MADE EASY

Leading Institute for ESE, GATE & PSUs

Detailed Solutions

ESE-2026 Mains Test Series

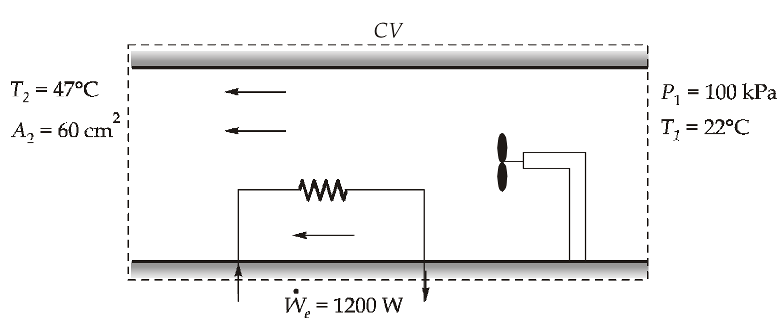
Mechanical Engineering Test No : 14

Section : A

1. (a) Solution:

Assumptions:

1. Steady state, steady flow process.
2. Air is an ideal gas.
3. $\Delta KE = \Delta PE = 0$
4. The power consumed by the fan is negligible.
5. The heat loss to the surrounding is negligible.



(i) Since there is only one flow path, we know from the mass conservation that

$$\dot{m}_1 = \dot{m}_2 = \dot{m}$$

from conservation of energy ($\Delta kE = \Delta PE = 0$)

$$\dot{m}h_1 + \dot{W}_e = \dot{m}h_2$$

$$\dot{W}_e = \dot{m}(h_2 - h_1) = \dot{m}c_p(T_2 - T_1)$$

The mass flow rate of the air is calculated as

$$\dot{m} = \frac{\dot{W}_e}{c_p(T_2 - T_1)} = \frac{1.2}{1.005 \times (47 - 22)} = 0.04776 \text{ kg/s}$$

The specific volume of the air can be determined using the ideal gas equation

$$\nu_1 = \frac{RT_1}{P_1} = \frac{0.287 \times (273 + 22)}{100} = 0.8467 \text{ m}^3/\text{kg}$$

Volumetric flow rate, $\dot{V}_1 = \dot{m} V_1$

$$= 0.04776 \times 0.8467 = 0.0404 \text{ m}^3/\text{s}$$ **Ans.**

(ii) The mass flow rate of air at the exit is given as

$$\dot{m} = \rho_2 A_2 V_2 = \frac{A_2 V_2}{\nu_2}$$

Specific volume at the exit is

$$v_2 = \frac{RT_2}{P_2} = \frac{0.287 \times 320}{100} = 0.9184 \text{ m}^3/\text{kg}$$

and velocity, $V_2 = \dfrac{\dot{m} v_2}{A_2} = \dfrac{0.04776 \times 0.9184}{60 \times 10^{-4}} = 7.31 \text{ m/s}$ **Ans.**

1. (b) Solution:

S.I. Engine:

(i) Brake thermal efficiency:

$$\eta_{bth} = \frac{BP(\text{kW}) \times 3600}{\text{fuel consumption in kg/hr} \times \text{CV of fuel kJ/kg}}$$

$$0.27 = \frac{BP \times 3600}{1 \times 44000}$$

Brake output, $BP = \dfrac{44000}{3600} \times 0.27 = 3.3 \text{ kW}$

(ii) Brake specific fuel consumption $= \dfrac{1 \text{ kWh}}{C.V. \times \eta_{bth}}$

$$= \frac{3600}{44000 \times 0.27} = 0.303 \text{ kg/kWh}$$

(iii) Air consumptions/kWh = 13.5 × 0.303 = 4.1 kg **Ans.**

C.I. Engine:

(i) Brake power per kg of fuel per hour = $\frac{C.V.\times\eta}{3600}$

$$= \frac{42000\times0.36}{3600} = 4.2 \text{ kW}$$ **Ans.**

(ii) Brake specific fuel consumption = $\frac{3600}{42000\times0.36}$ = 0.238 kg/kWh **Ans.**

(iii) Air consumptions/kW-hr = 0.238 × 25 = 5.9524 kg **Ans.**

Comparison:

$$\frac{(\text{Air consumption})_{SI}}{(\text{Air consumption})_{CI}} = \frac{4.1}{5.9524} = 0.689$$ **Ans.**

1. (c) Solution:

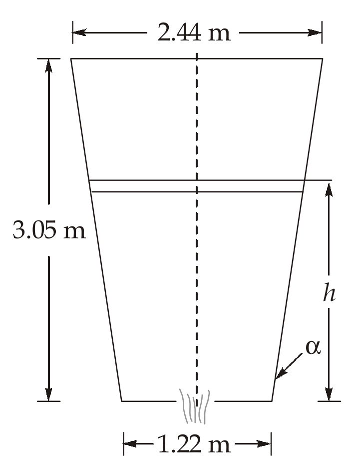
Let the diamter of orifice be d_0, and at any instant t, the height of the liquid level above the orifice be h. Then during an infinitesimal time dt, discharge through the orifice is

$$q = C_d \frac{\pi d_0^2}{4}\sqrt{2gh}\,dt = 0.60\times\frac{1}{4}\pi d_0^2\sqrt{2gh}\,dt$$

If the liquid level in the tank falls by an amount dh during this time, then from continuity.

$$-A_h dh = 0.60\frac{\pi d_0^2}{4}\sqrt{2gh}\,dt$$

where A_h is the area of the tank at height h. From the geometry of the tank,



A tank in the form of a frustum of a cone

$$\tan\alpha = \frac{(2.44-1.22)}{2\times 3.05} = 0.2$$

Therefore the diameter of the tank at height h = 1.22 + 2 × 0.2h

Hence, $$A_h = \left(\frac{\pi}{4}\right)(1.22 + 0.4h)^2$$

Substituting the value of A_h in eq, we have

$$0.60\times\left(\frac{1}{4}\right)\pi d_0^2\sqrt{2\times 9.81h}\,dt = -\frac{\pi}{4}(1.22 + 0.4h)dh$$

or $$d_0^2\int dt = -\frac{1}{0.60\times\sqrt{2\times 9.81}}\int_{3.05}^{0}(1.22+0.4h)^2 h^{-1/2}dh$$

Since, the time of emptying $\int dt = 360$ s

$$d_0^2 = \frac{1}{0.60\times\sqrt{2\times 9.81}\times 360}\int_{3.05}^{0}(1.22+0.4h)^2 h^{-1/2}dh$$

Integrating and solving for d_0, we get

$$d_0^2 = 0.01014 \text{ m}^2$$

or $$d_0 = 0.1007 \text{ m or } 101 \text{ mm}$$

1. (d) Solution:

Let t_i denote the temperature at the layer interface.

Average thermal conductivity of fire clay $= 0.37\left[1 + 0.000798\left(\frac{1300 + t_i}{2}\right)\right]$

$$= 0.37[1 + 0.000399(1300 + t_i)]$$

For a plane wall thermal resistance is δ/kA

∴ Thermal resistance of the fire clay $= \frac{0.15}{0.37[1 + 0.000399(1300 + t_i)]\times 1}$

$$= \frac{1}{2.466 + 0.000984(1300 + t_i)}$$

Thermal resistance of red brick $= \frac{0.60}{0.82\times 1} = 0.7317$

Total resistance
$$\Sigma R_t = \frac{1}{2.466 + 0.000984(1300 + t_i)} + 0.7317$$

$$\text{Heat loss from the wall} = \frac{\Delta T}{\Sigma R_t}$$

$$Q = \frac{(1300 - 70)}{\dfrac{1}{2.466 + 0.000984(1300 + t_i)} + 0.7317}$$

Under steady state conditions, the same amount of heat flows through each layer. Then considering heat flow through the red brick

$$Q = \frac{(t_i - 70)}{0.7317}$$

Equating the two expressions for heat loss,

$$\frac{1230}{\dfrac{1}{2.466 + 0.000984(1300 + t_i)} + 0.7317} = \frac{t_i - 70}{0.7317}$$

On solving, $t_1 = 1025.36°C$

$$\text{Heat loss from the wall} = \frac{1025.36 - 70}{0.7317} = 1305.67 \text{ W/m}^2 \text{ or } 1.305 \text{ kW/m}^2$$

1. (e) Solution:

(i)

