MADE EASY
Leading Institute for ESE, GATE & PSUs

Detailed Solutions

ESE-2026 Mains Test Series

Mechanical Engineering Test No : 2

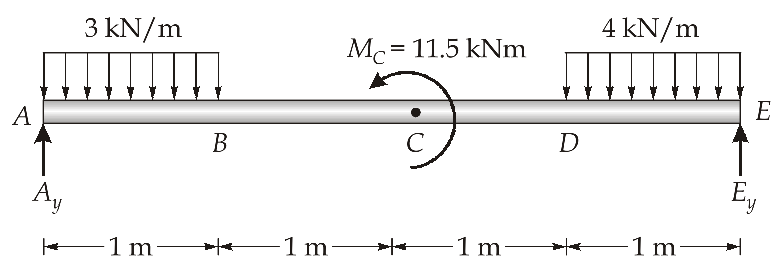
Section A : Strength of Materials & Mechanics **[All Topics]**

Section B : Thermodynamics-1 + IC Engine-1 + Refrigeration & Air-conditioning-1 **[Part Syllabus]**

Section A : Strength of Materials & Mechanics

1. (a) Solution:

Free body diagram of beam *ABCDE*



Couple at C, $M_C = 11.5 \times [0.5 + 0.5] = 11.5$ kNm

Force equilibrium in vertical,

$$\Sigma V = 0$$

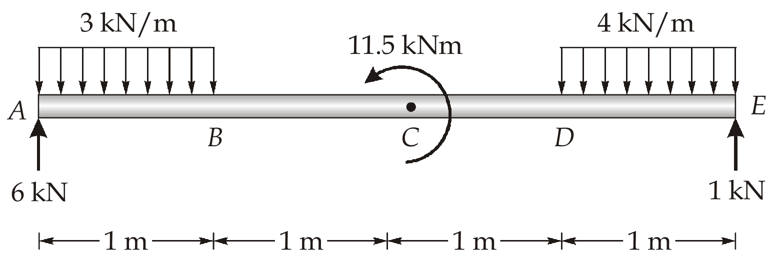
$\Rightarrow$ $A_y + E_y = 7$ kN ...(i)

$\Sigma M_A = 0$

$\Rightarrow 3 \times 1 \times 0.5 - 11.5 + 4 \times 1 \times [3 + 0.5) - 4E_y = 0$

$\Rightarrow$ $E_y = 1$ kN

From (i), we get $A_y = 6$ kN



Shear forces,

S_A = 6 kN; S_B = 6 – 3 × 1 = 3 kN; $S_C = S_D = S_B$ = 3 kN; S_E = 3 – 4 × 1 = –1 kN

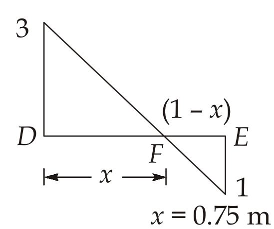
Bending moments,

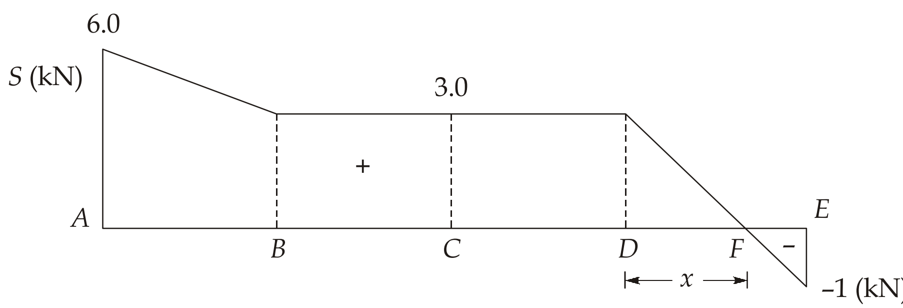
M_A = 0; M_B = 4.5 kNm; $(M_C)_{BC}$ = 7.5 kNm; $(M_C)_{CD}$ = –4 kNm; M_D = –1 kNm; M_E = 0

Shear force diagram:

To find x →

$$\frac{3}{x} = \frac{1}{1-x}$$
$$3.3x = x$$
$$3 = 4x$$
$$x = 0.75$$





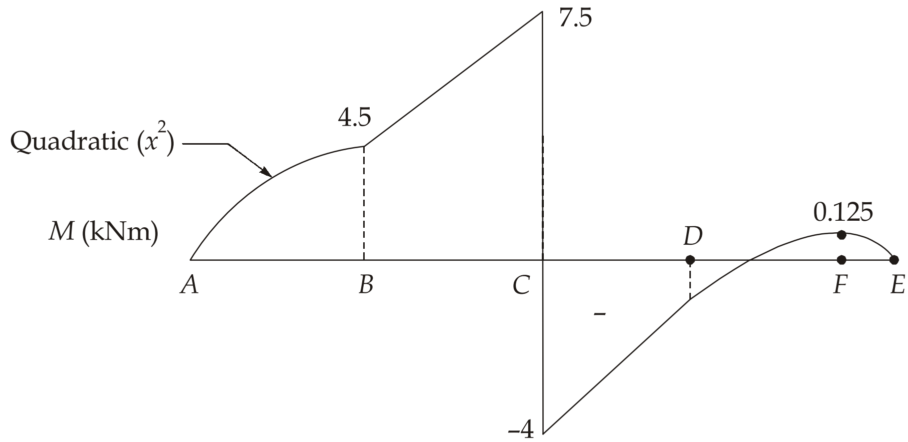
Bending moment at F,

$$M_F = \frac{1}{2} \times 1 \times (1 - x)$$

$$M_F = \frac{1}{2} \times 1 \times (1 - 0.75)$$

$$M_F = 0.125 \text{ kNm}$$

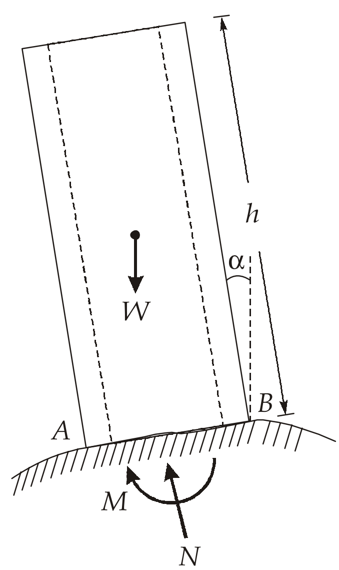
Bending moment diagram:



Hence, the maximum bending moment acting on the beam is 7.5 kN-m.

1. (b) Solution:

Given : h = 50 m; d_2 = 15 m; d_1 = 12 m; α = angle of tilt



Let W = Weight of the tower

$$\text{Area of cross-section, } A = \frac{\pi}{4}\left(d_2^2 - d_1^2\right)$$

$$\text{Area moment of inertia, } I = \frac{\pi}{64}\left(d_2^4 - d_1^4\right)$$

$$\therefore \qquad \frac{I}{A} = \frac{d_2^2 + d_1^2}{16}$$

At the base of the tower

$$\text{Normal, } N = W\cos\alpha$$

$$\text{Moment, } M = W\sin\alpha\left(\frac{h}{2}\right) \qquad [\because \text{ Weight will acts at the centre}]$$

At B, tensile stress due to bending and compressive stress due to weight develops.

Therefore, net maximum tensile stress

$$\sigma_t = -\frac{N}{A} + \frac{M}{Z} \qquad [Z \text{ is section modulus here}]$$

$$\sigma_t = -\frac{W\cos\alpha}{A} + \frac{W\sin\alpha}{I}\left(\frac{h}{2}\right)\left(\frac{d_2}{2}\right)$$

For tensile stress to be zero in tower

$$\sigma_t = 0$$

$$\Rightarrow \qquad \frac{\cos\alpha}{A} = \frac{d_2 h \sin\alpha}{4I}$$

$$\Rightarrow \qquad \tan\alpha = \frac{4I}{A d_2 h} = \frac{d_2^2 + d_1^2}{4hd_2}$$

Hence, maximum angle of inclination

$$\alpha_{max} = \tan^{-1}\left(\frac{d_2^2 + d_1^2}{4d_2 h}\right) \qquad \textbf{Ans.}$$

Substituting the numerical values,

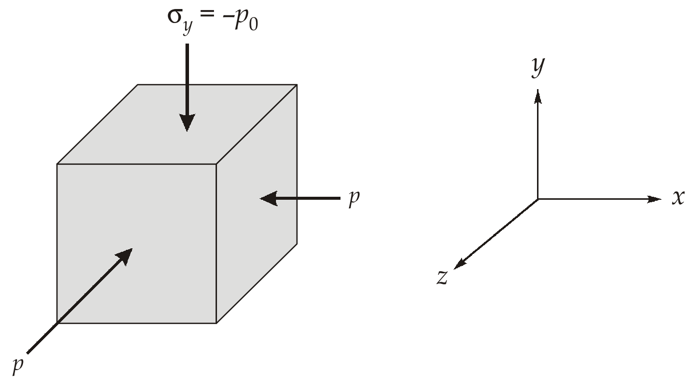
$$h = 50 \text{ m}; d_2 = 15 \text{ m}; d_1 = 12 \text{ m}$$

$$\alpha = \tan^{-1}\left(\frac{15^2 + 12^2}{4 \times 15 \times 50}\right) = 7.01°$$

$$\Rightarrow \qquad \alpha = 7.01° \qquad \textbf{Ans.}$$

1. (c) Solution:

Given : Modulus of elasticity = E ; Poisson's ratio = μ



Let, lateral pressure = p

$$\sigma_x = \sigma_z = -p$$

$$\in_x = \in_z = 0$$

(i) Lateral strain,

As we know,
$$\in_x = \frac{\sigma_x}{E} - \frac{\mu}{E}\left(\sigma_y + \sigma_z\right)$$

$$\in_x = \frac{-p}{E} - \frac{\mu}{E}[-p_0 + (-p_0)]$$

$$0 = -p - \mu\left(-p_0 - p\right)$$

$\Rightarrow$
$$p = \left(\frac{\mu}{1-\mu}\right)p_0 \qquad \textbf{Ans.}$$

$$\sigma_x = \sigma_z = -p_0\left(\frac{\mu}{1-\mu}\right)$$

(ii) Dilatation,
$$\in_v = \frac{1-2\mu}{E}\left(\sigma_x + \sigma_y + \sigma_z\right)$$

$\Rightarrow$
$$\in_v = \frac{1-2\mu}{E}\left(-p_0 - 2p_0\left(\frac{\mu}{1-\mu}\right)\right)$$

$\Rightarrow$
$$\in_v = -\frac{(1+\mu)(1-2\mu)p_0}{(1-\mu)E} \qquad \textbf{Ans.}$$

(iii) Strain energy density

$$u = \frac{1}{2E}\left(\sigma_x^2 + \sigma_y^2 + \sigma_z^2\right) - \frac{\mu}{E}\left(\sigma_x\sigma_y + \sigma_y\sigma_z + \sigma_x\sigma_z\right)$$

$$= \frac{1}{2E}\left((-p)^2 + (-p_0)^2 + (-p)^2\right) - \frac{\mu}{E}\left(p_0 p + p p_0 + p^2\right)$$

$$= \frac{1}{2E}\left(p_0^2 + 2p_0^2\left(\frac{\mu}{1-\mu}\right)^2\right) - \frac{\mu}{E}p_0^2\left[\frac{2\mu}{1-\mu} + \left(\frac{\mu}{1-\mu}\right)^2\right]$$

$$u = \frac{p_0^2}{2E}\left[1 - \frac{2\mu^2}{1-\mu}\right]$$ **Ans.**

1. (d) Solution:

Let the dimensions of the column at a distance x m below the top be d_x,

$\therefore$ $$d_x = 75 + \frac{x}{7.5}(150 - 75) = 75 + 10x \text{ mm}$$

$$I_x = \frac{d_x^4}{12} \text{ and } y_{max} = \frac{d_x}{\sqrt{2}} \text{mm}$$

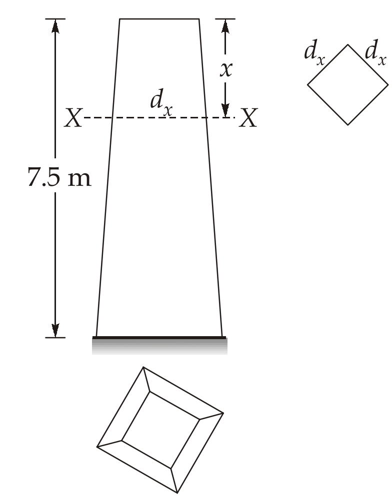
$\therefore$ $$z_x = \frac{I_x}{y_{max}} = \frac{d_x^3}{6\sqrt{2}}$$

or $$z_x = \frac{(75+10x)^3}{6\sqrt{2}}$$

Also, $$M_x = 5000x \text{ Nm} = 5 \times 10^6 \, x \text{ N.mm}$$

$\therefore$ $$\sigma_x = \frac{M_x}{z_x} = \frac{5 \times 10^6 \times 6\sqrt{2} \cdot x}{(75+10x)^3}$$

$$\sigma_x = \frac{42.42x \times 10^6}{(75+10x)^3}$$



For maximum bending stress,

$$\frac{d\sigma_x}{dx} = 0$$

$\therefore$ $$42.42\left[\frac{(75+10x)^3 - x \cdot 3(75+10x)^2 \cdot 10}{(75+10x)^6}\right] = 0$$

or $$(75 + 10x)^2(75 + 10x - 30x) = 0$$

$\therefore$ $$75 - 20x = 0$$

$\Rightarrow$ $$x = 3.75 \text{ m}$$

$\therefore$ $$\sigma_{max} = \frac{42.42 \times 3.75 \times 10^6}{(75 + 10 \times 3.75)^3} = 111.72 \text{ N/mm}^2$$

1. (e) Solution:

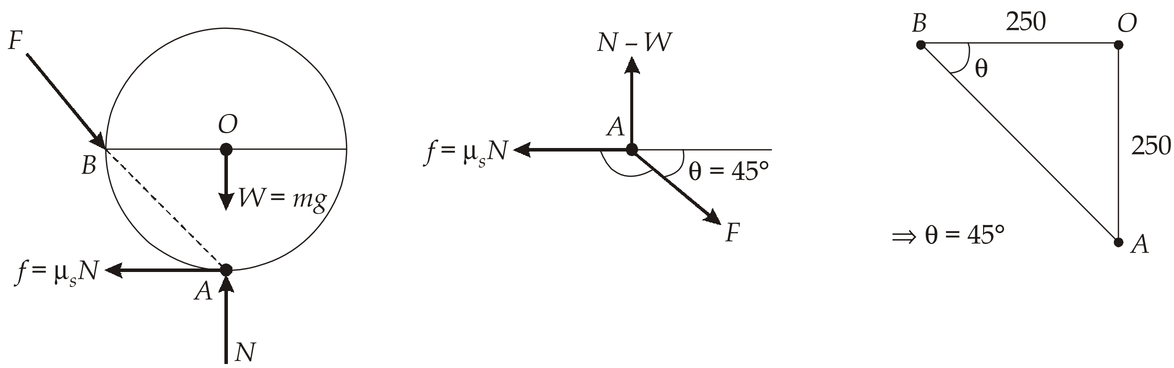
Given: m_{disc} = 50 kg, M = 60 Nm

Let coefficient of friction = μ_s.

So, friction is given as $f = \mu_s \times N$; where N is normal reaction

Assuming the disc is at verge of slip for minimum value of μ_s.

Free body diagram of disk.



For three force equilibrium, they should be concurrent.

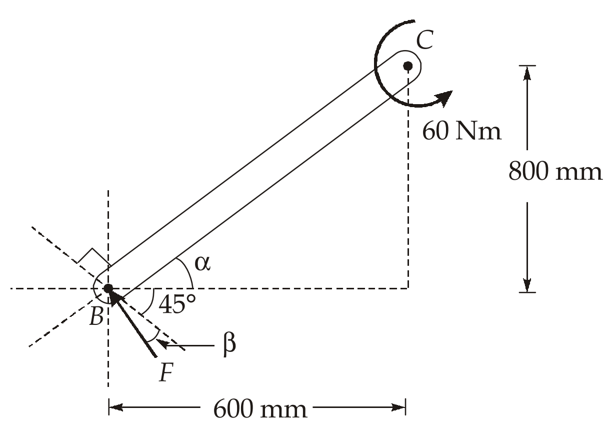
Using Lami's theorem,

$$\frac{N\text{-}W}{\sin 135°} = \frac{(f = \mu_s N)}{\sin 135°} = \frac{F}{\sin 90°}$$

$$N - W = \mu_s N \Rightarrow N(1 - \mu_s) = W \quad \text{...(i)}$$

$$\sqrt{2}\mu_s N = F \Rightarrow \mu_s N = \frac{F}{\sqrt{2}} \quad \text{...(ii)}$$

Free body diagram of bar



$$BC = \sqrt{600^2 + 800^2} = 1000 \text{ mm} = 1 \text{ m}$$

$$\sin\alpha = \frac{800}{1000} = \frac{4}{5}$$

$$\cos\alpha = \frac{3}{5}$$

$$\alpha = 53.13°$$

$$\beta = \alpha - 45° = 8.13°$$

Using equilibrium equation,

Take moment about C, $\Sigma M_C = 0$

$$\Rightarrow \quad F\cos\beta(BC) = 60$$

$$\Rightarrow \quad F \times \cos(8.13°)(1) = 60$$

$$\Rightarrow \quad F = 60.609 \text{ N}$$

By equation (i) ÷ (ii), we get

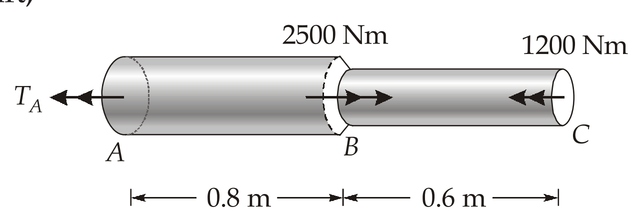
$$\frac{1-\mu_s}{\mu_s} = \frac{\sqrt{2}mg}{F}$$

$$\Rightarrow \quad \frac{1-\mu_s}{\mu_s} = \frac{\sqrt{2}\times 50\times 9.81}{60.609} = 11.445$$

$$\Rightarrow \quad (\mu_s)_{min} = 0.08$$ **Ans.**

2. (a) Solution:

FBD of overall shaft,



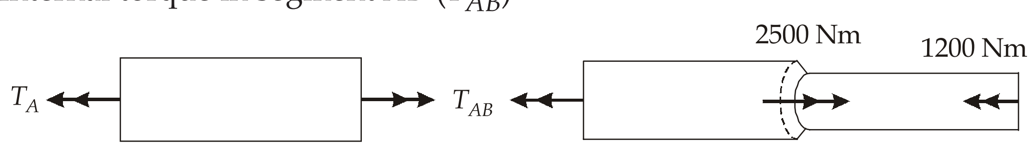
Using equilibrium equation of statics [When viewed from R.H.S.]

$$\Sigma T_x = 0$$

$$\Rightarrow \quad T_A - 2500 + 1200 = 0$$

$$\Rightarrow \quad T_A = 1300 \text{ Nm } (\circlearrowleft)$$

For Internal torque in segment AB (T_{AB})



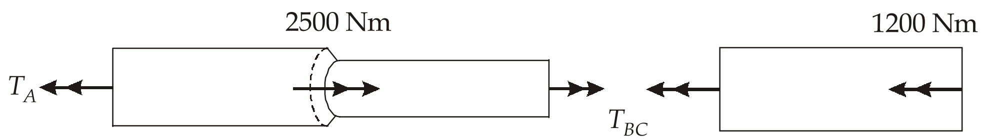
Left and Right FBD of shaft for segment AB

From Left FBD

$$T_A = T_{AB}$$

$$\Rightarrow \quad T_{AB} = -1300 \text{ Nm}$$

For Internal torque in segment *BC*

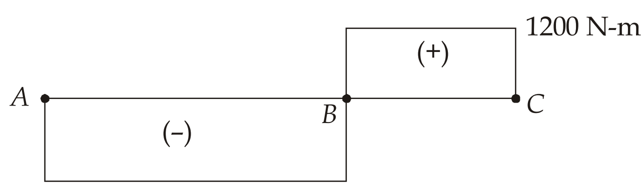


From right *FBD*,

$$T_{BC} + 1200 = 0$$

$$\Rightarrow \quad T_{BC} = 1200 \text{ Nm}$$

(ii) Torsional moment diagram



T_{AB} = –1300 N-m, T_{BC} = 1200 N-m, d_{AB} = 60 mm, d_{BC} = 45 mm

Shear stress in segment *AB*

$$\tau_{AB} = \left(\frac{16T}{\pi d^3}\right)_{AB} = \frac{16 \times 1300 \times 10^3}{\pi \times (60)^3} = 30.65 \text{ MPa}$$

Shear stress in segment *BC*,

$$\tau_{BC} = \left(\frac{16T}{\pi d^3}\right)_{BC} = \frac{16 \times 1200 \times 10^3}{\pi \times (45)^3} = 67.07 \text{ MPa}$$

Therefore, maximum shear stress in the shaft

$$\tau_{max} = \text{Maximum of } (\tau_{AB}, \tau_{BC}) = 67.07 \text{ MPa}$$ **Ans.**

Angle of twist at section $B = \theta_{BA}$ $\{\because \quad \theta_A = 0\}$

$$\theta_{BA} = \left(\frac{TL}{GJ}\right)_{AB} = \frac{-1300 \times 10^3 \times 800}{80 \times 10^3 \times \frac{\pi}{32} \times (60)^4} = -0.0102 \text{ rad} = -0.585°$$

Similarly, $\theta_{CA} = \theta_{CB} + \theta_{BA}$

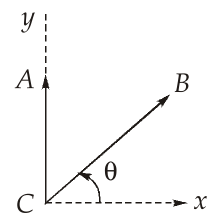
$$\Rightarrow \qquad \theta_{CA} = \left(\frac{TL}{GJ}\right)_B + \theta_{BA}$$

$$= \frac{1200 \times 10^3 \times 600}{80 \times 10^3 \times \frac{\pi}{32} \times (45)^4} - 0.0102 = 0.01213 \text{ rad} = 0.695°$$

Hence, angle of twist of section B is 0.58° and section C is 0.695°.

2. (b) Solution:

Given, $E = 200 \times 10^3$ MPa; $\nu = 0.3$, $d = 60$ mm; $e_A = -50 \times 10^{-6}$ and $\varepsilon_B = -160 \times 10^{-6}$



At centroidal axis, (Point C)

Combined stress (axial force and shear) acts.

$$\sigma_x = \frac{P\cos\beta}{A} = \frac{4P\cos\beta}{\pi d^2}$$

$$\sigma_y = 0$$

$$\tau_{xy} = \frac{-4}{3}\left(\frac{P\sin\beta}{A}\right) = \frac{-16P\sin\beta}{3\pi d^2}$$

At $\theta = 0°$, $\varepsilon = \varepsilon_x$

$$\theta = 90°, \varepsilon = \varepsilon_y = \varepsilon_A = -50 \times 10^{-6}$$

