$$

∴ The average daily global radiation, on horizontal surface

$$\overline{H}_g = \overline{H}_0 \times \left\{a + b\frac{\overline{t}_d}{\overline{t}_{d\max}}\right\}$$

$$\bar{H}_g = 31492 \times \left\{0.42 + 0.23 \times \frac{10.5}{11.43}\right\}$$

$$= 19880.44 \text{ kJ/m}^2\text{-day} \qquad \text{Ans.}$$

7. (a)

Let x_1 and x_2 denote the number of days in April for which plants at L_1 and L_2 must run.

Objective is to minimize the production cost i.e. minimize, $z = 600x_1 + 400x_2$

Constraints are on the demand,

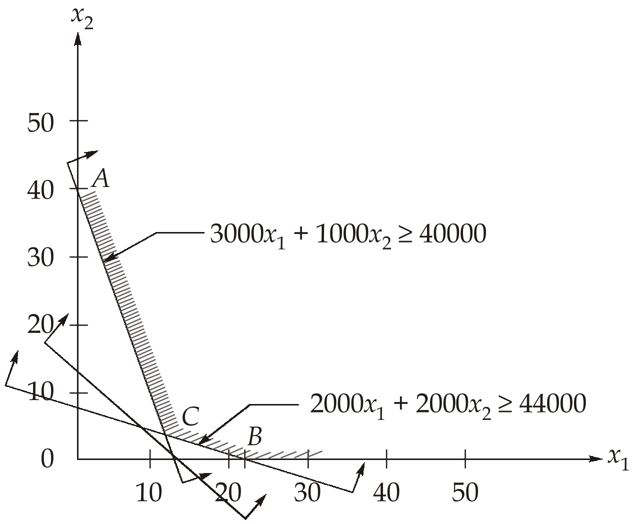
i.e. $1500x_1 + 1500x_2 \geq 20000$

$3000x_1 + 1000x_2 \geq 40000$

$2000x_1 + 5000x_2 \geq 44000$

where $x_1\ x_2 \geq 0$

The solution space satisfying the given constraints and meeting the non-negativity conditions is shown in figure below. Any point in this feasible region is a feasible solution to the given problem.



Thee three vertices of the convex set ACB are $A(0, 40)$, $B(22, 0)$ and $C(12, 4)$

Values of the objective function at these vertices are

$$z(A) = 600 \times 0 + 40 \times 400 = 16000/-$$

$$z(B) = 600 \times 22 + 40 \times 0 = 13200/-$$

$$z(C) = 600 \times 12 + 400 \times 4 = 8800/-$$

Thus, the minimum value of z is Rs. 8800/- and it occurs at the vertex $C(12, 4)$. Hence, the solution to the problem is

$$x_1 = 12 \text{ days}$$
$$x_2 = 4 \text{ days}$$
and $$z_{\min} = \text{Rs. } 8800/-$$

7. **(b)**

Daily requirement of water = 5000 litre/day

Total vertical lift = 50 m

Frictional head = 50 × 0.1 = 5 m

∴ Total dynamic head = 50 + 5 = 55 m

Hydraulic energy required per day to lift water = mgh

$$= 10^3 \times 5 \times 9.81 \times 55$$
$$= 2697750 \text{ J}$$
$$= 749.375 \text{ W-hr}$$

The required energy of 749.375 W-hr is to be supplied by the motor in 5 hours.

Thus, required output power of pump = $\frac{749.375}{5} = 149.875\,\text{W}$

The input energy required by pump = $\frac{149.875}{0.4} = 374.68\,\text{W}$

Thus, 374.68 W power is to be supplied by panel. Ans.

Now, considering the losses due to operating point and mismatch factor.

$\therefore$ Required number of PV modules = $\frac{551}{\text{Peak power}}$

$$= \frac{551}{17.5 \times 5.5} = 5.72 \simeq 6 \text{ modules}$$

7. **(c)**

(i)

Classification of nano-materials according to:

1. **Dimensionality :** From the point of view of their dimensionality, nanomaterials can be classified as nanomaterials with one, two, and three dimensions within the nanoscale, Materials with one dimension in the nanoscale are also called very thin films or surface coatings attached on a substrate usually made from a different material. Nanomaterials with two dimensions in the nanoscale are either nanoparticles attached onto a substrate, porous thin films with pores in the

nanoscale, or free long aspect ratio nanoparticles, wires, or tubes. Finally, nanomaterials with three dimensions within the nanoscales can be fixed small nanostructures on a substrate, membranes with nanopores on a substrate, or nanoparticles.