In a cyclone the wind velocity is given to vary according to the free-vortex law. The velocity distribution in a free-vortex is given by:

$$V.r = C \quad \text{...(i)}$$

At a radial location defined by

$$r_1 = 60 \text{ km}, V_1 = 20 \text{ km/hr}$$

$\therefore$ $C = 20 \times 60 = 1200 \text{ km}^2\text{/hr}$

Velocity at a radial distance of (60 – 20), i.e. 40 km

$$V_2 = \frac{C}{r_2} = \frac{1200}{40} = 30 \text{ km/hr.}$$

According to Bernoulli's equation

$$p + \rho\frac{V^2}{2} = \text{Constant}$$

On differentiating w.r.t. r

or $$\frac{dp}{dr} + \rho V \frac{dV}{dr} = 0$$

$$\frac{dp}{dr} = -\rho V \frac{dV}{dr}$$

from equation (i)

$$r\frac{dV}{dr} + V = 0, \text{ or } \frac{dV}{dr} = -\frac{V}{r}$$

∴ $$\frac{dp}{dr} = -\rho V \frac{dV}{dr} = \rho \frac{V^2}{r}$$

The pressure gradient at a radial distance of 60 km, where the velocity is 20 km/hr,

$$\left(\frac{dp}{dr}\right)_{r=60\text{ km}} = 1.208 \times \frac{\left(\frac{20 \times 1000}{3600}\right)^2}{60 \times 1000} = 6.214 \text{ N/m}^2 \text{ per metre}$$

$$= 0.6214 \text{ N/m}^2 \text{ per km}$$ **Ans.**

(ii)

Reduction in barometric pressure over a radial distance of 20 km from r_1 = 60 km to r_2 = 40 km

$$r_1 = 60 \text{ km}, V_1 = 20 \text{ km/hr} = 5.56 \text{ m/s}$$
$$r_2 = 40 \text{ km}, V_2 = 30 \text{ km/hr} = 8.33 \text{ m/s}$$

Using the Bernoulli's equation, the reduction in the barometric pressure is obtained :

$$p_1 + \rho \frac{V_1^2}{2} = p_2 + \rho \frac{V_2^2}{2}$$

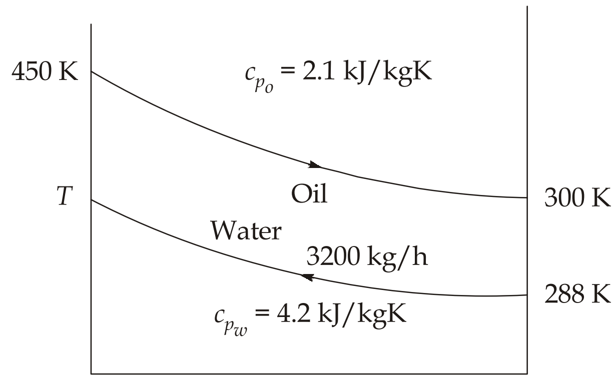
$$p_1 - p_2 = \frac{1}{2}\rho(V_2^2 - V_1^2)$$

$$= \frac{1.208}{2}(8.33^2 - 5.56^2) = 23.306 \text{ N/m}^2$$ **Ans.**

2. (a) Solution:

Given: $\dot{m}_w$ = 3200 kg/h, $(c_p)_o$ = 2.1 kJ/kgK

$\dot{m}_o$ = 900 kg/h; $(c_p)_w$ = 4.2 kJ/kgK



(i) Using energy balance

$$\dot{m}_w c_{p_w}(T-288) = \dot{m}_0 c_{p_0}(450-300)$$

$$3200 \times 4.2 \times (T-288) = 900 \times 2.1 \times (450-300)$$

$$T = 309.1 \text{ K}$$

(ii) Total entropy generation

$$\dot{s}_{gen} = (\Delta\dot{s})_0 + (\Delta\dot{s})_w$$

Since the flow in heat exchanger is at constant pressure

$$(\dot{s}_{gen}) = \dot{m}_o c_{p_o} \ln\left[\frac{T_{f_o}}{T_{i_o}}\right] + \dot{m}_w c_{p_w} \ln\left[\frac{T_{f_w}}{T_{i_w}}\right]$$

$$= \frac{900}{3600} \times 2.1 \times \ln\left[\frac{300}{450}\right] + \frac{3200}{3600} \times 4.2 \times \ln\left[\frac{309.1}{288}\right]$$

$$= 0.05109 \text{ kW/K}$$

Rate of energy destruction $= T_0 \times \dot{s}_{gen}$

$$= (19 + 273) + 0.05109$$

$$= 14.918 \text{ kW}$$ **Ans.**

(iii) Availability decrease of oil,

$$= A_1 - A_2$$

$$= h_1 - h_2 - T_0(s_1 - s_2)$$

$$= \dot{m}_o c_{p_o}\left[(T_1 - T_2) - T_0 \ln\left(\frac{T_1}{T_2}\right)\right]$$

$$= \frac{900}{3600} \times 2.1\left[(450-300) - 292 \times \ln\left(\frac{450}{300}\right)\right]$$

$$= 16.592 \text{ kW}$$

Increase in availability of water,

$$A_1 - A_2 = h_1 - h_2 - T_0(s_1 - s_2)$$

$$= \dot{m}_w c_{p_w}\left[(T_1 - T_2) - T_0 \ln\left(\frac{T_1}{T_2}\right)\right]$$

$$= \frac{3200}{3600} \times 4.2 \times \left[(309.1 - 288) - 292 \ln\left(\frac{309.1}{288}\right)\right]$$

$$= 1.696 \text{ kW}$$

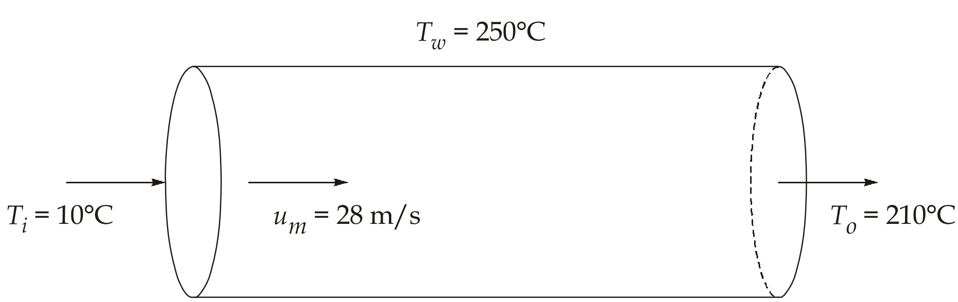
$\therefore$ Second low efficiency $(\eta_{II}) = \dfrac{\text{Gain of availability}}{\text{Loss in availability}}$

$$= \frac{1.696}{16.592} = 0.1022 \text{ or } 10.22\%$$ **Ans.**

2. (b) Solution:

Given : Tube diameter (D_i) = 0.023 m; T_w = 250°C; T_i = 10°C; T_o = 210°C; u_m = 28 m/s

$$f = \begin{cases} \dfrac{64}{\text{Re}}; & \text{for laminar flow} \\ \dfrac{0.3164}{\text{Re}^{0.25}}; & \text{for turbulent flow} \end{cases}$$



$$Re_{,d} = \frac{u_m \cdot D}{\nu} = \frac{28 \times 0.023}{3.6 \times 10^{-5}} \simeq 17888.9$$

$$Re_{,d} > 2300$$

$\Rightarrow$ Turbulent flow

$$\text{Friction factor } (f) = \frac{0.3164}{(\text{Re}_{,d})^{0.25}} \simeq 0.02736$$

$$\text{Pr} = \frac{\nu}{\alpha} = \frac{\nu \rho c_p}{k} = \frac{(3.6 \times 10^{-5})(1)(1.005) \times 10^3}{0.04}$$

$$\text{Pr} = 0.9045$$

Now, from Colburn-analogy

$$St_d \, \text{Pr}^{2/3} = \frac{f}{8} = \frac{0.02736}{8} \simeq 3.42 \times 10^{-3}$$

$$\text{Nu} = (3.42 \times 10^{-3})(17888.9)(0.9045)^{1/3}$$

$$\text{Nu} = 59.1669$$

$$h = \frac{Nu.K}{D} = \frac{(59.1669)(0.04)}{0.023} = 102.899 \text{ W/m}^2\text{K}$$