At $\theta = 60°$, $\varepsilon_{60°} = -160 \times 10^{-6} = \varepsilon_B$

$$\because \qquad \varepsilon_\theta = \frac{\varepsilon_x + \varepsilon_y}{2} + \frac{\varepsilon_x - \varepsilon_y}{2}\cos(2\theta) + \frac{\gamma_{xy}}{2}\sin 2\theta$$

at $\theta = 60°$

$$-160 \times 10^{-6} = \frac{\varepsilon_x - 50 \times 10^{-6}}{2} + \frac{\varepsilon_x + 50 \times 10^{-6}}{2}(-0.5) + \frac{\gamma_{xy}}{2}\left(\frac{\sqrt{3}}{2}\right)$$

$$\Rightarrow \qquad -122.5 \times 10^{-6} = \frac{\varepsilon_x}{4} + \frac{\sqrt{3}\gamma_{xy}}{4}$$

$$\Rightarrow \quad \varepsilon_x + \sqrt{3}\gamma_{xy} = -490 \times 10^{-6} \quad \text{...(i)}$$

$$\because \quad \gamma_{xy} = \frac{\tau_{xy}}{G} = \frac{-16P\sin\beta}{3\pi d^2}\left[\frac{2(1+\nu)}{E}\right] \quad \text{...(ii)}$$

$$\varepsilon_x = \frac{\sigma_x}{E} = \frac{4P\cos\beta}{E\pi d^2}$$

$\because$ From
$$\varepsilon_y = \frac{\sigma_y}{E} - \nu\frac{\sigma_x}{E} \text{ and } \sigma_y = 0$$

$$\sigma_x = -\frac{E\varepsilon_y}{\nu} = \frac{-200\times10^3\times(-50\times10^{-6})}{0.3} = 33.33 \text{ MPa}$$

and
$$\varepsilon_x = \frac{\sigma_x}{E} = 166.67\times10^{-6}$$

From (iii), we get

$$166.67 \times 10^{-6} = \frac{4P\cos\beta}{200\times10^3\times\pi(60)^2}$$

$$\Rightarrow \quad P\cos\beta = 94247.78 \text{ N} \quad \text{...(iv)}$$

From (i), substituting value of ε_x

$$166.67 \times 10^{-6} + \sqrt{3}\gamma_{xy} = -490 \times 10^{-6}$$

$$\gamma_{xy} = -379.13 \times 10^{-6}$$

Substituting γ_{xy} in equation (ii)

$$-379.13 \times 10^{-6} = \frac{-16P\sin\beta}{3\pi(60)^2}\left[\frac{2\times1.3}{200\times10^3}\right]$$

$$P\sin\beta = 61843.582 \text{ N} \quad \text{...(v)}$$

Now, by (v) ÷ (iv), we get

$$\tan\beta = 0.656$$

$$\beta = 33.27° \quad \textbf{Ans.}$$

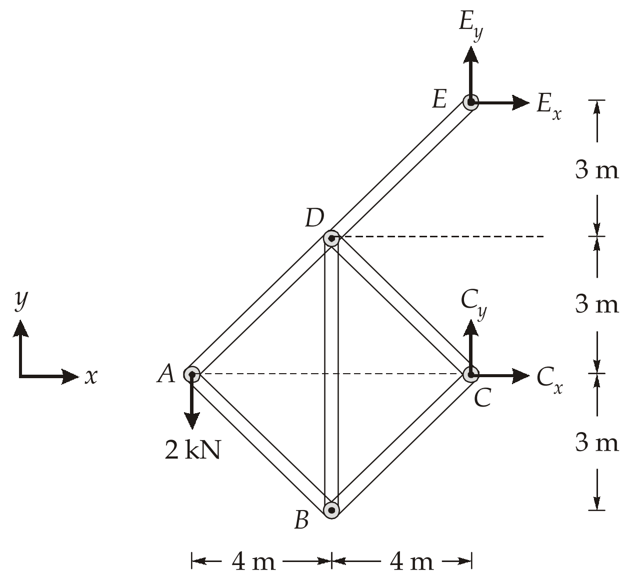
Using equation (v),

$$P \times (\sin 33.27°) = 61843.582$$

$$\Rightarrow \quad P = 112726.886 \text{ N}$$

$$\text{or} \quad P = 112.727 \text{ kN} \quad \textbf{Ans.}$$

2. (c) Solution:



Support reaction:

Applying the equations of equilibrium,

$$\Sigma F_x = 0 \quad \text{[As no external force in } x \text{ direction]}$$

$\Rightarrow$ $$E_x + C_x = 0$$

$$\Sigma M_C = 0$$

$\Rightarrow$ $$6E_x = 8 \times 2$$

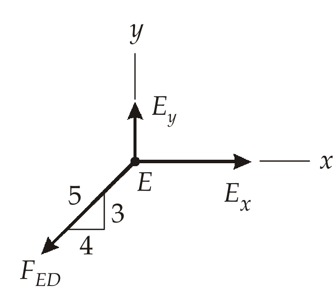
$\Rightarrow$ $$E_x = 2.67 \text{ kN}$$

$\therefore$ $$C_x = -E_x = -2.67 \text{ kN}$$

$$\Sigma F_y = 0$$

$\Rightarrow$ $$E_y + C_y = 2 \quad \text{...(i)}$$

Joint E : F_{ED} is assumed to be tensile.



$$\Sigma F_x = 0$$

$\Rightarrow$ $$E_x - \frac{4}{5}F_{ED} = 0$$

$\Rightarrow$ $$2.67 - \frac{4}{5}F_{ED} = 0$$

$\Rightarrow$ $$F_{ED} = +3.33 \text{ kN}$$

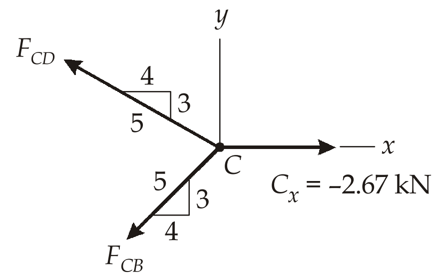
$$\Sigma F_y = 0$$

$\Rightarrow$ $$E_y = \frac{3}{5}F_{ED} = +2 \text{ kN}$$

From equation (i), we get

$$C_y = 0$$

Joint *C* : F_{CD} and F_{CB} are assumed to be tensile in *FBD*.



$$\Sigma F_x = 0$$

$$\Rightarrow \quad -2.67 - \frac{4}{5}(F_{CD} + F_{CB}) = 0$$

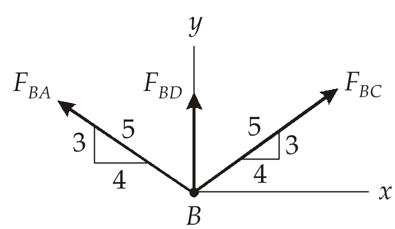
$$\Rightarrow \quad F_{CD} + F_{CB} = -3.33 \text{ kN}$$

$$\Sigma F_y = 0$$

$$\Rightarrow \quad \frac{3}{5}F_{CD} - \frac{3}{5}F_{CB} = 0$$

$$\Rightarrow \quad F_{CD} = F_{CB} = -1.67 \text{ kN}$$

Joint *B* :



$$\Sigma F_x = 0$$

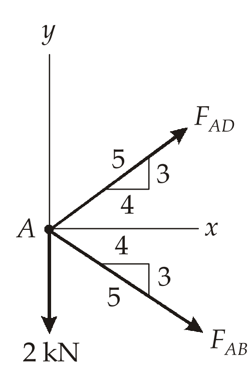
$$\Rightarrow \quad F_{BC} = F_{BA} = -1.67 \text{ kN}$$

$$\Sigma F_y = 0$$

$$\Rightarrow \quad \frac{3}{5}(F_{BA} + F_{BC}) + F_{BD} = 0$$

$$\Rightarrow \quad F_{BD} = 2 \text{ kN}$$

Joint *A* :



$$\Sigma F_x = 0$$

$$\Rightarrow \quad F_{AD} = -F_{AB}$$

$$F_{AD} = 1.67 \text{ kN}$$

Since we assumed all members in tension, hence negative sign indicates opposite sense.

Therefore,
$$F_{AB} = 1.67 \text{ kN (Compression)}$$
$$F_{BC} = 1.67 \text{ kN (Compression)}$$
$$F_{CD} = 1.67 \text{ kN (Compression)}$$
$$F_{AD} = 1.67 \text{ kN (Tension)}$$
$$F_{BD} = 2 \text{ kN (Tension)}$$
$$F_{DE} = 3.33 \text{ kN (Tension)}$$

3. (a) Solution:

Given: $m = 40$ kg, $h = 1.2$ m, $A = 45$ mm^2, $E = 150$ GPa; $W = mg = 392.4$ N

$$\text{Static stress, } \sigma_{st} = \frac{W}{A} = \frac{392.4}{45} = 8.72 \text{ MPa}$$

(i) Let, σ = Maximum stress developed in the cable.

$$\therefore \quad \text{The axial extension, } \delta = \frac{\sigma L}{E}$$

$$\text{Workdone by falling mass} = mg(h + \delta)$$

$$\text{Strain energy stored in the cable} = \frac{\sigma^2}{2E}(AL)$$

Using energy balance,

$$mg(h + \delta) = \frac{\sigma^2}{2E}(AL)$$

$$mg\left[h + \frac{\sigma L}{E}\right] = \frac{\sigma^2}{2E}[A \times L]$$

$$\Rightarrow \quad \sigma^2 - \frac{2mg}{A}\sigma - \frac{2mgEh}{AL} = 0$$

For tensile stress,

$$\sigma = \frac{mg}{A} \pm \sqrt{\left(\frac{mg}{A}\right)^2 + \frac{2mgEh}{AL}}$$

$$\Rightarrow \qquad \sigma_{max} = \frac{mg}{A}\left[1+\sqrt{1+\frac{2Eh}{L}\frac{A}{mg}}\right]$$

or
$$\sigma_{max} = \sigma_{st}\left[1+\sqrt{1+\frac{2Eh}{L\sigma_{st}}}\right] \qquad \left\{\because \sigma_{st} = \frac{mg}{A}\right\}$$

(ii)
$$\sigma_{max} = \sigma_{allowable} = 450 \text{ MPa}$$

We have

$$\sigma_{max} = \sigma_{st}\left[1+\sqrt{1+\frac{2Eh}{L\sigma_{st}}}\right]$$

or
$$\frac{\sigma_{max}}{\sigma_{st}} - 1 = \sqrt{1+\frac{2Eh}{L\sigma_{st}}}$$

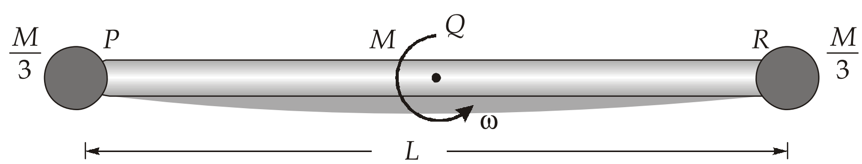
or
$$\left(\frac{\sigma_{max}}{\sigma_{st}} - 1\right)^2 = \left(1+\frac{2Eh}{L\sigma_{st}}\right)$$

For minimum length, substituting the numerical values

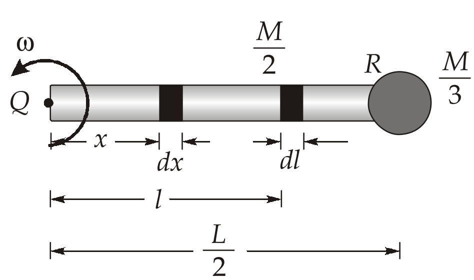
$$\left(\frac{450}{8.72} - 1\right)^2 = 1+\frac{2\times 150\times 10^3\times 1.2}{L_{min}\times 8.72}$$

$$\Rightarrow \qquad L_{min} = 16.13 \text{ m}$$ **Ans.**

3. (b) Solution:



Free body diagram of QR



$$A = \frac{\pi}{4}d^2$$

Let, $F(x)$ = axial force in the bar at distance x

$\because$ $F(x)$ contains centrifugal force due to mass of the bar from x to $\frac{L}{2}$ and the point mass at R.

Taking a element at distance l of the length dl.

$$\text{Mass of element, } dm = \frac{(M/2)}{(L/2)}dl$$

$$\text{Acceleration of element} = l\omega^2$$

Centrifugal force produced by element

$$dF(x)_1 = dm\,(\text{acceleration})$$

$$= \frac{M}{L}dl \cdot l\omega^2$$

Total centrifugal force due to mass of the bar from x to $\frac{L}{2}$.

$$F(x)_1 = \int_x^{L/2} \frac{M}{L}\omega^2 l\,dl = \frac{M\omega^2}{2L}\left(\frac{L^2}{4} - x^2\right)$$

And the centrifugal force due to point mass at end

$$F(x)_2 = \frac{M}{3}\left(\frac{L}{2}\right)\omega^2 = \frac{ML}{6}\omega^2$$

$\therefore$ Total centrifugal force on the element dx at x.

$$F(x) = F(x)_1 + F(x)_2$$

$$F(x) = \frac{M\omega^2}{2L}\left(\frac{L^2}{4} - x^2 + \frac{L^2}{3}\right)$$

Elongation of element dx

$$\delta_x = \frac{F(x)dx}{AE}$$

$$\text{Total elongation of QR, } \delta = \int_0^{L/2} \frac{F(x)dx}{AE} = \frac{M\omega^2}{2LAE}\int_0^{L/2}\left(\frac{L^2}{4} - x^2 + \frac{L^2}{3}\right)dx$$

$$= \frac{M\omega^2}{2LAE}\left(\frac{7L^2}{12}x - \frac{x^3}{3}\right)_0^{L/2} = \frac{M\omega^2 L^2}{8AE}$$

$$\Rightarrow \quad \delta = \frac{M\omega^2 L^2}{2\pi d^2 E}$$

Therefore, total elongation of the bar = 2δ

$$= \frac{M\omega^2 L^2}{\pi d^2 E}$$ **Ans.**

3. (c) Solution:

Given : r = 250 mm; t = 20 mm

$$\frac{d}{t} = 25 > 20 \quad \text{(Thin pressure vessel)}$$

$$p = 3 \text{ MPa}; T = 100 \text{ kNm}$$

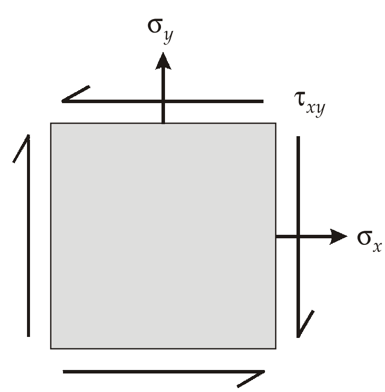
$$J = 2\,\pi r^3 t$$

(i)

$$\sigma_x = \frac{pr}{2t} = \frac{3 \times 250}{2 \times 20} = 18.75 \text{ MPa}$$

$$\sigma_y = 2\sigma_x = 37.5 \text{ MPa}$$

As $\sigma_x = \sigma_{longitudinal}$; $\sigma_y = \sigma_{hoop} = \frac{pr}{t}$



$$\tau_{xy} = \frac{Tr}{J} = \frac{T}{2\pi r^2 t} = \frac{100 \times 10^6}{2\pi \times 250^2 \times 20}$$

$$= 12.73 \text{ MPa}$$

Principal stresses and maximum shear stress

$$\sigma_1 = \frac{\sigma_x + \sigma_y}{2} + \sqrt{\left(\frac{\sigma_x - \sigma_y}{2}\right)^2 + \left(\tau_{xy}\right)^2}$$

$$= \frac{18.75 + 37.5}{2} + \sqrt{\left(\frac{18.75 - 37.5}{2}\right)^2 + (12.73)^2}$$

$$= 43.94 \text{ MPa}$$

$$\sigma_2 = \left(\frac{18.75+37.5}{2}\right) - \sqrt{\left(\frac{18.75-37.5}{2}\right)^2 + (12.73)^2}$$

$$= 12.31 \text{ MPa}$$

$$\therefore \quad \tau_{max} = \sqrt{\left(\frac{\sigma_x - \sigma_y}{2}\right)^2 + \left(\tau_{xy}\right)^2} = 15.81 \text{ MPa}$$

$$\therefore \quad (\sigma_{max})_t = 43.94 \text{ MPa}, (\sigma_{max})_c = 0, (\tau_{max})_{in\text{-}plane} = 15.81 \text{ MPa}$$

(ii) $T = 150$ kNm, $P = 3$ MPa, $\sigma_a = 50$ MPa, $\tau_a = 20$ MPa

$$\sigma_x = \frac{Pr}{2t} = \frac{375}{t}, \ \sigma_y = 2\sigma_x = \frac{750}{t} \qquad \text{[Here, 't' is in mm]}$$

$$\tau_{xy} = \frac{T.r}{2\pi r^3 t} = \frac{150 \times 10^6}{2\pi \times (250)^2 t} = \frac{381.972}{t}$$

$$\sigma_1 = \frac{562.5}{t} + \sqrt{\left(\frac{375}{2t}\right)^2 + \left(\frac{382}{t}\right)^2} = (\sigma_a = 50)$$

$$\Rightarrow \quad t = 19.76 \text{ mm}$$

$$\tau_{max} = \sqrt{\left(\frac{375}{2t}\right)^2 + \left(\frac{382}{t}\right)^2}$$

$$\Rightarrow \quad 20 = \sqrt{\left(\frac{375}{2t}\right)^2 + \left(\frac{382}{t}\right)^2}$$

$$\Rightarrow \quad t = 21.28 \text{ mm}$$

$\therefore$ Minimum required wall thickness = Maximum of (19.76, 21.28)

$$\Rightarrow \quad t_{min} = 21.28 \text{ mm}$$ **Ans.**

4. (a) Solution:

Given : $D = 16$ mm; $\alpha = 11 \times 10^{-6}$/°C; $E = 200$ GPa; $d = 10$ mm

(i) $\tau_{bolt} = 50$ MPa

Temperature drop results in tensile stress in rod and shearing stress in bolt.

Normal stress in the rod, $\sigma = E\alpha\Delta T$ [This is only thermal stress]

Tensile force in the rod, $P = \sigma(\text{Area})$

$$\Rightarrow \quad P = (E\alpha\Delta T)\left(\frac{\pi}{4}D^2\right)$$

$\therefore$ Bolt in double shear with shear stress,

$$\tau = \frac{\left(\frac{P}{2}\right)}{\frac{\pi}{4}d^2} = \frac{E\alpha\Delta T}{2}\left(\frac{D}{d}\right)^2$$

$$\Rightarrow \quad \tau = \frac{200\times10^3\times11\times10^{-6}\times\Delta T}{2}\left(\frac{16}{10}\right)^2 = 50 \text{ MPa}$$

$\Rightarrow$ ΔT = 17.75°C [Decrease in the temperature] **Ans.**

Normal tensile stress in the rod,

$$\sigma_{rod} = E\alpha\Delta T = 200 \times 10^3 \times 11 \times 10^{-6} \times 17.75$$

$$\Rightarrow \quad \sigma_{rod} = 39.0625 \text{ MPa}$$

(ii) For connection at B, ΔT =40°C

Bolts with diameter d_b will be subjected to tensile stress due to temperature drop.

$$\sigma_{allowable} = 80 \text{ MPa}$$

Force in rod due to temperature drop,

$$P = (E\alpha\Delta T)\left(\frac{\pi}{4}D^2\right) = \left(200\times10^3\times11\times10^{-6}\times40\right)\left(\frac{\pi}{4}\times16^2\right)$$

$$\Rightarrow \quad P = 17.693 \text{ kN}$$

Each bolt carries half of the load due to force P,

$$\Rightarrow \quad \frac{17.693\times10^3}{2} = \sigma_{allowable}\times\frac{\pi}{4}\times d_b^2$$

$$\Rightarrow \quad d_b = \sqrt{\frac{17.693\times10^3\times4}{2\times\pi\times80}}$$

$\Rightarrow$ d_b = 11.87 mm **Ans.**

4. (b) Solution:

Given : σ_x = 28 MPa, σ_y = –14 MPa, τ_{xy} = –10 MPa

Maximum Shear Stresses:

$$\tau_{max} = \sqrt{\left(\frac{\sigma_x-\sigma_y}{2}\right)^2+\tau_{xy}^2} = \sqrt{(21)^2+(10)^2}$$

$$\Rightarrow \quad \tau_{max} = 23.26 \text{ MPa}$$

$$\tan 2\theta_P = \left(\frac{2\tau_{xy}}{\sigma_x-\sigma_y}\right)$$

$$2\theta_P = \tan^{-1}\left(\frac{2\tau_{xy}}{\sigma_x - \sigma_y}\right) = \tan^{-1}\left(\frac{-20}{42}\right)$$

$$\theta_{P_1} = -12.73° \qquad \theta_P = \text{Principal plane angle}$$

$$\theta_{P_2} = -12.73° + 90° = 77.27° \qquad [\because \theta_{P_2} = \theta_{P_1} + 90°]$$

For $\theta_{s_1} = \theta_{P_1} - 45° = -57.73°$

$$\sigma_{n_1} = \frac{\sigma_x + \sigma_y}{2} + \frac{\sigma_x - \sigma_y}{2}\cos(2\theta_{s_1}) + \tau_{xy}\sin(2\theta_{s_1})$$

$$= \frac{14}{2} + \frac{42}{2}\cos(-115.46) - 10\sin(-115.46)$$

$$= 7 \text{ MPa}$$

$$\tau_1 = -\left(\frac{\sigma_x - \sigma_y}{2}\right)\sin(2\theta_{s_1}) + \tau_{xy}\cos(2\theta_{s_1}) = 14.66 \text{ MPa}$$

For $\theta_{s_2} = \theta_{P_2} - 45° = 32.27°$

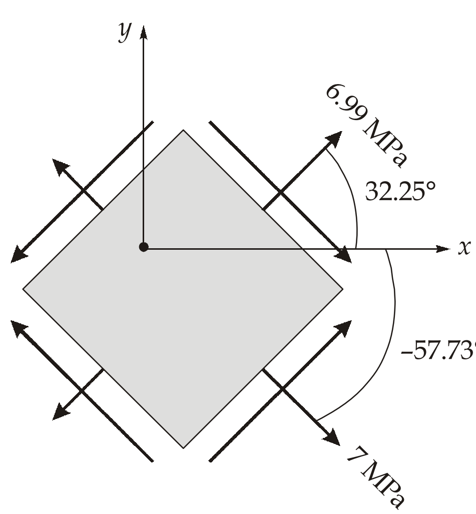
$$\sigma_{n_2} = \frac{\sigma_x + \sigma_y}{2} + \frac{\sigma_x - \sigma_y}{2}\cos(2\theta_{s_2}) + \tau_{xy}\sin(2\theta_{s_2})$$

$$= 7 + 21\cos(64.54) + (-10)\sin(64.54) = 6.99 \text{ MPa}$$

Hence, $\tau_{max} = 14.66$ MPa

$$\theta_{s_1} = -57.73°, \ \sigma_{n_1} = 7 \text{ MPa}$$

$$\theta_{s_2} = 32.27°, \ \sigma_{n_2} = 6.99 \text{ MPa}$$



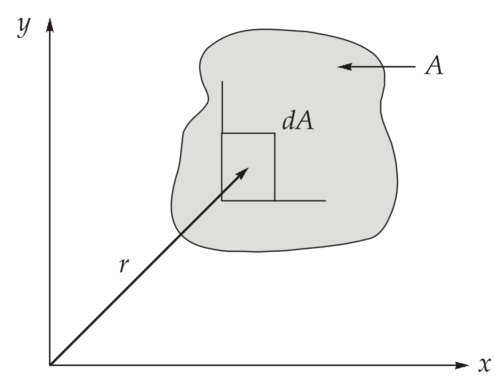
4. **(c) (i) Solution:**

1. **Centre of gravity:** A body is composed of an infinite number of particles of differential size, and so if the body is located within a gravitational field, then each of these particles will have a weight dw. These weights will form an approximately parallel force system, and the resultant of this system is the total weight of the body, which passes through a single point called the centre of gravity. This concept is applicable for all 2D and 3D bodies.

   Centre of mass: The centre of mass of a body is a point at which the entire mass of a body is concentrated. It is the point such that the first moment of geometric object about every line which is passing through the point is zero. In general for symmetric body both COG and COM are same.

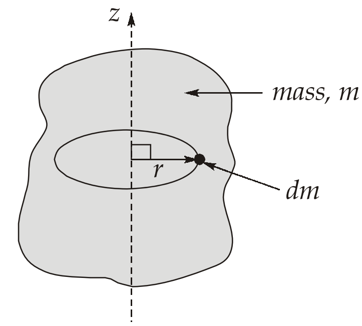
   Centroid: The centroid of a body is the geometric centre of its volume, i.e., the point at which the entire volume of the body may be assumed to be concentrated.

2. **Area Moment of Inertia:** The area moment of inertia of a plane area about an axis is defined as the integral of the distance of each elemental area from that axis over the entire area. This will define that how the area of a body is distributed about any axis. Its S.I. unit is m^4.



$$I_0 = \int_A r^2 dA$$

Mass moment of inertia: The mass moment of inertia of a body is a measure of body's resistance to angular acceleration. This also indicates that how the complete mass is distributed with respect to that particular axis, about which we are calculating the mass moment of inertia. Its S.I. unit is kg-m^2.



$$I = \int_m r^2 dm$$

3. **Radius of gyration of an area:** The radius of gyration of an area about a given axis is defined as the distance from that axis at which the entire area may be assumed to be concentrated without altering the value of the area moment of inertia about that axis.

$$k = \sqrt{\frac{I}{A}}$$

where, I = Area moment of inertia about the given axis, A = Total area of section

S.I. unit of radius of gyration is meter (m).

4. **(c) (ii) Solution:**

Given : $m_{boy} = 80$ kg, $m_A = m_B = 40$ kg, $V_{boy} = 4$ m/s, $\theta = 36°$

Since there is no force acting in horizontal direction. So Conservation of momentum in x-direction: [At cart A]

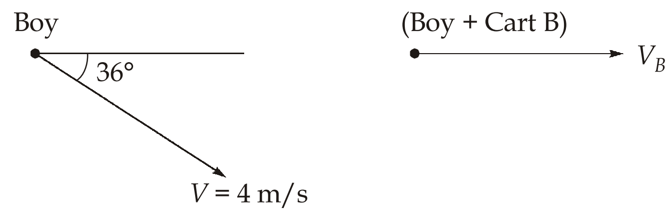
$$m_A(-V_A) + m_{Boy}(-V_x)_{boy} = 0 \text{ \{Since initially both at rest\}}$$

$$\Rightarrow \quad 40 \times V_A = 80 \times 4 \times \cos 36°$$

$$\Rightarrow \quad V_A = 6.47 \text{ m/s}$$

Hence, cart A moves in opposite direction of boy with 6.47 m/s of velocity.