2. **Morphology :** A classification of nanomaterials according to their morphology divides them in low- and high aspect ratio particles. The high aspect ratio nanoparticles can have different shapes, such as low aspect ratio nanoparticles can have many shapes as well, such as spherical, helical, pillar-like, pyramidal, cubes, among others.
3. **Composition :** According to their composition, nanoparticles can be made of a single material, compact or hollow. Nanomaterials can also be comprised of two or more materials that can be as coatings, encapsulated, barcode, or mixed.
4. **Uniformity and Agglomeration :** According to their uniformity, nanoparticles can be classified as isometric and inhomogeneous. From the point of view of their agglomeration status, nanoparticles can be dispersed or agglomerate. Their agglomeration state depends on their electromagnetic properties, such as surface charge and magnetism. When in a liquid, their agglomeration depends on their surface morphology and functionalization which can confer it either hydrophobicity or hydrophilicity.

The most important physicochemical properties of nanoparticles are:

- Composition and surface composition
- Crystalline phase
- Particle size distribution
- Agglomeration/ Aggregation
- Shape
- Specific surface area
- Roughness/ Porosity
- Water solubility/ Dispersability or hydrophobicity/ Hydrophilicity
- Zeta potential or surface charge
- Surface chemistry
- Catalytic/ Photocatalytic activity
- Magnetic properties
- Optical properties

(ii)

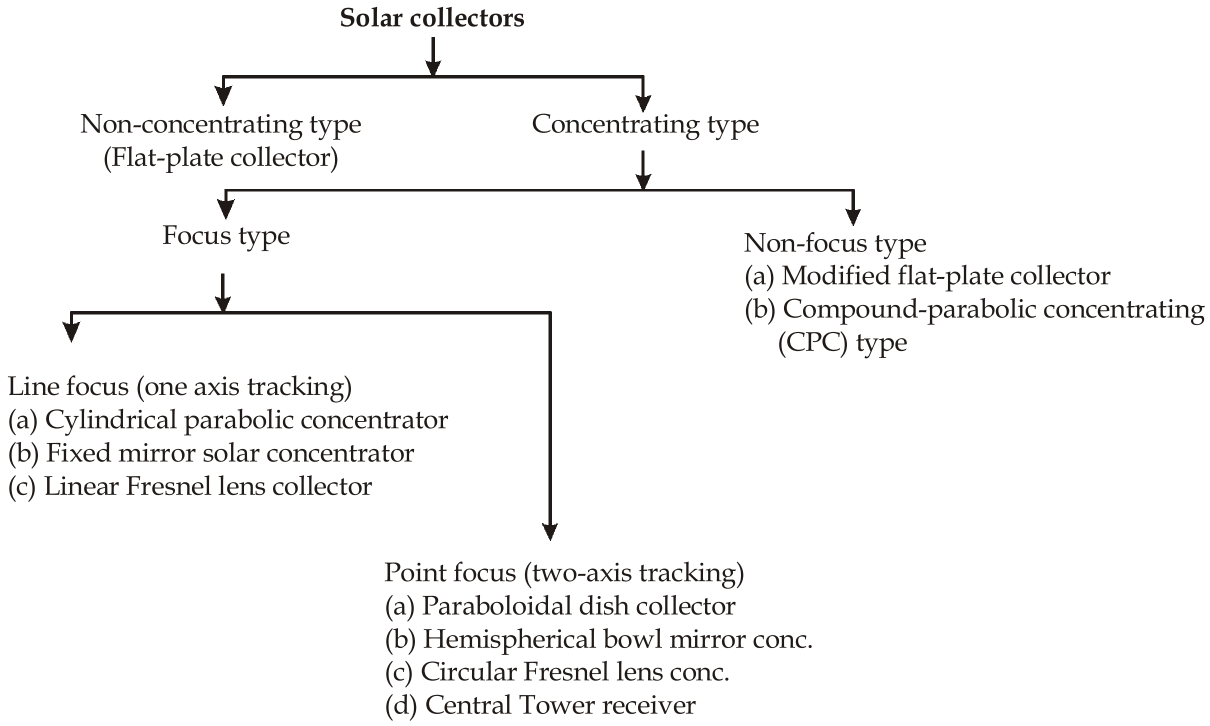
Methods regarding prevention of corrosion:

1. There is sizable loss to the industrial economy of the country due to corrosion and oxidation of domestic, commercial and industrial parts. Corrosion can be prevented by the use of the following:
   (a) Nobel metals
   (b) Oxidation and corrosion-resistant materials
   (c) Preventive coatings
   (d) Inhibitors

   Moreover, deaeration of water, cathodic protection techniques and proper design of components so as to avoid formation of galvanic cells.
2. Simplest coating for corrosion control is conversion coating obtained by simple immersion treatments. Most often, it is only an atmospheric corrosion and there is no effect in chemical environment.
3. Affecting corrosion control with polymer coatings requires that the coating should be more than 1 mm thickness, free from pin holes, impermeable and inert to desired environments.
4. Metal coatings that are anodic to substrate, as zinc galvanizing, are very effective for control under atmospheric corrosion because they are not sensitive to pin holes.
5. Chromizing is effective in improving corrosion resistance of steels.
6. Diffusion-controlled cyaniding helps in preventing atmospheric rusting of steels. But nitriding of stainless steels lowers their chemical resistance.
7. When stainless steels are sensitized annealing and water quench.
8. Some cast alloys are annealed or normalized before using them in corrosion environments.
9. A good surface greatly aids in cleanability, which in turn prevents under-deposit attack and crevice corrosion.

8. (a)

The overall view of classification of solar collectors into categories and subcategories is shown in figure below.



The classification is based on the way they collect solar radiation. The non-concentrating type absorbs the radiation as it is received on the surface of the collector while the concentrating type first increases the concentration of radiation per unit area before absorbing it. Further, based on the techniques employed for concentration of radiation, the concentrating type is further subdivided into focus and non-focus types. The focus type is further divided into line or point focus depending on the focusing method.

Comparison of concentrating and non-concentrating types (Flat-plate type) of solar collectors:

1. In concentrating-type solar collectors, solar radiation is converged from a large area into a smaller area using optical means. Beam radiation, which has a unique direction and travels in a straight line, can be converged by reflection or refraction techniques. Diffused radiation however, has no unique direction and so does not obey optical principles. Therefore, the diffused component cannot be concentrated. Thus, concentrating-type solar collectors mainly make use of the beam radiation component (plus very little diffuse-component coming directly over the absorber), while non-concentrating (flat plate) collectors absorb both beam as well as diffused radiation, a distinct advantage of a flat-plate collector.

2. A flat-plate collector is simple in construction and does not require sun tracking. Therefore, it can be properly secured on a rigid platform, and thus becomes mechanically stronger than those requiring flexibility for tracking purpose. As the collector is installed outdoors and exposed to atmospheric disturbances (rain, storm, etc.), the flat-plate type is more likely to withstand harsh outdoor conditions. Also, because of its simple stationary design, a flat-plate collector requires little maintenance.
3. The principal disadvantage of a flat-plate collector is that because of the absence of optical concentration, the area from which heat is lost is large. Also, due to the same reason, high temperatures cannot be attained.
4. The main advantage of concentrating-type collectors is that high temperatures can be attained due to concentration of radiation. This also yields high-temperature thermal energy.

Effect of various parameters on performance:

(i) **Selective Surface :** Absorber plate surfaces which exhibit characteristics of a high value of absorptivity for incoming solar radiation and low value of emissivity for outgoing re-radiation are called selective surfaces. Such surfaces are desirable because they maximize the net energy collection. Some examples of selective surface layers are copper oxide, nickel black and black chrome.