Mass flow rate, $\dot{m} = \frac{\pi}{4}(0.023)^2 \times 28 \times 1$

$$\dot{m} = 0.011633 \text{ kg/s}$$

Heat received by air (Q), $\dot{Q} = \dot{m}c_p(T_o - T_i)$

$$= 0.011633 \times 1.005 \times (210 - 10) = 2.3383 \text{ kW}$$

Also, $\dot{Q} = hA(\text{LMTD})$

$$\text{LMTD} = \frac{\Delta T_1 - \Delta T_2}{\ln\left(\frac{\Delta T_1}{\Delta T_2}\right)} = \frac{(250-10)-(250-210)}{\ln\left(\frac{250-10}{250-210}\right)} = 111.622°\text{C}$$

$$A = \frac{\dot{Q}}{h(LMTD)} = \frac{2.3383 \times 10^3}{102.899 \times 111.622} = 0.20358 \text{ m}^2$$

$$A = \pi DL$$

$$0.20358 = \pi \times 0.023 \times L$$

$$L = 2.817 \text{ m}$$ **Ans.**

Pumping power (P) = $Fu_m = \tau_w \cdot \pi DL \cdot u_m$

$$P = \Delta P \cdot \frac{\pi}{4} D^2 \cdot u_m$$

$$P = \frac{fL}{D} \rho \frac{u_m^2}{2} \cdot \frac{\pi}{4} D^2 \cdot u_m = \frac{f}{8} \rho u_m^2 LD\pi$$

$$P = \frac{0.02736}{8} \times 1 \times 28^3 \times 2.817 \times 0.023 \times \pi$$

$$P = 15.284 \text{ W}$$ **Ans.**

2. (c) (i) Solution:

(i) Difference in tension on either side of brake pulley, $W = 400$ N

Arm length, $r = \dfrac{\text{circumference}}{2\pi} = \dfrac{2.4}{2\pi} = 0.381$ m

Torque, $T = Wr = 410 \times 0.381 = 156.62$ N m

$\therefore \quad bp = \dfrac{2\pi NT}{60} = \dfrac{2\pi \times 600 \times 156.62}{60} = 9840.72 \text{ W} = 9.84 \text{ kW}$ **Ans.**

(ii) Mean height of indicator diagram $= \dfrac{\text{net area of indicator diagram}}{\text{length of indicator diagram}}$

$$= \frac{515 - 35}{50} = 9.6 \text{ mm}$$

imep = mean height of indicator diagram × spring constant = 9.6 × 0.8333 $\simeq$ 8 bar

$$\therefore \quad ip = \frac{\text{imep} \times L \times A \times N}{2 \times 60}$$

$$= 8 \times 10^5 \times 0.16 \times \frac{\pi}{4}(0.15)^2 \times \frac{600}{2 \times 60} \times \frac{1}{1000} = 11.31 \text{ kW}$$

(iii) $$\eta_m = \frac{bp}{ip} = \frac{9.84}{11.31} = 0.87 \text{ or } 87\%$$

(iv) $$\eta_b = \frac{bp}{\dot{m}_f \times CV} = \frac{9.84 \times 60}{0.0575 \times 42000} = 0.2445 = 24.45\%$$

(v) $$\eta_i = \frac{ip}{\dot{m}_f \times CV} = \frac{\eta_b}{\eta_m} = \frac{0.2445}{0.87} = 0.281 = 28.1\%$$

(vi) $$bsfc = \frac{\dot{m}_f}{bp} = \frac{0.0575 \times 60}{9.84} = 0.351 \text{ kg/kWh}$$

2. (c) (ii) Solution:

Diesel to natural gas conversion requires careful engineering on the base engine modifications as well as the control system. Following is an overview of modifications required for a successful conversion:

Compression Ratio: A typical diesel engine has a compression ratio between 16 and 18. CNG usually works best between 10 and 12; so new or modified pistons are required, with an appropriately shaped combustion chamber to allow proper air-fuel mixing.

Spark Plug: Diesel engines have diesel fuel injectors instead of spark plugs. A diesel conversion replaces the injector with a spark plug and may also require an insert to go through the valve cover - depending on the engine. Spark plug wear is a common problem, and the high compression ratio and use of gaseous fuel requires higher spark voltage than a petrol car.

Valves: Natural Gas is a dry fuel so valve seats in a converted engine need to be hardened to prevent abnormal wear. Older engines need valve guide seals to prevent engine vacuum from drawing oil into the combustion chamber.

Thermal Issues: Spark ignited engines run hotter than diesels. Such engines may require upgraded thermal management components, including larger oil coolers, larger radiators, and heat shields around exhaust components.

Catalytic Converter: A catalyst will generally be required to meet emission regulations. The exception is Solved Papers lean-burn engines, which, if carefully engineered, can meet certain emissions targets without a converter.

Engine Management System: The choice of system will depend on the exhaust emissions requirements, efficiency targets, durability expectations, technology level of the vehicle and peripheral device control requirements such as cruise control, power take-off, automatic transmissions etc.

3. (a) (i) Solution:

Initial head loss = 25 m

from Darcy-Weisbach equation,

$$h_f = \frac{fLV^2}{2gd}$$

$$h_f = \frac{fLQ^2}{2g\times\left(\frac{\pi}{4}\right)^4 \times d^5}$$

$$h_f = \frac{fLQ^2}{12.1\times d^5} \qquad \text{[Here we have, } h_f = 25 \text{ m, } d = 0.5 \text{ m]}$$

$$25 = \frac{fLQ^2}{12.1\times(0.5)^5} \qquad \text{...(i)}$$

Let d_2 be the diameter of the pipe required to be connected in parallel to the existing pipe and Q_1 and Q_2 be the discharge through the pipes of diameters, 500 mm and d_2 respectively.

As the total discharge remains same,

$$Q = Q_1 + Q_2 \qquad \text{...(ii)}$$

The head loss is reduced to 15 m and both the pipes have same length L and same friction f. Thus from Darcy-Weisbach equation, we have

$$15 = \frac{fLQ_1^2}{12.1 \times (0.5)^5} \qquad \text{...(iii)}$$

$$15 = \frac{fLQ_2^2}{12.1 \times (d_2)^5} \qquad \text{...(iv)}$$

from equation (i) and (iii)

$$\frac{25}{15} = \left(\frac{Q}{Q_1}\right)^2$$

or
$$\frac{Q_1}{Q} = \sqrt{\frac{15}{25}} = 0.7746$$

$$Q_1 = 0.7746\, Q$$

Now from equation (ii), $Q_2 = Q - Q_1 = Q - 0.7746\,Q$

$$Q_2 = 0.2254\,Q$$

from equations (iii) and (iv), we obtain

$$\frac{Q_1^2}{(0.5)^5} = \frac{Q_2^2}{(d_2)^5}$$

$$\left(\frac{d_2}{0.5}\right)^5 = \left(\frac{Q_2}{Q_1}\right)^2$$

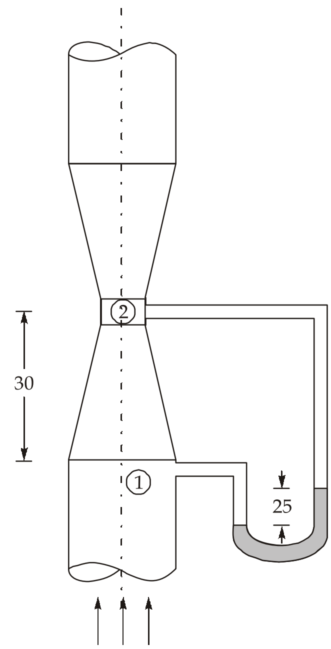
or
$$d_2 = 0.5\left(\frac{Q_2}{Q_1}\right)^{2/5} = 0.5\left(\frac{0.2254}{0.7746}\right)^{0.4}$$

$$d_2 = 0.30515 \text{ m}$$

$$d_2 = 305.15 \text{ mm}$$

3. (a) (ii) Solution:

1.



Diameter at inlet, d_1 = 36 cm

$$\text{Area, } a_1 = \frac{\pi}{4}d_1^2 = \frac{\pi}{4}\times(36)^2 = 1017.876 \text{ cm}^2$$

Diameter at throat, d_2 = 18 cm

$$\text{Area, } a_2 = \frac{\pi}{4}d_2^2 = \frac{\pi}{4}\times(18)^2 = 254.47 \text{ cm}^2$$

Let section (1) represents inlet and section (2) represents throat. Then $z_2 - z_1$ = 30 cm.