Now, just before and after he lands at cart B.



Before **After**

Using, conservation of momentum in horizontal direction. [At cart B]

$$(mv)_i = (mv)_f$$

$$\Rightarrow \quad 80 \times 4 \times \cos(36°) = (80 + 40) \times V_B$$

$$\Rightarrow \quad V_B = 2.157 \text{ m/s}$$

Section B : Thermodynamics-1 + IC Engine-1 + Refrigeration & Air-conditioning-1

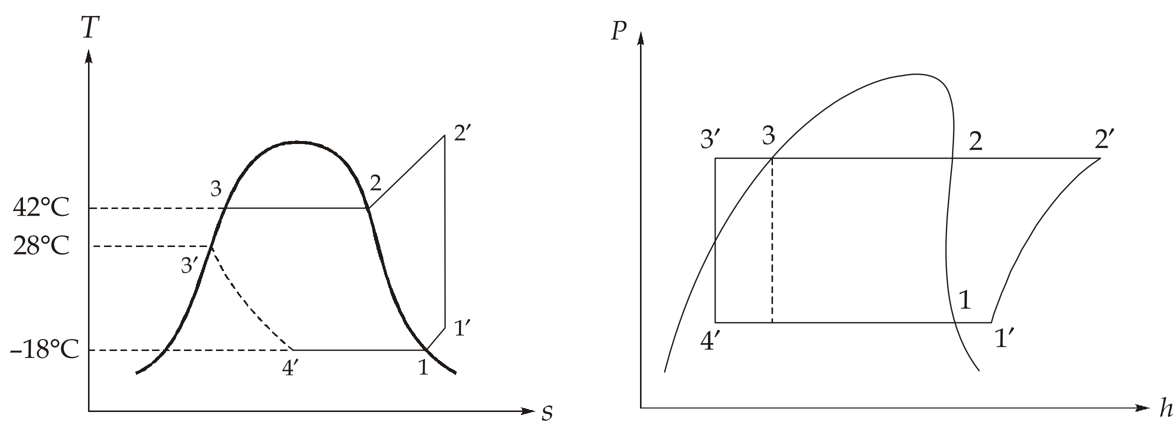
5. (a) Solution:

Given data : $T_2 = T_3 = 42°C = 42 + 273 = 315$ K

$$T_1 = T_{4'} = -18°C = -18 + 273 = 255 \text{ K}$$

$$T_{3'} = 28°C = 28 + 273 = 301 \text{ K}$$

$$RC = 10 \text{ kW}$$



From table,

$$v_1 = 0.0864 \text{ m}^3/\text{kg}; \quad v_2 = 0.0144 \text{ m}^3/\text{kg}$$

$$h_1 = 398.37 \text{ kg}; \quad h_3 = (h_f)_{\text{at } 42°C} = 251.68 \text{ kJ/kg}$$

$$s_{f1} = 0.9226 \text{ kJ/kgK}; \quad s_2 = (s_g)_{\text{at } 42°C} = 1.696 \text{ kJ/kgK}$$

$$s_{fg1} = 0.8580 \text{ kJ/kgK}; \quad h_{3'} = (h_f)_{\text{at } 28°C} = 233.81 \text{ kJ/kgK}$$

$$s_1 = (s_{g1})_{at-18°C} = 1.7806 \text{ kJ/kgK}; h_2 = (h_g)_{at\,42°C} = 416.21 \text{ kJ/kgK}$$

Heat lost by liquid refrigerant = Heat gained by vapour refrigerant

$$h_{f3} - h_{f3'} = h_{1'} - h_1$$

$$251.68 - 233.8 = h_{1'} - 398.37$$

$$h_{1'} = 416.25 \text{ kJ/kg}$$

Let, $T_{1'}$ = Temperature of refrigerant leaving the heat exchanger

$$c_{p_v}(T_{1'} - T_1) = h_{1'} - h_1$$

$$1.03 \times (T_{1'} - T_1) = 416.25 - 398.37$$

$$T_{1'} = 272.35 \text{ K} = 272.35 - 273 = -0.64°\text{C}$$

Now,

$$s_{1'} = s_1 + c_{p_v} \ln\left[\frac{T_{1'}}{T_1}\right]$$

$$= 1.7806 + 1.03 \times \ln\left[\frac{272.35}{255}\right]$$

$$= 1.8484 \text{ kJ/kgK}$$

$$s_{2'} = s_2 + c_{p_v} \ln\left(\frac{T_{2'}}{T_2}\right)$$

$$= 1.6969 + 1.03 \times \ln\left(\frac{T_{2'}}{315}\right)$$

$\because$ $s_{1'} = s_{2'}$ [due to isentropic compression]

$$1.8484 = 1.6969 + 1.03 \ln\left[\frac{T_{2'}}{315}\right]$$

$$T_{2'} = 364.92 \text{ K}$$

Now,

$$h_{2'} = h_2 + c_{p_v}(T_{2'} - T_2)$$

$$= 416.21 + 1.03 \times (364.92 - 315)$$

$$= 467.63 \text{ kJ/kg}$$

Now, Refrigeration effect $= h_1 - h_{4'} = h_1 - h_{3'}$

$$\text{RE} = 398.37 - 233.81$$

$$= 164.56 \text{ kJ/kg}$$

$$\text{Mass flow rate of refrigerant} = \frac{RC}{RE}$$

$$\dot{m}_r = \frac{10}{164.56} = 0.0607 \text{ kg/s or } 3.64 \text{ kg/min}$$

$$\text{Power required} = \dot{m}_r\left(h_{2'} - h_{1'}\right)$$

$$P = 0.0607 \times [467.63 - 416.25]$$

$$P_{in} = 3.118 \text{ kW}$$ **Ans.**

$$\text{Coefficient of performance, COP} = \frac{RC}{P_{in}} = \frac{10}{3.118} = 3.206$$ **Ans.**

5. (b) Solution:

Scavenging:

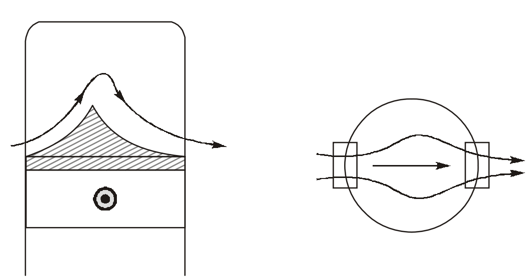
- The operation of clearing the exhaust gases from the cylinder and filling it more or less completely with fresh-charge is called scavenging.
- The fresh charge is supplied to engine cylinder at a high enough pressure to displace the burned gases from the previous cycle.
- The process of scavenging includes both intake and exhaust processes.
- Scavenging process takes place during the overlapping period of valves or ports.

Methods of scavenging or Scavenging arrangements

1. Return flow scavenging
   - Applicable to single-piston engines.
   - In return-flow scavenging the scavenge air is directed towards the other end of the cylinder by a slant of the inlet-ports or by shape of the piston head or by both and then the air is returned to the piston-head pushing the burned gases out through exhaust-ports.

Types of return-flow Scavenging arrangements

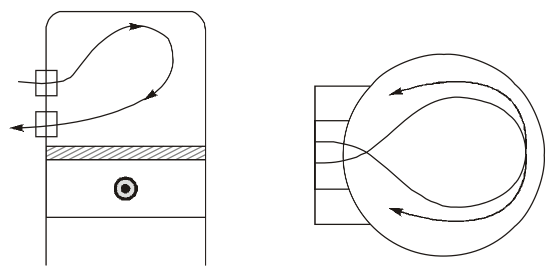
(a) Cross flow scavenging:



Front-view **Top-view**

- Simplest scavenging process
- Least efficient
- Requires piston with shaped crown
- Odd shaped deflector piston has the advantage of heat stressing unevenly which makes it liable to distortions.
- In this process there is change of short-circuiting the charge and may not able to adequately displace exhaust gases.

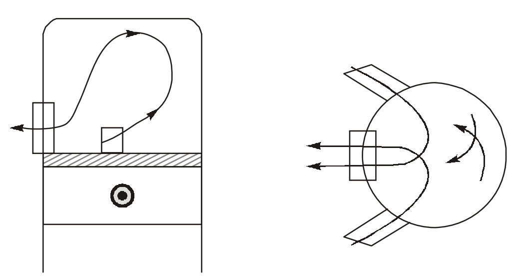
(b) Full-loop-scavenging [MAN type]



Side-view Top-view

- Loop-scavenged system in its various forms is designed to direct the incoming charge by means of inclined and aimed ports in such a way that both charge loss and mixing are minimized.
- No piston deflector is required in loop-scavenged system.
- In MAN-loop scavenge system the entry ports are located immediately above the exhaust-ports.

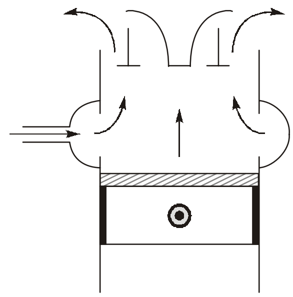
(c) Tangential loop-scavenging [Schnuerle type]



Side-view Top-view

- Schnuerle-loop scavenging system consists of two or more transfer ports generally.
- The flow of charge is directed tangentially and upwards.
- The location of transfer ports are at sides instead of directly opposite to exhaust ports.

2. Uniflow-scavenging



- Fresh-charge admits from one end of the cylinder and exhausting the burned gases from the other end gives a straight flow called uniflow-scavenging.
- This is the best from the viewpoint of thoroughly-purging the cylinder of its exhaust content.
- The straight flow reduces turbulence and hence the mixing of the fresh charge with burned gases.

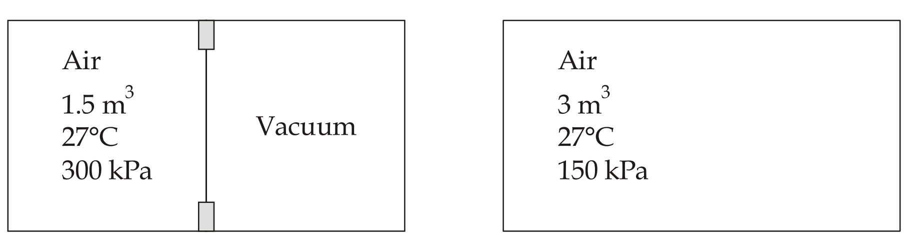
5. (c) Solution:

Free Expansion: It is a thermodynamic process in which gas expands into vacuum without any opposing pressure.

- Highly irreversible process.
- $T_{\text{initial}} = T_{\text{Final}}$ i.e. $\Delta T = 0$, even though process is not isothermal.
- Work done by gas undergoing free expansion is Zero

$$W = \int \cancelto{0}{P_{ext}}\, dV = 0 \,; \quad (\because \text{ No resistance offered by vacuum i.e. } P_{ext} = 0)$$

Initial State **Final State**



Process assumptions:

1. Rigid and perfectly thermally insulated container.
2. Initial and final states are steady.
3. There is no work done in breaking the membrane.
4. Initial and final kinetic energies and potential energies of system are same.
5. There is no chemical changes in the content of air during the process.