(ii) **Number of Covers :** With increase in the number of covers, the values of both $(\tau\alpha)_b$ and $(\tau\alpha)_d$ decrease and thus the flux absorbed by the absorber plate decreases. The value of heat loss from the absorber plate also decreases. However, the amount of decrease is not the same in both cases. Maximum efficiency is obtained with one or two covers.

(iii) **Spacing :** Heat loss also varies with spacing between two covers and that between the absorber plate and first cover. The spacing at which minimum loss occurs varies with temperature and also with tilt. Since collectors are designed to operate at different locations with varying tilts and under varying service conditions, an optimum value of spacing is difficult to specify. Spacing in the range from 4 to 8 cm is normally suggested.

(iv) **Collector Tilt :** Flat-plate collectors are normally used in a fixed position and do not track the sun. Therefore, the tilt angle at which they are fixed is very important. Optimum tilt depends on the nature of the application. The usual practice is to recommend a value of $(\phi + 10°)$ or $(\phi + 15°)$ for winter applications (e.g. water heating, space heating, etc.) and $(\phi - 10°)$ or $(\phi - 15°)$ for summer applications (e.g., absorption refrigeration plant etc.)

(v) **Dust on the top of the cover :** When a collector is deployed in a practical system, dust gets accumulated over it, reducing the transmitted flux through the cover. This requires continuous cleaning of the cover, which is not possible in a practical situation. Cleaning is generally done once in a few days. For this reason, it is recommended that the incident flux be multiplied by a correction factor which accounts for the reduction in intensity because of accumulation of dust. In general, a correction factor from 0.92 to 0.99 seems to be indicated.

8. **(b)**

(i)

The three levels of manufacturing flexibility in FMS are :

- Machine Flexibility i.e., the ease with which a machine can process various operations.
- Material handling flexibility i.e., a measure of the ease with which different part types can be transported and properly positioned at various machine tools.
- Operation flexibility, i.e., a measure of the ease with which alternative operation sequences can be used for processing a part type.

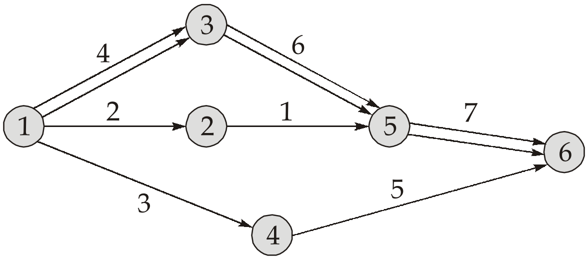
Role of AGVs in extending flexibility of FMS systems. AGVs increase flexibility of FMS in regard to

- **Plant integration :** AGVs provide the integrating links between all production facilities like machining centres, deburring and other special machines, washing plants, tool changing areas, set-up stations, buffer stations and storage areas.
- **Layout arrangement :** Transport routes can be laid out to accommodate any arrangement of production facilities.
- **Process sequences :** AGVs can transport workpieces through variable sequences of machining and other operations. Machines out of order can be automatically bypassed.
- **Transport capacity :** AGVs can be dynamically scheduled to meet the current transport loads in different areas.
- **Working time :** AGVs can support unmanned shifts thereby permitting round the clock operation.
- **Load handling :** AGVs can handle a variety of loads like machine pallets, wooden pallets, tool dispensers, etc.
- **Accessibility :** AGVs do not require fixed installation and can share transport routes with forklift trucks etc and keep machines freely accessible.

- **Breakdowns :** By having a redundant AGV, breakdown is immaterial.
- **System extension :** Layout can be easily extended to link additional machines, etc.

(ii)

The project network diagram along with their expected time is as shown below.



(a)

Critical path = 1 - 3 - 5 - 6

Expected duration of project = 4 + 6 + 7 = 17 Weeks Ans.

The standard deviation of the project is equal to the standard deviation of the critical path.

For activity, 1 - 3; $\sigma_1^2 = \left(\frac{7-1}{6}\right)^2 = 1$

For activity, 3 - 5; $\sigma_2^2 = \left(\frac{14-2}{6}\right)^2 = 4$

For activity, 5 - 6; $\sigma_3^2 = \left(\frac{15-3}{6}\right)^2 = 4$

$\therefore$ $\sigma_{\text{project}} = \sqrt{\sigma_1^2 + \sigma_2^2 + \sigma_3^2} = \sqrt{1+4+4} = 3$ Ans.