Specific gravity of oil, S_o = 0.9

Specific gravity of mercury, s_g = 13.6

Reading of differential manometer, x = 25 cm

The differential head, h is given by

$$h = \left(\frac{p_1}{\rho g}+z_1\right)-\left(\frac{p_2}{\rho g}+z_2\right)$$

$$= x\left(\frac{s_g}{s_0}-1\right) = 25\left(\frac{13.6}{0.9}-1\right) = 352.77 \text{ cm of oil}$$

$$\text{Discharge } Q \text{ of oil} = C_d\frac{a_1 a_2}{\sqrt{a_1^2-a_2^2}}\sqrt{2gh}$$

$$= \frac{0.98 \times 1017.876 \times 254.47}{\sqrt{(1017.876)^2 - (254.47)^2}} \sqrt{2 \times 9.81 \times 100 \times 352.77}$$

$$= 214275.47 \text{ cm}^3/\text{s}$$

$$= 214.3 \text{ litres/second}$$ **Ans.**

2. Pressure difference between entrance and throat section

$$h = \left(\frac{P_1}{\rho g} + z_1\right) - \left(\frac{P_2}{\rho g} + z_2\right) = 352.77$$

$$\left(\frac{P_1}{\rho g} - \frac{P_2}{\rho g}\right) + z_1 - z_2 = 352.77$$

But $z_2 - z_1 = 30 \text{ cm}$

$$\left(\frac{P_1}{\rho g} - \frac{P_2}{\rho g}\right) - 30 = 352.77$$

$$\frac{P_1}{\rho g} - \frac{P_2}{\rho g} = 382.77 \text{ cm of oil} = 3.8277 \text{ m of oil}$$ **Ans.**

$$(P_1 - P_2) = 900 \times 3.8277 \times 9.81$$

$$= 33795 \text{ N/m}^2 = 33.795 \text{ kPa}$$ **Ans.**

3. (b) (i) Solution:

Heat conducted from outside surface of wire = Heat convected to air

$$-k \left.\frac{dT}{dr}\right|_R = h\,(T_w - T_\infty)$$

where; T_w = Wire outside surface temperature; T_∞ = Ambient temperature

At centre,

$\because$ $T = T_{max}$ and temperature profile is differentiable

$\therefore$ $$\left.\frac{dT}{dr}\right|_{r=0} = 0$$

From the conduction equation

$$\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial T}{\partial r}\right) + \frac{q_g}{k} = 0$$

$$\frac{\partial T}{\partial r} = -\frac{q_g r}{2k} + \frac{c_1}{r}$$

$$T = -\frac{q_g r^2}{4k} + c_1 \ln r + c_2 \quad \text{...(ii)}$$

At $r = r_0$,

$$\left(\frac{\partial T}{\partial r}\right)_{r=r_0} = -\frac{q_g r_0}{2k} + \frac{c_1}{r_0}$$

Also,

$$q_g \pi r_0^2 L = -k 2\pi r_0 L \left(\frac{\partial T}{\partial r}\right)_{r=r_0}$$

$$\left(\frac{\partial T}{\partial r}\right)_{r=r_0} = \frac{-q_g r_0}{2k}$$

From equation (ii) and (iii),

$$c_1 = 0$$

At $r = r_0$;

$$T = T_w$$

$$T = T_w + \frac{q_g}{4k}\left(r_0^2 - r^2\right)$$

$$T = \frac{q_g r_0^2}{4k}\left(1 - \left(\frac{r}{r_0}\right)^2\right) + \frac{q_g r_0}{2h} + T_\infty$$

$$\frac{T - T_\infty}{T_\infty} = \frac{q_g \cdot r_o}{2hT_\infty}\left[1 + \frac{hr_0}{2k} + \frac{hr^2}{2r_0^2 \cdot k}\right]$$

Putting $r = 0$; $T = T_{max}$

$$T_{max} = T_\infty + \frac{q_g r_0}{2h}\left[1 + \frac{hr_0}{2k}\right]$$

Since;

$$q_g = \frac{I^2 R}{V} = \frac{I^2 R}{\pi r_0^2 L}$$

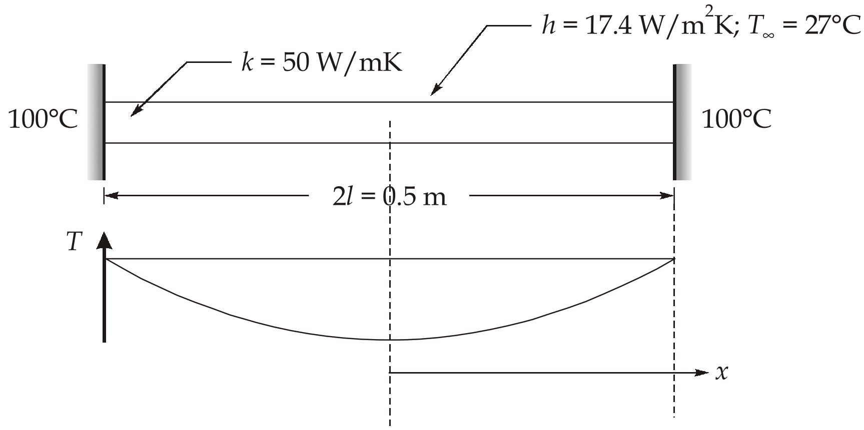
$$T_{max} = T_\infty + \frac{I^2}{2\pi r_0 L}\frac{R}{L}\left(1 + \frac{hr_0}{2k}\right)$$

$$200 = 27 + \frac{I^2}{2\pi\left(0.5 \times 10^{-3}\right) \times 10}(0.04)\left(1 + \frac{10 \times 0.5 \times 10^{-3}}{2 \times 200}\right)$$

$$I = 11.6564 \text{ Amp}$$ **Ans.**

3. (b) (ii) Solution:

Given:



Because of symmetry we would consider half length of the bar

$$P = 2(a + b) = 2(50 + 50) = 200 \text{ mm} = 0.2 \text{ m}$$

$$A = 50 \times 50 = 2500 \text{ mm}^2 = 25 \times 10^{-4} \text{ m}^2$$

Here,
$$m = \sqrt{\frac{hP}{kA}} = \sqrt{\frac{17.4 \times 0.2}{50 \times 25 \times 10^{-4}}} = 5.27636$$

$$ml = 5.27636 \times 0.25 = 1.31909$$

$$\tanh(ml) = 0.86656$$

$$\frac{Q}{2} = mkA\theta_0 \tanh(ml)$$

$$\frac{Q}{2} = 5.27636 \times 50 \times 0.0025 \times (100 - 27)0.86656$$

$$\frac{Q}{2} = 41.72196$$

Rate of heat loss from the bar,

$$Q = 83.44392 \text{ W}$$

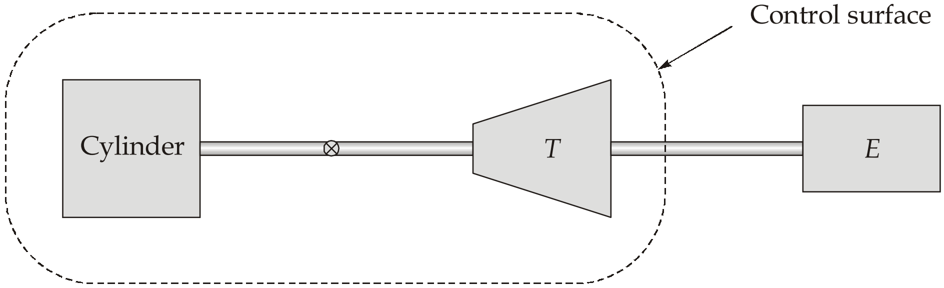
$$\theta_1 = T_1 - T_\infty = \frac{T_0 - T_\infty}{\cosh(ml)}$$

$$T - 27 = \frac{100 - 27}{\cosh(1.31909)} = 36.4326$$

$$T_1 = 63.4326°\text{C}$$ **Ans.**

3. (c) Solution:

Given : $m_a = 15$ kg; $P_1 = 38$ bar; $P_2 = 4$ bar; $T_1 = 27°C = 300$ K; $P_0 = 1$ bar $= P_e$



Maximum possible work output will be obtained when the whole process is reversible (i.e. no entropy generation) and air leaves the turbine continuously at atmospheric pressure and temperature.