From 1st law

$$\underset{0\text{ (Insulated)}}{\cancel{Q}} = \Delta U + \underset{0\text{ (Free expansion)}}{\cancel{W}}$$

$\Rightarrow$ $$\Delta U = 0$$

Considering air as an ideal gas

$$U = f(T)\text{ only}$$

$\Rightarrow$ $$\Delta T = 0 \text{ for ideal gas undergoing free expansion}$$

$\Rightarrow$ $$T_1 = T_2$$

$\Rightarrow$ $$P_1V_1 = P_2V_2$$

$\Rightarrow$ $$P_2 = \frac{P_1V_1}{V_2} = \frac{300\times 1.5}{3} = 150\text{ kPa}$$

From "Gouy-Stodola" Theorem

$$I = T_0 \cdot s_{gen}$$

$$= T_o\left[s_{gen,sys} + \overset{0}{\cancel{s}}_{gen,surr}\right] = T_0\left[m\left(c_p \ln\frac{T_2}{T_1} - R\ln\frac{P_2}{P_1}\right)\right]$$

$$= T_0\left(\frac{P_1V_1}{RT_1}\right)\left(R\ln\frac{P_1}{P_2}\right); \quad \{T_1 = T_2 = T_o = 27°\text{C} = 300\text{ K}\}$$

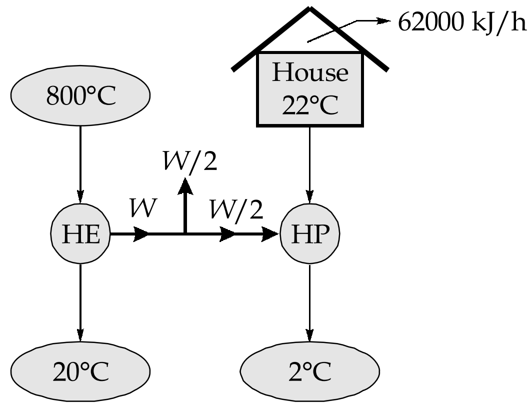
$$I = P_1V_1\ln\frac{P_1}{P_2}$$

Isothermal work potential is lost during process.

$$I = 300\times 1.5\times \ln\left(\frac{300}{150}\right) = 450\ln(2)\text{ kJ}$$

$$I = 311.91\text{ kJ}$$

5. (d) Solution:



$$\text{COP of Carnot heat pump} = \frac{1}{1-\frac{T_L}{T_H}}$$

$$\text{Lower temperature, } T_L = 2 + 273 = 275 \text{ K}$$

$$\text{Higher temperature, } T_H = 22 + 273 = 295 \text{ K}$$

$$(\text{COP})_{\text{HP}} = \frac{1}{1-\frac{275}{295}} = 14.75$$

Power input to the heat pump,

$$W_{\text{input}} = \frac{\text{Heating rate}}{(\text{COP})_{HP}}$$

$$= \frac{62000}{14.75} = 4203.34 \text{ kJ/h}$$

$(W_{\text{input}})_{\text{HP}}$ = Half the power produced by the heat engine

$$(W_{\text{NET}})_{\text{HE}} = 2 \times W_{\text{input}} = 2 \times 4203.34 = 8406.68 \text{ kJ/h}$$

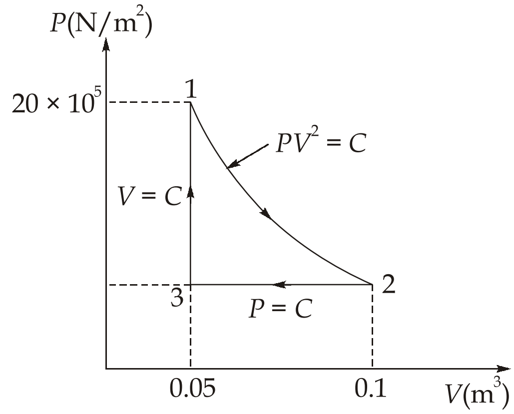
Thermal efficiency of Carnot heat engine,

$$\eta_{\text{th}} = 1-\frac{T_L}{T_H} = 1-\frac{293}{1073} = 0.727$$

Rate of heat supply to heat engine can be determined as

$$Q = \frac{8406.68}{0.727} = 11563.5 \text{ kJ/h}$$

5. (e) Solution:



$$\text{Mass of fluid, } m = 1 \text{ kg}$$

$$P_1 = 20 \text{ bar} = 20 \times 10^5 \text{ N/m}^2$$

$$V_1 = 0.05 \text{ m}^3$$

Considering the process 1-2:

$$P_1V_1^2 = P_2V_2^2 = C$$

$$\Rightarrow \quad P_2 = P_1\left(\frac{V_1}{V_2}\right)^2 = 20\times\left(\frac{0.05}{0.1}\right)^2 = 5 \text{ bar}$$

Work done by the fluid in process 1-2 :

$$W_{1\text{-}2} = \int_1^2 PdV = \int_{V_1}^{V_2} \frac{C}{V^2}dV = C\left[\frac{1}{V_1}-\frac{1}{V_2}\right]$$

$$= P_1V_1^2\left[\frac{1}{V_1}-\frac{1}{V_2}\right]$$

$$= 20\times10^5\times(0.05)^2\times\left[\frac{1}{0.05}-\frac{1}{0.1}\right] = 50000 \text{ J}$$

Work done on fluid in process 2-3:

$$W_{2\text{-}3} = P_2(V_3 - V_2) = 5\times10^5\times(0.05-0.1)$$

$$= -25000 \text{ J}$$

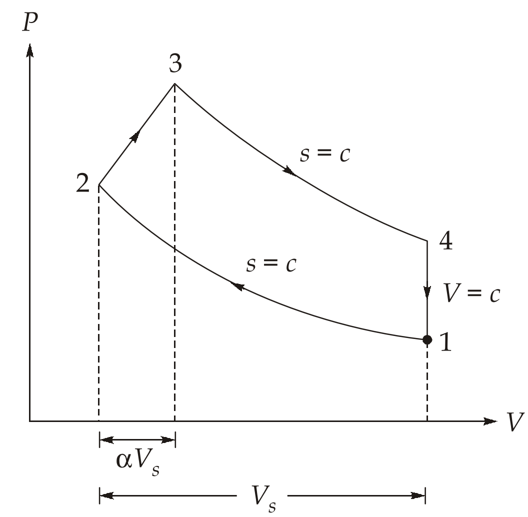
Work done during process 3-1: $W_{3\text{-}1} = 0$

$$\therefore \text{ Net work done by the fluid} = W_{1\text{-}2} + W_{2\text{-}3} + W_{3\text{-}1}$$

$$= 50000 - 25000 + 0 = 25000 \text{ J}$$

6. (a) Solution:

Given data : Stroke volume = V_s; Compression ratio = r



$$(P_1, V_1, T_1) = (P, V, T)$$

$$P_3 = KP$$

$$V_3 = V_2 + \alpha V_s$$

$$\left(\frac{F}{A}\right)_{ratio} = \frac{M_f}{M_a} = M$$

Calorific value of fuel = C.V.

Characteristic gas constant of working fluid = R

Specific heat ratio of working fluid = γ

Heat lost per kg of charge during combustion

$$= \left[(\text{Heat liberated}) - (\text{Heat utilised})\right] \text{ per kg charge}$$

$$= \frac{m_f \times C.V. - Q_{2\to3}}{\text{Mixture-mass (m)}}$$

$$= \frac{\frac{mM}{M+1}(C.V.) - \left[\Delta U_{2\to3} + W_{2\to3}\right]}{m}$$

$$\left\{\because \frac{m_f}{m_a} = M \Rightarrow \frac{m_a}{m_f} + 1 = \left(\frac{1}{M} + 1\right) \Rightarrow \frac{m}{m_f} = \left(\frac{M+1}{M}\right) \Rightarrow m_f = \frac{mM}{M+1}\right\}$$

where; m = Mixture mass

$$m = \frac{PV}{RT}$$

Heat lost per kg of charge during combustion

$$= \frac{M}{M+1}(CV) - \left[\underset{2\to3}{\Delta u} + \underset{2\to3}{\Delta w}\right] \quad \text{...(i)}$$

$$\underset{2\to3}{\Delta u} = C_v(T_3 - T_2) = \frac{R}{\gamma - 1}(T_3 - T_2) \quad \text{...(ii)}$$

$$\underset{2\to3}{\Delta w} = \left(\frac{1}{m}\right)\left[\left(\frac{P_2 + P_3}{2}\right)(\alpha V_s)\right] \quad \text{...(iii)}$$

$$V_s = V_1 - V_2 = V - \frac{V}{r} = V\left(1 - \frac{1}{r}\right)$$

Process 1 $\rightarrow$ 2 : Isentropic compression

$$\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}} = \left(\frac{V_1}{V_2}\right)^{\gamma-1}$$

$$r = \frac{V_1}{V_2} \Rightarrow V_2 = \frac{V_1}{r} = \frac{V}{r} \quad \text{...(iv)}$$

$$T_2 = T_1\left(\frac{V_1}{V_2}\right)^{\gamma-1} = Tr^{\gamma-1} \quad \text{...(v)}$$

$$P_2 = P_1\left(\frac{V_1}{V_2}\right)^{\gamma} = Pr^{\gamma} \quad \text{...(vi)}$$

$$V_3 = V_2 + \alpha V_s = \frac{V}{r} + \alpha V\left(1 - \frac{1}{r}\right) = V\left[\alpha + \frac{1-\alpha}{r}\right] \quad \text{...(vii)}$$

$$P_3 = KP \quad \text{...(viii)}$$

Using equation of states between 2 and 3

$$\frac{P_3 V_3}{T_3} = \frac{P_2 V_2}{T_2}$$

$$T_3 = \left[\frac{P_3 V_3}{P_2 V_2}\right]T_2 = \frac{(KP)V\left[\alpha + \frac{1-\alpha}{r}\right]}{(\Pr^{\gamma})\frac{V}{r}}\left(Tr^{\gamma-1}\right)$$

$$= K\left[\alpha + \frac{1-\alpha}{r}\right]T \quad \text{...(ix)}$$

Putting these values in equation (i)

Heat lost per kg of charge during combustion

$$= \left[\frac{M}{M+1}\right](C.V.) - \left[\frac{R}{\gamma-1}(T_3 - T_2) + \frac{1}{m}\left(\frac{P_2 + P_3}{2}\right)(\alpha V_s)\right]$$

$$= \left[\frac{M}{M+1}\right](C.V.) - \left[\frac{R}{\gamma-1}\left\{K\left(\alpha + \frac{1-\alpha}{r}\right)T - r^{\gamma-1}.T\right\} + \frac{RT}{PV}\left[\frac{\text{Pr}^{\gamma} + KP}{2}\right](\alpha V)\left(1 - \frac{1}{r}\right)\right]$$

$$= \left[\frac{M}{M+1}\right](C.V.) - RT\left[\frac{1}{\gamma-1}\left\{K\left(\alpha + \frac{1-\alpha}{r}\right) - r^{\gamma-1}\right\} + \left[\frac{\text{r}^{\gamma} + K}{2}\right](\alpha)\left(1 - \frac{1}{r}\right)\right] \quad \textbf{Ans.}$$

6. (b) (i) Solution:

The refrigerants may, broadly classified into the following two groups:

(1) Primary refrigerants

(2) Secondary refrigerants

The refrigerants which directly take part in the refrigeration system are called primary refrigerants whereas the refrigerants which are first cooled by primary refrigerants and then used for cooling purposes are known as secondary refrigerants.

The primary refrigerants are further classified into four groups:

1. Halo-Carbon or Organic Refrigerant.
2. Azeotrope Refrigerant.
3. Inorganic Refrigerants
4. Hydro Carbon Refrigerants

Designation System for Refrigerants: The refrigerant nomenclature system is a standardized method developed by ASHRAE to designate refrigerant based on their chemical composition.

Refrigerants are designated by the letter R followed by a numerical code.

Eg. R-12, R-22, R-134a

For saturated halocarbon refrigerants *R-xyz*

$R - (m - 1)(n + 1)(P)$

where, m = Number of carbon atoms; n = Number of hydrogen atom;

P = Number fluorine atom

Number of chlorine atoms, $q = 2m + 2 - n - P$

Ex. R-12

$$m - 1 = 0; \quad m = 1$$
$$n + 1 = 1; \quad n = 0$$
$$P = 2$$
$$\Rightarrow \quad q = 2(1) + 2 - 0 - 2 = 2$$

Hence, R-12 is $CF_2\,Cl_2$

Unsaturated refrigerants

For refrigerants with double bonds, it is represent by R-1xyz, where prefix 1 indicates one double bond in molecule and $x = (m - 1)$, $y = (n + 1)$, $z = P$

Ex. R-1150

$$m - 1 = 1$$
$$\text{Number of carbon atom, } m = 2$$
$$n + 1 = 5$$
$$\text{Number of hydrogen atom, } n = 4$$
$$\text{Number of fluorine atom; } P = 0$$
$$\text{Number of chlorine atom, } q = 2m - n - P$$
$$q = 4 - 4 = 0$$
$$q = 0$$

Hence, R-1150 is C_2H_4

Inorganic refrigerants

These are designated as R-7xx, where

$$R - 7xx = 700 + \text{Molecular weight}$$

Ex. R-717 → Ammonia (NH_3)

R-718 → Water (H_2O)

6. **(b) (ii) Solution:**

Harmful Effect of R-12 Refrigerant: The earth's ozone layer in the upper atmosphere (stratosphere) is needed for the absorption of harmful ultraviolet rays from the sun. These UV rays can cause skin cancer. R-12 is dichlorodifluoromethane and comes under CFCs category of refrigerant. In 1985, as per scientific observations, it was found that there is a gaping hole above Antarctic in the ozone layer which protects earth from UV rays. R-12 refrigerant has been linked to the depletion of this ozone layer.