(b)

The standard normal variate,

$$z = \frac{\text{Due date – Expected data}}{\sqrt{\text{Variance}}}$$

$\therefore$ $$z = \frac{21 - 17}{3} = 1.33$$

$\therefore$ The probability of completing the project in not more than 4 weeks later than expected time is (1 – 0.0918) = 0.9082 or 90.82% Ans.

8. (c)

Given : Basic size = 95 mm; Type of fit = H_8e_9; $i = 0.45\sqrt[3]{D} + 0.001D$; Value of IT8 = 25$i$; Value of IT9 = 40$i$; F.D. of '$e$' type shaft = $-11D^{0.41}$

$$D = \sqrt{80 \times 100} = 89.4427 \text{ mm}$$

$$i = 0.45\sqrt[3]{D} + 0.001D$$

$$= 0.45 \times (89.4427)^{1/3} + 0.001 \times 89.4427$$

$$= 2.1019\ \mu\text{m} = 2.1019 \times 10^{-3} \text{ mm}$$

Value of tolerance on hole = 25i

$$= 25 \times 2.1019 \times 10^{-3}$$

$$= 0.05254 \text{ mm}$$

Fundamental deviation for H-type hole = 0

∴ Minimum size of hole = 95.000 mm Ans.

Maximum size of hole = 95.000 + 0.05254

= 95.0525 Ans.

Fundamental deviation for 'e' type shaft

$$= -11D^{0.41} = -11 \times (89.4427)^{0.41}$$

$$= -69.4266\ \mu\text{m}$$

$$= -0.06943 \text{ mm}$$

∴ Maximum size of shaft = 95.000 – 0.06943

= 94.9306 mm Ans.

Tolerance for IT9 = $40i = 40 \times 2.1019 \times 10^{-3}$

= 0.084076 mm

∴ Minimum size of shaft = 94.9306 – 0.084076 = 94.8465 mm

Gauge tolerance for hole = 10% of 0.05254 = 0.005254 mm

Wear allowance for hole = 5% of 0.05254 = 2.627×10^{-3} mm

= 0.0026 mm

Similarly gauge tolerance for shaft = 10% of 0.084076 = 8.4076×10^{-3} mm

Wear allowance for shaft = 5% of 0.084076 = 4.2038×10^{-3} mm

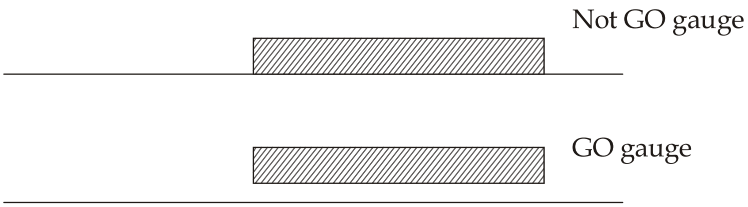
According to present British system, the tolerance zone for the GO gauges should be placed inside the work-limits and tolerance for the NO-GO gauges outside the work limits.

For hole:

$$\text{GO gauge} : (95.000 + 0.0026)_{0}^{+0.0052}$$

$$= (95.0026)_{0}^{+0.0052}$$

$$\text{Not GO gauge} : (95.0525)_{0}^{+0.0052}$$

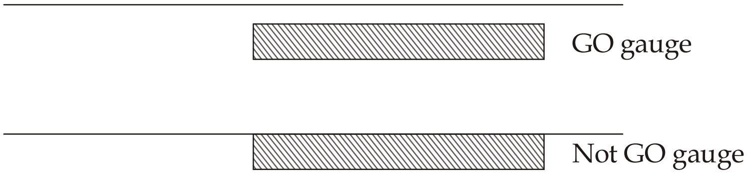


For shaft:

$$\text{GO gauge} : (94.9306 - 0.0042)_{-0.0084}^{0}$$

$$= (94.9264)_{-0.0084}^{0}$$

$$\text{Not GO gauge} : (94.8465)_{-0.0084}^{0}$$



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