Then, the state of air leaving, the control volume is constant and assuming uniform state within the cylinder.

$$m_1 = 15 \text{ kg}$$

$$m_f = \text{mass in same volume of cylinder, at low pressure}$$

Since air is treated as ideal gas

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

$$m_2 = \frac{P_2V_2}{RT_2} \text{ and } m_1 = \frac{P_1V_1}{RT_1}$$

$$m_2 = m_1\left(\frac{P_2}{P_1}\right) = 15 \times \left(\frac{4}{38}\right) = 1.579 \text{ kg}$$

Mass conservation, $m_2 - m_1 = \cancelto{0}{m_i} - m_e$

$$1.579 - 15 = -m_e$$

$$m_e = 13.42 \text{ kg}$$

Energy balance, $U_2 - U_1 = \cancelto{0}{m_1 h_i} + Q - m_e h_e + W$

$$m_2u_2 - m_1u_1 = Q + W - m_eh_e$$

$\because$ $T_2 = T_1$

So, $u_1 = u_2 = u_0$

$$[m_2 - m_1]u_0 + m_eh_e = Q + W_{cv}$$

$$-W_{cv} = Q + m_e u_0 - m_e h_e \quad \text{...(i)}$$

Using entropy equation,

$$S_2 - S_1 = S_i - S_e + \dot{S}_{gen} + \frac{Q_{cv}}{T_0}$$

For reversible process, $\dot{s}_{gen} = 0$

$$m_2 s_2 - m_1 s_1 = \cancelto{0}{m_i s_i} - m_e s_e + \frac{Q_{cv}}{T_0}$$

$$Q_{cv} = T_0\left[m_s s_2 - m_1 s_1 + m_e s_e\right]$$

Substituting in energy equation, i.e. equation (i)

$$-W_{cv} = T_0 m_2 s_2 - T_0 m_1 s_1 + T_0 m_e s_e + m_e u_o - m_e h_e$$

$$= m_e u_o + T_o m_2 s_2 - T_o m_1 s_1 - m_e\left(h_e - T_o s_e\right)$$

Again $m_e = m_1 - m_2$

$$-W_{cv} = \left(m_1 - m_2\right)u_o + T_0 m_2 s_2 - T_0 m_1 s_1 - (m_1 - m_2)(h_e - T_0 s_e)$$

$$= m_1\left[u_0 - T_0 s_1 - h_e + T_0 s_e\right] - m_2\left[u_0 - T_0 s_2 - h_e + T_0 s_e\right]$$

Also, $h_e = u_e + pv_e$

$$= u_e + RT_e$$

$$= u_0 + RT_0$$

$\because$ Internal energy of an ideal gas is a function of temperature alone so, $u_e = u_o$.

$$-W_{cv} = m_1\left[u_o - T_o s_1 - u_o - RT_o + T_o s_e\right] - m_2\left[u_o - T_o s_2 - u_o - RT_o + T_o s_e\right]$$

$$-W_{cv} = m_1 T_o\left(s_e - s_1\right) - m_1 RT_o - m_2 T_o\left(s_e - s_2\right) + m_2 RT_o$$

$$-W_{cv} = m_1 T_o\left(s_e - s_1\right) - m_2 T_o\left(s_e - s_2\right) + \left(m_2 - m_1\right)RT_o$$

$$-W_{cv} = -m_1 T_o\left[R\ln\left(\frac{P_e}{P_1}\right)\right] + m_2 T_o\left[R\ln\left(\frac{P_e}{P_2}\right)\right] + (-m_e)RT_o$$

Putting the values,

$$-W_{cv} = -15 \times 300 \times\left[0.287\ln\left(\frac{1}{38}\right)\right] + 1.579 \times 300 \times\left[0.287 \times \ln\left(\frac{1}{4}\right)\right] - 13.42 \times 0.287 \times 300$$

$$W_{cv} = 3354.01 \text{ J}$$

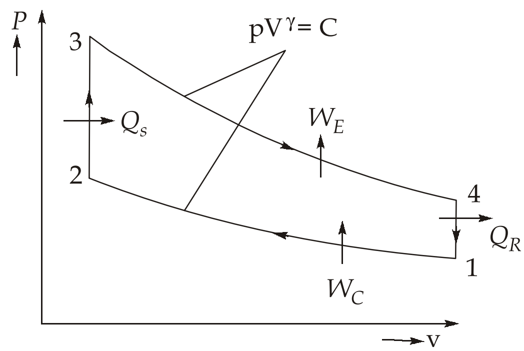
$$= 3.35 \text{ kJ}$$

4. (a) (i) Solution:

Given: $T_1 = 273 + 35 = 308$ K, $P_1 = 0.1$ MPa $= 100$ kPa, $Q_s = 2100$ kJ/kg, $r = 9$,

$$\gamma = \frac{c_p}{c_v} = \frac{1.005}{0.718} = 1.4$$

$$\eta_{cycle} = 1 - \frac{1}{r^{\gamma-1}} = 1 - \frac{1}{(9)^{0.4}} = 0.5847$$



Cycle efficiency, $\eta_{cycle} = 0.5847$ or 58.47% **Ans.**

$$\frac{v_1}{v_2} = 9,\ v_1 = \frac{RT_1}{P_1} = \frac{0.287 \times 308}{100} = 0.884\ \text{m}^3/\text{kg}$$

$$v_2 = \frac{0.884}{9} = 0.09822\ \text{m}^3/\text{kg}$$

$$\frac{T_2}{T_1} = \left(\frac{v_1}{v_2}\right)^{\gamma-1} = (9)^{0.4} = 2.4082$$

$$T_2 = 308 \times 2.4082 = 741.7256\ \text{K} \approx 741.73\ \text{K}$$

$$Q_s = c_v(T_3 - T_2) = 2100\ \text{kJ/kg}$$

$$T_3 - 741.73 = \frac{2100}{0.718} = 2924.8\ \text{K}$$

$$T_3 = 3666.53\ \text{K} = T_{max}$$ **Ans.**

$$\frac{P_2}{P_1} = \left(\frac{v_1}{v_2}\right)^{\gamma} = (9)^{1.4} = 21.674$$

$$P_2 = 2.1674\ \text{MPa}$$

Again, for process 2–3 $$\frac{P_3 v_3}{T_3} = \frac{P_2 v_2}{T_2}$$

$$\frac{P_3}{P_2} = \frac{v_2}{v_3} \times \frac{T_3}{T_2} = 1 \times \frac{3666.53}{741.73} = 4.9432$$

$$P_3 = 2.1674 \times 4.9432 = 10.714 \text{ MPa} = P_{max}$$ **Ans.**

$$W_{net} = Q_1 \times \eta_{cycle}$$
$$= 2100 \times 0.5847 = 1227.87 \text{ kJ/kg}$$
$$W_{net} = P_m(v_1 - v_2)$$
$$P_m = \frac{1227.87}{(0.884 - 0.09822)} = 1562.613 \text{ kPa or } 1.562 \text{ MPa}$$

4. (a) (ii) Solution:

The main purpose is to ensured quick and complete combustion. Fuel injector increase the surface area of the fuel droplets resulting in better mixing and subsequent combustion by means of atomizing the fuel into very fine droplets. Atomization is done by forcing the fuel through a small orifice under high pressure. The fuel injector is a small nozzle into which liquid fuel is injected at high pressure. It works like spay nozzle on a pressure washer.

For a proper running and good performance from the engine, the following requirements must be met by the injection system:

(i) Accurate metering of the fuel injected per cycle. This is very critical due to the (act that very small quantities of fuel being handled. Metering errors may cause drastic variation From the desired output The quantity of the fuel metered should vary to meet changing speed and bad requirements of the engine.

(ii) Timing the injection of the fuel correctly In the cycle so that maximum power is obtained ensuring fuel economy and clean burning

(iii) Proper control of rate of injection so that the desired beat-release pattern is achieved during combustion.

(iv) Proper atomization of fuel into very fine droplets.

Proper spray pattern to ensure rapid mixing of fuel and air

(vi) Uniform distribution of fuel droplets throughout the combustion chamber.

(vii) To supply equal quantities of metered fuel to all cylinders in case of multi cylinder engines.

(viii) No lag during beginning and end of injection i.e., to eliminate dribbling of fuel droplets into the cylinder.

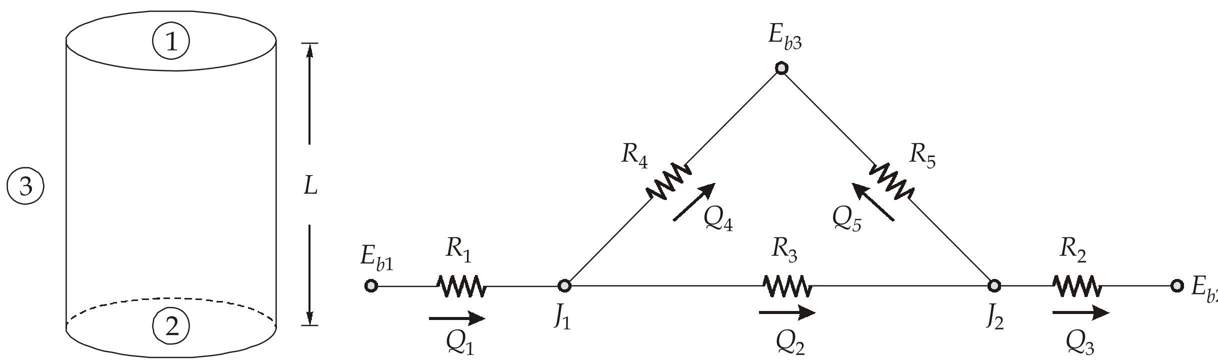
The injector assembly mainly consists of