CFCs are having varying degrees of ozone depletion potential (ODP). In addition, they act as greenhouse gases. Hence, CFCs have global warming potential (GWP) as well. According to an international agreement (montreal protocol), the use of fully halogenated CFCs (no hydrogen in the molecule) are considered to high ODP and R-12 falls in this category. The problem with CFC refrigerant is mainly that a single atom of Cl released from CFC reacts taking out 100,000 O_3 (ozone) molecules. That's why use of R-12 refrigerant is detrimental to the environment.

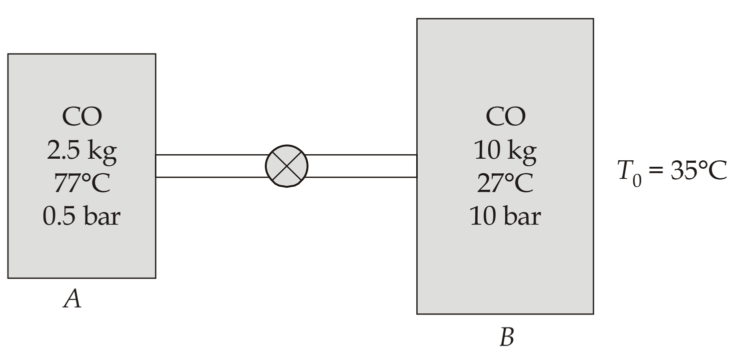
Harmful effect of R-22 Refrigerant: R-22 is Hydro-chlorofluorocarbons refrigerant which contain hydrogen atom alongwith chlorine atom. HCFCs have much lower ODP and GWP as compared to R-12 refrigerant. ODP of R-22 is only 5% of that of R-12. R-22 is considered to be transitional refrigerant and will have to be ultimately phased out by 2030 AD.

Refrigerant	R-12	R-22
Chemical formula	CCl_2F_2	$CHClF_2$
NBP temperature	–29.8°C	–40.8°C

Refrigerant used before year 2000	**Substitute Refrigerant**	
	Short Term	**Long Term**
R-12	R-134a	R-134a
R-22	R-22 (upto 2030 AD)	HFC 134 a, R 407C, R410A
	R-134a	Other blends of R-32, R-134a and other

6. (c) Solution:

Given data :



Final temperture, T_2 = 35°C

Assumptions :

1. No outside work interaction.
2. Constant specific heats.

3. No chemical changes in content of containers.
4. No leakage during the process from valves and fittings.
5. No change in kinetic or potential energies of tanks.
6. CO is exhibiting ideal gas behaviour

(i) From ideal-gas state equation

$$P_2 = \frac{mRT_2}{V_{total}} = \frac{(m_A + m_B)RT_2}{(V_A + V_B)}$$

$$= \frac{(m_A + m_B)RT_2}{\frac{m_A RT_A}{P_A} + \frac{m_B RT_B}{P_B}} = \frac{(m_A + m_B)T_2}{\frac{m_A T_A}{P_A} + \frac{m_B T_B}{P_B}}$$

$$P_2 = \frac{(2.5+10)(273+35)}{\frac{(2.5)(273+77)}{0.5} + \frac{(10)(273+27)}{10}} \simeq 1.878 \text{ bar}$$

$$P_2 = 1.878 \text{ bar}$$ **Ans.**

(ii) Now, from 1st law,

$$Q = dU + \cancelto{0}{\delta W}$$

$$Q = U_2 - U_1$$

$$Q = mc_v T_2 - (m_A c_v \times 350 + m_B c_v \times 300)$$

$$Q = 12.5 c_v \times 308 - (2.5 \times c_v \times 350 + 10 \times c_v \times 300)$$

$$Q = -25 c_v = -25\left(\frac{R}{\gamma - 1}\right) = -25\left(\frac{\bar{R}/M}{\gamma - 1}\right)$$

Since: C = O [Diatomic]

But degree of freedom, $n = 3T + 2R = 5$

$$\gamma = \left(1 + \frac{2}{n}\right) = \left(1 + \frac{2}{5}\right) = 1.4$$

$$c_p = \frac{\gamma R}{\gamma - 1} = \frac{1.4 \times \frac{8.314}{28}}{1.4 - 1} = 1.039 \text{ kJ/kgK}$$

$$Q = -25\left(\frac{\frac{8.314}{28}}{1.4-1}\right) = -18.558 \text{ kJ}$$ **Ans.**

(iii) Loss of available energy during the process:

$$\text{Irreversibility, } I = T_0\, s_{gen}$$
$$= T_0(s_{gen,sys} + s_{gen,surr})$$
$$s_{gen,sys} = \Delta s_A + \Delta s_B$$
$$= m_A\left[c_p \ln\left(\frac{T_2}{T_A}\right) - R\ln\left(\frac{P_2}{P_A}\right)\right] + m_B\left[c_p \ln\left(\frac{T_2}{T_B}\right) - R\ln\left(\frac{P_2}{P_B}\right)\right]$$
$$= 2.5\left[1.039\ln\left(\frac{308}{350}\right) - 0.297\ln\left(\frac{1.878}{0.5}\right)\right] + 10\left[1.039\ln\left(\frac{308}{300}\right) - 0.297\ln\left(\frac{1.878}{10}\right)\right]$$
$$= (-1.3146) + (5.2404) = 3.9258 \text{ kJ/K}$$
$$s_{gen,surr} = \frac{Q}{T_o} = \frac{18.558}{308} = 0.06025 \text{ kJ/K}$$
$$\Delta s_{total} = s_{gen} = s_{gen,sys} + s_{gen,surr}$$
$$= 3.9258 + 0.06025$$
$$= 3.986 \text{ kJ/K}$$
$$\text{Loss of available energy} = T_0 s_{gen}$$
$$= 308 \times 3.986$$
$$= 1227.7 \text{ kJ}$$ **Ans.**

7. (a) Solution:

$$\text{Indicated power, I.P.} = \frac{P_{imep}\, L.A.n.k}{60}$$

For 4-stroke engine, $n = \dfrac{N}{2}$

$$\text{IP} = \frac{PLANk}{120} = \frac{(8\times10^5)(0.3)\left(\frac{\pi}{4}\times0.15^2\right)(300)(1)}{120}$$
$$\text{IP} = (3375)\pi \text{ Watt} \simeq 10.6029 \text{ kW}$$

$$\eta_{i,th} = \frac{IP}{\dot{Q}_s} \qquad \left\{\because\ \dot{Q}_s = \dot{m}_f \times C.V.\right\}$$

$$= \frac{3375\pi\ \text{W}}{\left[\frac{2.5\,\text{kg}}{3600\ \text{sec}}\right] \times \left[45 \times 10^6\ \text{J/kg}\right]} \simeq 33.9292\% \qquad \textbf{Ans.}$$

$$\dot{V}_{act} = \frac{\dot{m}_a}{\rho_a} = \frac{\left(\frac{2.5 \times 22}{60}\right)}{\left(\frac{1 \times 10^5}{287 \times 293}\right)} = 0.7708$$

Hence, volumetric efficiency,

$$\eta_{vol} = \frac{\dot{V}_{act}}{\dot{V}_s} = \frac{0.7708}{\frac{\pi}{4} \times 0.15^2 \times 0.3 \times \frac{300}{2}}$$

$$\eta_{vol} = 0.9692 \text{ or } 96.92\%$$

$$\text{Brake power (BP)} = \frac{2\pi NT}{60} = \frac{2\pi \times 300 \times 200}{60}$$

$$= 2000\ \pi\text{W} \simeq 6.2832\ \text{kW}$$

$$= 376.992\ \text{kJ/min}$$

$$\text{Heat input} = \frac{2.5 \times 45 \times 10^6}{60} = 1875\ \text{kJ/min}$$

$$\text{Heat equivalent of BP} = \text{BP} = 376.992\ \text{kJ/min}$$

$$\text{Heat in cooling water} = mc_{p,w}\Delta T = 5 \times 4.18 \times 35 = 731.5\ \text{kJ/min}$$

1 kg of H_2 in the fuel will be converted to 9 kg of H_2O during combustion.

Assuming the steam in the exhaust is in the superheated state, heat carried away by the steam.

$$h = c_{p,w}\left(100 - T_a\right) + h_{fg} + C_{p,a}\left(T_{\text{sup}} - 100\right)$$

$$h = 4.18(100 - 20) + 2250 + 2.1(450 - 100)$$

$$h = 3319.14\ \text{kJ/kg}$$

Now, heat carried away by steam

$$= \dot{m}_s\left(h - c_{p,w}t_R\right)$$

$$= 9\times\left(\frac{15}{100}\right)\times\frac{2.5}{60}(3319.4-4.18\times 20)$$

$$= 182.01375 \text{ kJ/min}$$

Heat carried away by exhaust gases

$$= \left(\dot{m}_a+\dot{m}_f-\dot{m}_{H_2}\right)\times c_{p,exhaust}\times(\Delta T)$$

$$= \left(\frac{2.5\times 22}{60}+\frac{2.5}{60}-9\times 0.15\times\frac{2.5}{60}\right)\times 1\times(450-20)$$

$$= 387.8958 \text{ kJ/min}$$

Unaccounted loss (Using difference)

$$= Heat\,input-\left(BP+\dot{Q}_{cooling\,water}+\dot{Q}_{steam}+\dot{Q}_{exhaust}\right)$$

$$= 1875-(376.992+731.5+182.014+387.9)$$

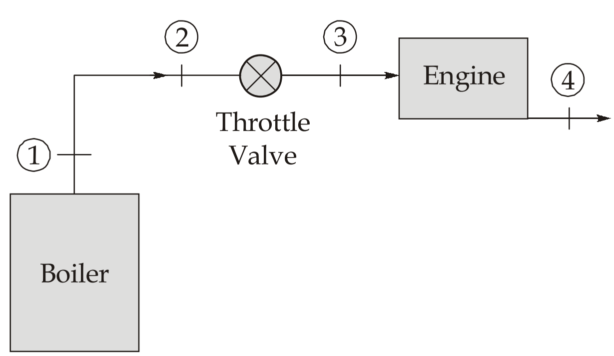
$$= 196.594 \text{ kJ/min}$$

Heat Balance sheet :

Heat Input (kJ/min)	Heat expenditure (kJ/min)
Heat supplied by fuel = 1680 kJ/min	1. Heat equivalent to B.P. = 376.992 kJ/min 2. Heat lost to cooling medium = 731.5 kJ/min 3. Heat carried away by steam = 182.014 kJ/min 4. Heat lost in exhaust = 387.9 kJ/min 5. Unaccounted losses = 196.594 kJ/min
Net input = 1680 kJ/min	**Net expenditure = 1680 kJ/min**

7. (b) Solution:

Given : P_1 = 10 bar = 1 MPa; T_1 = 300°C; P_2 = 9 bar = 0.9 MPa; T_2 = 250°C;
P_3 = 6 bar = 0.6 MPa; P_4 = 0.1 bar; x_4 = 0.85



Throttle valve

Process 2 → 3 throttling ($dh = 0$)

Assumptions:

- Adiabatic throttling
- Steady flow process
- $\Delta KE = 0$ and $\Delta PE = 0$

From table data:

At $P_2 = 0.9$ MPa and $T_2 = 250°C$

$u_2 = 2713.1$ kJ/kg; $h_2 = 2946.8$ kJ/kg; $s_2 = 6.9805$ kJ/kg

Now, $$h_2 = h_3$$

From table data at $P_3 = 0.6$ MPa corresponding to $h = 2946.8$.

Temperature T_3 is not mentioned directly but at $P = 0.6$ MPa.

$h = 2936.5$ kJ/kg; $t = 240°C$; $s = 7.1426$ kJ/kgK

$h' = 2957.6$ kJ/kg; $t' = 250°C$; $s' = 7.1832$ kJ/kgK

$h_3 = 2946.8$ kJ/kg; $t_3 = ?$

Using interpolation for approximate result.

$$\frac{t_3 - t}{t' - t} = \frac{h_3 - h}{h' - h}$$

$$\frac{t_3 - 240}{250 - 240} = \frac{2946.8 - 2936.5}{2957.6 - 2936.5}$$

$$t_3 = 244.88°C$$

Temperature drop across throttle valve = $(t_2 - t_3)$

$$= 250 - 244.88$$

$$= 5.118°C$$ **Ans.**

Work output of engine per kg of steam = $(h_3 - h_4)$

$$h_4 = h_{f4} + x_4 h_{fg4}$$

Now at 0.1 bar or 0.01 MPa and $x = 0.85$, $T_{sat} = 45.8°C$

$$h_f = 191.81 \text{ kJ/kg}, s_f = 0.6492 \text{ kJ/kgK}$$

$$h_{fg} = 2392.1 \text{ kJ/kg}, s_{fg} = 7.4996 \text{ kJ/kgK}$$

$$h_4 = 191.81 + 0.85 \times 2392.1$$

$$h_4 = 2225.095 \text{ kJ/kg}$$

Engine work output $= h_3 - h_4$

$= 2946.8 - 2225.095$

$= 721.705$ kJ/kg **Ans.**

Entropy change in throttling

$$\underset{2\to3}{\Delta s} = (s_3 - s_2)$$

From interpolation of table data

$$s_3 = \frac{(t_3 - t)(s' - s)}{(t' - t)} + s$$

$$= \frac{(244.88 - 240)}{(250 - 240)}(7.1832 - 7.1426) + 7.1426$$

$= 7.1624$ kJ/kgK

$\Delta s = 7.1624 - 6.9805 = 0.1819$ kJ/kgK **Ans.**

Entropy change in passing through engine

$$\underset{3\to4}{\Delta s} = (s_4 - s_3) = \left[s_{f4} + x_4\, s_{fg4}\right] - s_3$$

$= 0.6492 + 0.85 \times 7.4996$

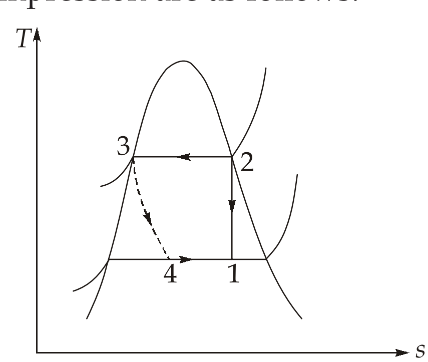
$= 7.02386 - 7.1624$

$$\underset{3\to4}{\Delta s} = -0.13854 \text{ kJ/kgK}$$ **Ans.**

This implies although we have assumed perfect insulation but there is heat loss from engine.

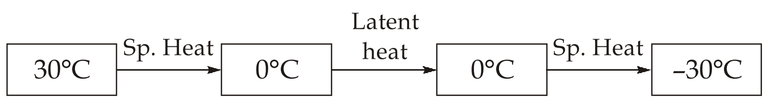
7. (c) Solution:

(i) The compression process 1-2 shown in T-s diagram is called wet compression because entire process occurs in the mixture region with droplets of liquid present. The disadvantages of wet compression are as follows:



1. Liquid refrigerant may be tapped in the head of cylinder and possibly may damage the valves or the cylinder head.
2. Another possible danger of wet compression is that the droplets of liquid may wash out the lubricating oil from the walls of cylinder thus accelerating wear.
3. The wet compression is undersirable as it reduces the refrigerating effect.

(ii)



$$m_s = 32400 \text{ kg}$$

So,
$$\dot{m}_s = \frac{32400}{24 \times 60 \times 60} = 0.375 \text{ kg/s}$$

$$C_{tf} = 3.77 \text{ kJ/kg°C}$$

$$C_{ff} = 1.67 \text{ kJ/kg°C}$$

$$\text{Latent heat, } LH = 251.2 \text{ kJ/kg}$$

Heat absorbed per kg of fish ($q_{absorbed}$) $= LH + C_{tf} \times (30 - 0) + C_{ff} \times [0 - (-30)]$

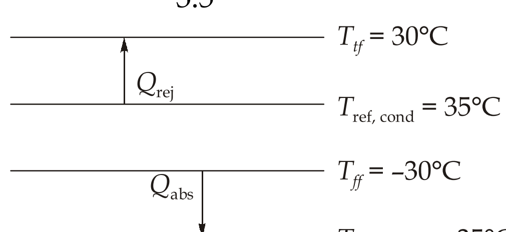
$$= 251.2 + 3.77 \times 30 + 1.67 \times 30$$

$$= 414.4 \text{ kJ/kg}$$

(a) Refrigeration capacity $= \dot{m} \times q_{absorbed}$

$$= 0.375 \times 414.4 = 155.4 \text{ kW}$$

$$= \frac{155.4}{3.5} = \mathbf{44.4 \text{ TR}}$$



$$\text{Ideal COP} = \frac{T_L}{T_H - T_L} = \frac{273 - 35}{35 - (-35)} = 3.4$$

So, Actual COP $= 0.4 \times$ Ideal COP

$$= 0.4 \times 3.4 = 1.36$$

$\because$
$$\text{COP} = \frac{RC}{\dot{W}_{in}}$$

$$\dot{W}_{in} = \frac{RC}{COP} = \frac{155.4}{1.36} = 114.265 \text{ kW}$$

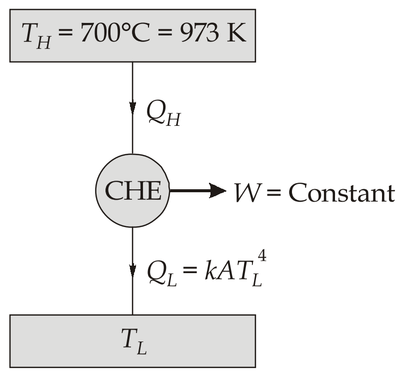
Energy consumption per year = 114.265 × 365 × 24 kW-hr

= 1000961.4 kW-hr

Electricity cost = 0.5 × 1000961.4 = Rs. 5,00,480.7

8. (a) Solution:

Given : $Q_L \propto AT_L^4$



$$Q_L = kAT_L^4 \quad \text{...(i)}$$

$$\frac{Q_H}{T_H} = \frac{Q_L}{T_L} \quad \text{(For reversible cycles)}$$

$$Q = \frac{T_H}{T_L}(Q_L) \quad \text{...(ii)}$$

Work done, $W = (Q_H - Q_L)$

$$W = \frac{T_H}{T_L} kAT_L^4 - kAT_L^4$$

$$W = \left(\frac{T_H}{T_L} - 1\right) kAT_L^4$$

Let $\frac{T_H}{T_L} = x$; where T_H is constant

$$W = \left(\frac{T_H}{T_L} - 1\right) kA \frac{T_H^4}{\left(\frac{T_H}{T_L}\right)^4}$$

$$W = \frac{x-1}{x^4} kAT_H^4$$

Since W = constant

$$\therefore \qquad A = W\cdot\frac{x^4}{(x-1)}\cdot\frac{1}{k\cdot T_H^4}$$

Now; for minimum area with respect of temperature ratio (x).

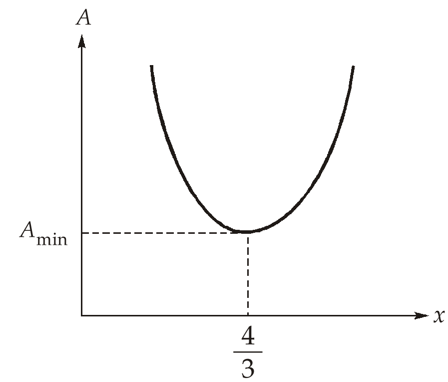
$$\frac{dA}{dx} = 0 \text{ and } \frac{d^2A}{dx^2} > 0$$

$$\Rightarrow \qquad \frac{W}{k\cdot T_H^4}\left\{\frac{4x^3(x-1)-1\times x^4}{(x-1)^2}\right\} = 0$$

$$\Rightarrow \qquad 4x^4 - 4x^3 - x^4 = 0$$

$$\Rightarrow \qquad x^3(3x-4) = 0$$

$$x = \frac{4}{3}$$



$\frac{dA}{dx}$ increases beyond $x = \frac{4}{3}$

$$\Rightarrow \qquad \frac{d^2A}{dx^2} > 0$$

$$\Rightarrow \qquad x = \frac{4}{3} \text{ is the point of minima}$$

$$\Rightarrow \qquad \frac{T_H}{T_L} = \frac{4}{3}$$

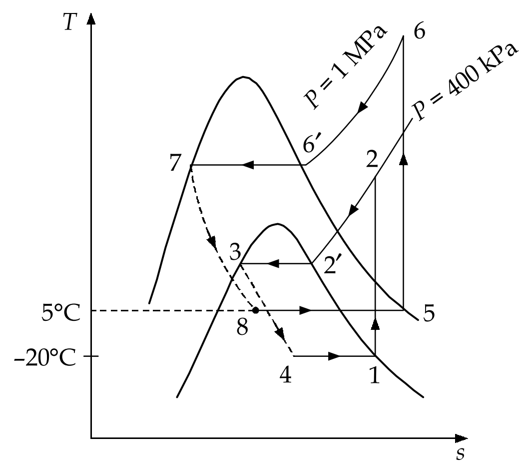
$$\Rightarrow \qquad T_L = \frac{3}{4}T_H = \frac{3}{4}(973)$$

$$= 729.75 \text{ K} = 456.75°\text{C}$$

Ans.

8. (b) Solution:

Figure shows T-s diagram of cascade system having water VCRS cycle 5-6-7-8 and R-12 VCRS cycle 1-2-3-4.



$\because$ $RC = 100 \text{ TR} = 100 \times 3.5 = 350 \text{ kW}$

For R-12 cycle, $h_1 = h_{g@-20°C} = 178.73 \text{ kJ/kg}$

$$h_4 = h_3 = h_{f@\,400 \text{ kPa}} = 43.74 \text{ kJ/kg}$$

$$s_1 = s_{g@-20°C} = 0.7087 \text{ kJ/kgK}$$

$\because$ $$s_1 = s_2 = s_{g@400 \text{ kPa}} + c_{pv} \ln\left(\frac{T_2}{T_2'}\right)$$

$\Rightarrow$ $$0.7087 = 0.6928 + 0.95 \ln\left(\frac{T_2}{273 + 8.28}\right)$$

$\Rightarrow$ $$T_2 = 286.02 \text{ K}$$

$$h_2 = h_{g@400 \text{ kPa}} + c_{p.v}(T_2 - T_2')$$
$$= 191.02 + 0.95[286.02 - (273 + 8.28)]$$
$$= 195.52 \text{ kJ/kg}$$

$\because$ $$RC = \dot{m}_{R-12}(h_1 - h_4)$$

$$\dot{m}_{R-12} = \frac{RC}{h_1 - h_4} = \frac{350}{178.73 - 43.74} = 2.59 \text{ kg/s}$$

Work input to compressor for R-12, $\dot{W}_{R-12} = \dot{m}_{R-12}(h_2 - h_1)$

$$= 2.59(195.52 - 178.73)$$
$$= 43.486 \text{ kW}$$

For water cycle :

$$h_5 = h_{g@5°C} = 2510.1 \text{ kJ/kg}$$
$$s_5 = s_{g@5°C} = 9.0249 \text{ kJ/kgK}$$

$$\because \quad s_5 = s_6 = 9.0249 = s_{g@1\text{ MPa}} + c_{p.\text{steam}} \ln\left(\frac{T_6}{T_6'}\right)$$

$$\Rightarrow \quad 9.0249 = 6.5850 + 2.1\ln\left(\frac{T_6}{273+179.88}\right)$$

$$\Rightarrow \quad T_6 = 1447.34 \text{ K}$$

$$h_6 = h_{g@1\text{ MPa}} + c_{p.\text{steam}}(T_6 - T_6')$$
$$= 2777.1 + 2.1[1447.34 - (273 + 179.88)]$$
$$= 4865.46 \text{ kJ/kg}$$

$$h_7 = h_8 = h_{f@1\text{ MPa}} = 762.51 \text{ kJ/kg}$$

$\because$ Heat absorbed by water in evaporator = Heat rejected by R-12 in condenser

$$\Rightarrow \quad \dot{m}_W(h_5 - h_8) = \dot{m}_{R-12}(h_2 - h_3)$$

$$\Rightarrow \quad \dot{m}_W = \frac{2.59(195.52-43.74)}{(2510.1-762.51)} = 0.225 \text{ kg/s}$$

Work input to compressor for water cycle,

$$\dot{W}_W = \dot{m}_W(h_6 - h_5)$$
$$= 0.225(4865.46 - 2510.1)$$
$$= 529.96 \text{ kW}$$

$$\text{COP} = \frac{RC}{W_{\text{input}}} = \frac{100\times3.5}{529.96+43.486} = 0.61$$

8. (c) Solution:

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

Brake power developed = 0.75 × 53.136 = 39.852 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.**

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