(i) a needle valve
(ii) a compression spring
(iii) a nozzle
(iv) an injector body
(v) Nozzle body
(vi) Nozzle valve
(vii) Spindle
(viii) End cap

4. (b) Solution:

Given : $A_1 = A_2 = 1\text{ m}^2, \in_1 = \in_2 = 0.6$ and $F_{1-2} = F_{2-1} = 0.65; E_{b1} = 50\text{ kW/m}^2;$

$E_{b2} = 8\text{ kW/m}^2; T_3 = 24 + 273 = 297\text{ K}.$



The values of the resistances are:

$$R_1 = \frac{1-\in_1}{A_1 \in_1} = \frac{1-0.6}{1\times 0.6} = 2/3$$

$$R_2 = \frac{1-\in_2}{A_2 \in_2} = \frac{1-0.6}{1\times 0.6} = 2/3$$

$$R_3 = \frac{1}{A_1 F_{1-2}} = \frac{1}{1\times 0.65} = 1.538$$

$$F_{1\text{-}3} = F_{2-3} = 1 - F_{1-2} = 1 - 0.65 = 0.35$$

$$R_4 = \frac{1}{A_1 F_{1-3}} = \frac{1}{1\times 0.35} = 2.857$$

$$R_5 = \frac{1}{A_2 F_{2-3}} = \frac{1}{1\times 0.35} = 2.857$$

(i) Temperature of the plates, T_1 and T_2 :

$$E_{b1} = \sigma T_1^4 = 5.67\times 10^{-8} T_1^4 = 50\times 1000$$

or $$T_1^4 = \frac{50\times 1000\times 10^8}{5.67}$$

$$\therefore \qquad T_1 = \left(\frac{50 \times 1000 \times 10^8}{5.67}\right)^{1/4} = 969.05 \text{ K} \qquad \textbf{Ans.}$$

$$E_{b2} = \sigma T_2^4 = 5.67 \times 10^{-8} T_2^4 = 8 \times 1000$$

or
$$T_2^4 = \frac{8 \times 1000 \times 10^8}{5.67}$$

$$\therefore \qquad T_2 = \left(\frac{8 \times 1000 \times 10^8}{5.67}\right)^{1/4} = 612.88 \text{ K} \qquad \textbf{Ans.}$$

(ii) Heat transfer to the surroundings from the plates, Q :

$$E_{b1} - E_{b3} = Q_1 R_1 + Q_4 R_4 = Q_1 R_1 + (Q_1 - Q_2) R_4$$

But $\quad E_{b1} - E_{b3} = \sigma(T_1^4 - T_3^4) = 50000 - 5.67 \times 10^{-8} (297)^4 = 49558.82 \quad \ldots(1)$

$$\therefore \quad 49558.82 = Q_1 R_1 + (Q_1 - Q_2) R_4$$

$$E_{b1} - E_{b2} = Q_1 R_1 + Q_2 R_3 + Q_3 R_2$$

But, $\quad E_{b1} - E_{b2} = \sigma(T_1^4 - T_2^4) = 5.67\left[\left(\frac{969.05}{100}\right)^4 - \left(\frac{612.88}{100}\right)^4\right] = 41999.84 \quad \ldots(2)$

$$\therefore \quad 41999.84 = Q_1 R_1 + Q_2 R_3 + Q_3 R_2$$

$$E_{b2} - E_{b3} = (-Q_3 R_2) + (Q_2 - Q_3) R_5$$

But, $E_{b2} - E_{b3} = \sigma(T_2^4 - T_3^4) = 5.67\left[\left(\frac{612.88}{100}\right)^4 - \left(\frac{297}{100}\right)^4\right] = 7558.73 \quad \ldots(3)$

$$\therefore \quad 7558.73 = -Q_3 R_2 + (Q_2 - Q_3) R_5$$

Now substituting the values of the resistances in eqns. (1), (2) and (3), we get

$$\frac{2}{3} Q_1 + 2.857(Q_1 - Q_2) = 49558.82$$

or, $3.524 Q_1 - 2.857 Q_2 = 49558.82$ ...(i)

$$\frac{2}{3}Q_1 + 1.538Q_2 + \frac{2}{3}Q_3 = 41999.84 \quad \text{...(ii)}$$

$$-\frac{2}{3}Q_3 + 2.857(Q_2 - Q_3) = 7558.73$$

or $2.857Q_2 - 3.524Q_3 = 7558.73$ ...(iii)

Now solving eqns. (i), (ii) and (iii), we get

$Q_1 = 24605.11$ W; $Q_2 = 13003.01$ W; $Q_3 = 8396.95$ W

$$Q_4 = Q_1 - Q_2$$
$$= 11.602 \text{ kW}$$
$$Q_5 = Q_2 - Q_3$$
$$= 4.606 \text{ kW}$$
$$Q_{surr} = Q_4 + Q_5$$
$$= 11.602 + 4.606$$
$$= 16.208 \text{ kW}$$

Ans.

Alternatively,

At node J_1

$$\frac{E_{b_1} - J_1}{R_1} + \frac{J_2 - J_1}{R_3} + \frac{E_{b_3} - J_1}{R_4} = 0$$

$$\frac{3(50 - J_1)}{2} + \frac{J_2 - J_1}{1.538} + \frac{0.44 - J_1}{2.857} = 0$$

$75 - 1.5J_1 + 0.65J_2 - 0.65J_1 + 0.154 - 0.35J_1 = 0$

$-2.5J_1 + 0.65J_2 + 75.154 = 0$ ...(i)

At node J_2

$$\frac{3(8 - J_2)}{2} + \frac{J_1 - J_2}{1.538} + \frac{0.44 - J_2}{2.857} = 0$$

$2 - 1.5J_2 + 0.65J_1 - 0.65J_2 + 0.154 - 0.35J_2 = 0$

$0.65J_1 - 2.5J_2 + 12.154 = 0$ ...(ii)

On solving equation (i) and (ii),

$$J_1 = 33.59$$

$$J_2 = 13.59$$

$$Q_4 = \frac{33.59 - 0.44}{2.857} = 11.60 \text{ kW}$$

$$Q_5 = \frac{13.59 - 0.44}{2.857} = 4.60 \text{ kW}$$

$$Q = Q_4 + Q_5 = 16.2 \text{ kW}$$ **Ans.**

4. (c) Solution:

Free steam velocity,

$$U_0 = 180 \text{ km/hr}$$

$$= \frac{180 \times 1000}{3600} = 50 \text{ m/s}$$

(i)
$$\text{R}_{el} = \frac{U_0 \cdot l}{\nu} = \frac{50 \times 2}{15 \times 10^{-6}} = 6.66 \times 10^6$$

where the full length of the plate has been used to determine the Reynolds number, (laminar flow is assumed to exist over the entire plate).

Now,
$$C_D = \frac{1.328}{\sqrt{R_{el}}} = \frac{1.328}{\sqrt{6.66 \times 10^6}} = 5.145 \times 10^{-4}$$

$$\text{Drag force, } F_D = C_D \times \frac{1}{2}\rho U_0^2 \times \text{area of plate on both sides}$$

$$= 5.145 \times 10^{-4} \times \left(\frac{1}{2} \times 1.2 \times 50^2\right) \times 2(6 \times 2)$$

$$= 18.52 \text{ N}$$

At a point 1.3 m from the leading edge, $x = 1.3$ m

$$R_{ex} = \frac{50 \times 1.3}{15 \times 10^{-6}} = 4.33 \times 10^6$$

Hence,
$$\delta = \frac{5x}{\sqrt{R_{ex}}} = \frac{5 \times 1.3}{\sqrt{4.33 \times 10^6}}$$

$$= 3.123 \times 10^{-3} \text{ m}$$

$$R_{el} = 6.66 \times 10^6$$

For turbulent boundary layer,

$$C_D = \frac{0.455}{(\log_{10} R_{el})^{2.58}} = \frac{0.455}{(\log_{10} 6.66 \times 10^6)^{2.58}} = 0.320 \times 10^{-2}$$

$$F_D = C_D \times \frac{1}{2}\rho U_0^2 \times \text{area of plate on both sides}$$

$$= 0.320 \times 10^{-2} \times \left(\frac{1}{2} \times 1.2 \times 50^2\right) \times 2(6 \times 2)$$

$$= 115.2 \text{ N}$$

At a point 1.3 m from the leading edge, $x = 1.3$ m

$$R_{ex} = 4.33 \times 10^6$$

Hence,
$$\delta = \frac{0.371x}{(R_{ex})^{1/5}} = \frac{0.371 \times 1.3}{(4.33 \times 10^6)^{1/5}}$$

$$= 0.02269 \text{ m or } 2.269 \times 10^{-2} \text{ m}$$

(ii) With a critical Reynolds number of 1×10^6, the distance x_c to transition point is obtained from the relation:

$$R_{xc} = \frac{U_0 x_c}{\nu} = 1 \times 10^6$$

∴
$$x_c = \frac{1 \times 10^6 \times (15 \times 10^{-6})}{50} = 0.3 \text{ m}$$

Consequently, the flow will be laminar to a point 0.3 m aft of the leading edge. The drag, on both sides from the laminar boundary layer region from A to B is

$$(F_D)_l = C_D \times \frac{1}{2}\rho U_0^2 \times \text{area of plate on both sides}$$

$$= \frac{1.328}{\sqrt{R_{ex}}} \times \frac{1}{2}\rho U_0^2 \times (2 \times \text{plate width } b \times \text{distance})$$

$$= \frac{1.328}{\sqrt{1 \times 10^6}} \times \left(\frac{1}{2} \times 1.2 \times 50^2\right) \times 2(6 \times 0.3)$$

$$= 7.17 \text{ N}$$

The drag on the remaining portion BC of the plate is due to the presence of turbulent boundary layer; this drag is calculated by first assuming that the drag over the entire plate AC is due to turbulent flow and then subtracting the drag over the region AB affected by laminar flow. The turbulent drag over the entire plate has been worked out to be $(FD)_l = 115.2$ N in part (ii) above. Fictitious turbulent drag for region AB is

$$(F_D)_{ft} = \frac{0.455}{(\log_{10} 10^6)^{2.58}} \times \left(\frac{1}{2} \times 1.2 \times 50^2\right) \times 2(6 \times 0.3)$$

$$= 24.14 \text{ N}$$

Therefore, drag over the entire plate with part laminar and part turbulent boundary layer flow is:

$$(F_D)_{fl} = (F_D)_l + (F_D)_t - (F_D)_{ft}$$

$$= 7.17 + 115.2 - 24.14 = 98.23 \text{ N}$$

Section : B

5. (a) Solution:

Assumption: Only latent heat of steam is used for heating purposes.

T_g = Generator temperature

= Saturation temperature of steam at 0.2 MPa

= 120.2 + 273 = 393.2 K

T_c = Condenser and absorber temperature

= 30 + 273 = 303 K

T_e = Evaporator temperature

= – 10 + 273 = 263 K

The maximum COP of the absorption refrigeration system is given by

$$(COP)_{max} = \frac{(T_g - T_c)T_e}{(T_c - T_e)T_g}$$

$$= \frac{(393.2 - 303) \times 263}{(303 - 263) \times 393.2} = \frac{90.2 \times 263}{40 \times 393.2} = 1.508 \quad \textbf{Ans.}$$

Also, Actual COP = 1.508 × 0.4 = 0.6032

Since,
$$COP = \frac{Q_E}{Q_G}$$

$$Q_G = \frac{Q_E}{COP} = \frac{20 \times 3.5167}{0.6032} = 116.60 \text{ kW}$$

Heat transferred by 1 kg of steam on condensation

$$= (h_f + xh_{fg}) - h_f = xh_{fg}$$

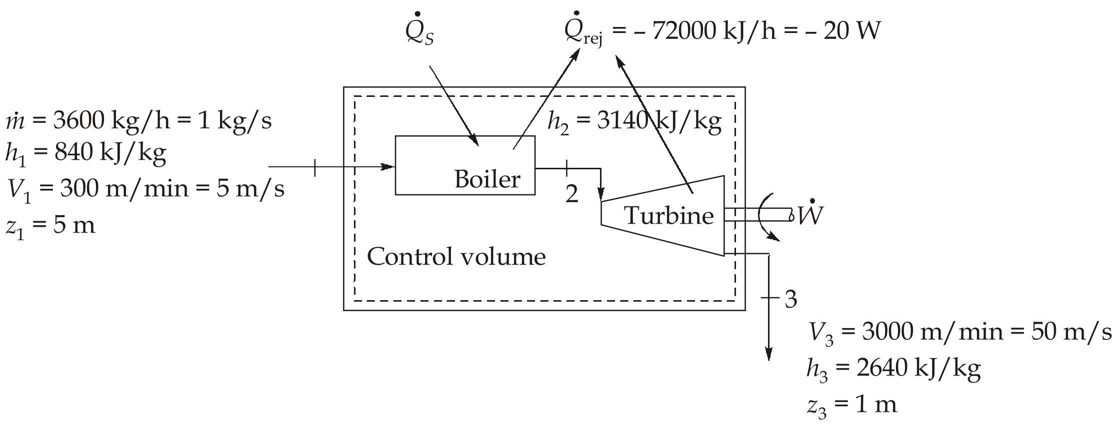
$$= 0.9 \times 2201.9 = 1981.71 \text{ kJ/kg}$$

Steam flow rate required per hour $= \dfrac{116.6}{1981.71}$

= 0.05884 kg/s or 3.5303 kg/min or 211.81 kg/hr **Ans.**

5. **(b) Solution:**

The steam power plant operates as a steady flow system as shown below:



Applying SFEE for the combined system:

$$\dot{Q} - \dot{W} = \dot{m}[\Delta h + \Delta kE + \Delta PE] \qquad \text{...(i)}$$

The net heat transfer rate:

$\dot{Q}$ = heat supplied to the boiler – heat rejected from the system

$$= \dot{m}(h_2 - h_1) - \dot{Q}_{\text{rejection}}$$

$$= 1(3140 - 840) - 20 = 2280 \text{ kJ/kg} \qquad \text{(for 1 kg/s)}$$

The change in specific enthalpy:

$$\Delta h = h_3 - h_1$$

$$= 2640 - 840 = 1800 \text{ kJ/kg}$$

$$\text{The change in kE} = \frac{V_3^2 - V_1^2}{2000} \text{ kJ/kg}$$

$$= \frac{50^2 - 5^2}{2000} = 1.237 \text{ kJ/kg}$$

$$\text{The change in PE} = g(z_3 - z_1)$$

$$= 9.81(1 - 5) \times 10^{-3} = -0.039 \text{ kJ/kg}$$

Substituting the values of these terms in SFEE:

$$2280 - \dot{W} = 1 \times [1800 + 1.237 - 0.0392]$$

$$\dot{W} = 478.8 \text{ kW}$$ **Ans.**

5. (c) Solution:

Given : Number of nozzles, n = 4; Nozzle diameter, d_j = 52 mm = 0.052 m; Coefficient of velocity, c_v = 0.98, Bucket mean diameter, D = 0.85 m; Relative reduction factor, $k = (1 - 0.16) = 0.84$; Jet deflection, $\phi = 180° - 165° = 15°$; Mechanical efficiency, $\eta_{mech} = 94\%$

Available head at the nozzle, $H = 300 - 32 = 268$ m

$$\text{Velocity of jet, } V_1 = c_v\sqrt{2gh} = 0.98 \times \sqrt{2 \times 9.81 \times 268} = 71.06 \text{ m/s}$$

$$\text{Bucket speed, } u = 0.46 \times \text{Jet velocity}$$

$$= 0.46 \times 71.06 = 32.69 \text{ m/s}$$

Total quantity of water flowing through the pipeline,

$$Q_T = n \times A \times V_1$$

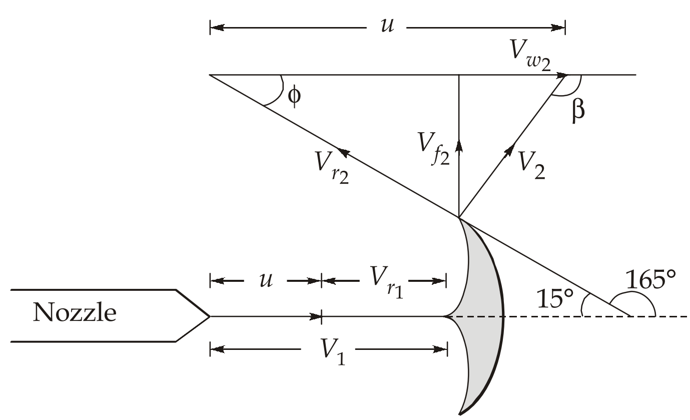
$$= 4 \times \left(\frac{\pi \times 0.052^2}{4}\right) \times 71.06 = 0.6036 \text{ m}^3/\text{s}$$

From Darcy equation for head loss through the pipeline,

$$h_f = \frac{4flV^2}{2gd} = \frac{32flQ^2}{\pi^2 gd^5}$$

$$d = \left[\frac{32fLQ^2}{\pi^2 g h_f}\right]^{1/5} = \left[\frac{32 \times 0.0058 \times 360 \times 0.6036^2}{\pi^2 \times 9.81 \times 32}\right]^{1/5}$$

$\Rightarrow$ $d = 0.38$ m **Ans.**



At inlet to turbine : $V_{w_1} = V_1 = 71.06$ m/s

$$V_{r_1} = V_1 - u = 71.06 - 32.69$$

$$= 38.37 \text{ m/s} \qquad (\because \; u_1 = u_2 = u)$$

At exit from turbine:

$$V_{r_2} = kV_{r_1} = 0.84 \times 38.37 = 32.23 \text{ m/s}$$

$$V_{r_2}\cos\phi = 32.23 \times \cos 15° = 31.13 \text{ m/s}$$

As $V_{r_2}\cos\phi$ is less than blade speed u_2, the velocity triangle at outlet will be as in above figure ($\beta > 90°$).

$$V_{w_2} = u_2 - V_{r_2}\cos\phi$$
$$= 32.69 - 31.13 = 1.56 \text{ m/s} \qquad [\because u_1 = u_2 = u]$$

$\therefore$ Bucket power, $RP = \rho Q(V_{w_1} - V_{w_2}) \cdot u$

$$= 1000 \times 0.6036 \times (71.06 - 1.56) \times 32.69$$

$$= 1371.35 \text{ kW}$$ **Ans.**

Also, water power, $WP = \rho Q g H$

$$= 1000 \times 0.6036 \times 9.81 \times 268$$

$$= 1586.91 \text{ kW}$$

$\therefore$ Hydraulic efficiency, $\eta_H = \dfrac{\text{Bucket power}}{\text{Water power}} = \dfrac{1371.40}{1586.91}$

$$= 0.8642 \text{ or } 86.42\%$$ **Ans.**

Overall efficiency, $\eta_0 = \eta_H \cdot \eta_m \cdot \eta_v$

Assuming that there is no leakage and volumetric efficiency equals 100%, then

$$\eta_0 = \eta_m \cdot \eta_H = 0.8642 \times 0.94$$

$$= 0.8123 \text{ or } 81.23\%$$ **Ans.**

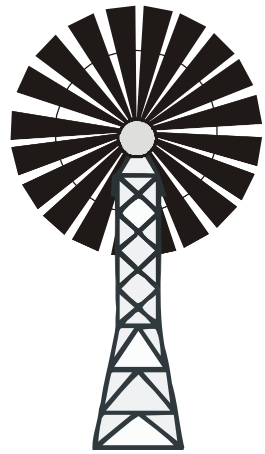
5. (d) Solution:

Types of Rotors :

Different types of rotors used in wind turbines are: (i) multiblade type, (ii) propeller type, (iii) Savonious type, and (iv) Darrieus type. The first two are installed in horizontal-axis turbines, while the last two in vertical-axis turbines.

Multiblade Rotor :

The multiblade rotor is fabricated from curved sheet metal blades. The width of blades increases outwards from the centre. Blades are fixed at their inner ends on a circular rim. They are also welded near their outer edge to another rim to provide a stable support. The number of blades used ranges from 12 to 18, as shown in figure.



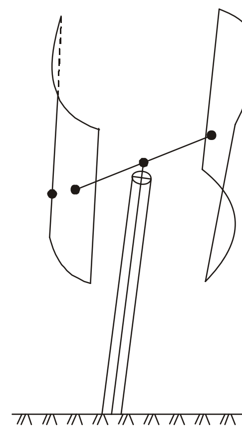
Propeller Rotor :

The propeller rotor comprises two or three aerodynamic blades made from strong but lightweight material such as fibre glass reinforced plastic. The diameter of the rotor ranges from 2 m to 25 m as detailed in figure. The blade slope is designed by using the same aerodynamic theory as for aircraft.

Propeller rotor installed on a tower

Savonious Rotor :

The Savonious rotor comprises two identical hollow semi-cylinders fixed to a vertical axis. The inner side of two half-cylinders face each other to have an S shaped cross section as detailed in figure.

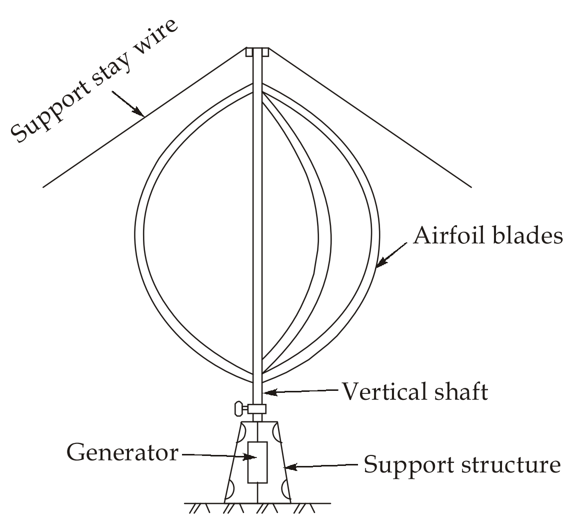


Savonious vertical-axis rotor

Irrespective of wind direction, the rotor rotates due to pressure difference between the two sides. This vertical axis rotor was developed by an engineer Savonious of Finland in the year 1920. It is self starting and the driving force is mainly of drag type. The rotor possesses high solidity so as to produce a high starting torque and hence this rotor is suitable for water pumping.

Darrieus Rotor :

This rotor has two or three thin curved blades of flexible metal strips. It looks like an egg beater and operates with the wind coming from any direction. Both the ends of the blades are attached to a vertical shaft as shown in figure. It has an advantage that it can be installed close to the ground eliminating the cost of the tower structure.



Darrieus rotor

Lift is the driving force, creating maximum torque when the blade moves across the wind. This rotor was designed by a French engineer G.M. Darrieus in 1925. It is used for decentralized electricity generation.

5. (e) Solution:

The turbojet engine is propelled by the thrust produced due to acceleration of hot combustion gases through the exhaust nozzle. Therefore at higher speed, the thrust developed is more and the Turbojet gives higher propulsive efficiency.

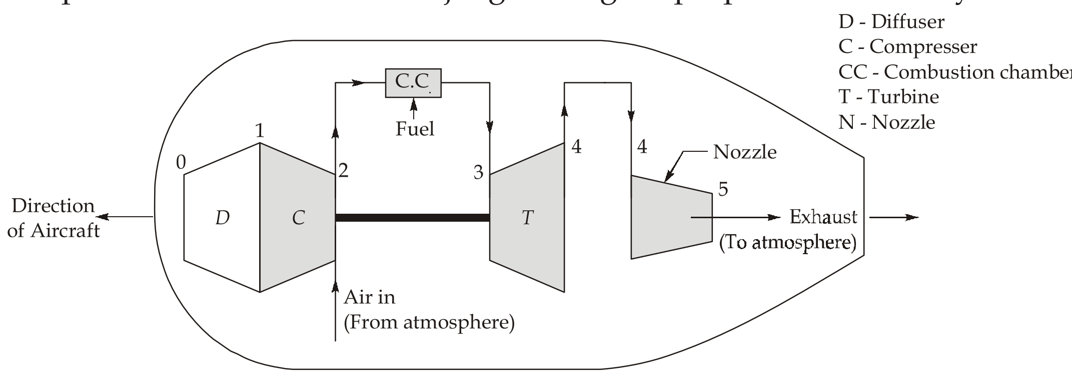


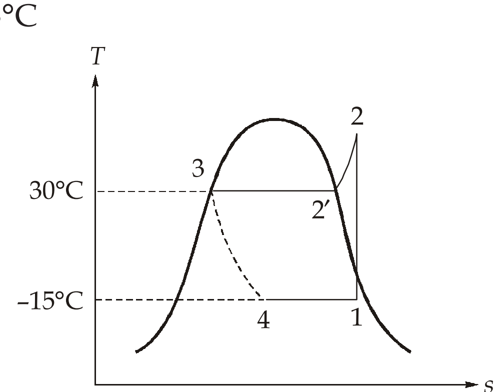
Figure: Gas turbine plant for Turbo-jet

- The engine consists of the following components:
  - Diffuser (D)
  - Mechanical compressor (C)
  - Combustion chamber (CC)
  - Mechanical turbine (T)
  - Exhaust nozzle (N)
- The function of the diffuser is to **convert the kinetic energy of the entering air into static pressure rise** which is achieved by the **ram effect**.
- The compressor used in a Turbojet can be either centrifugal type or axial flow type. The advantages of centrifugal compressors are high durability, ease of manufacturing and low cost, and good operation under adverse circumstances such as icing and when sand and small foreign particles are inhaled in inlet duct.

6. (a) Solution:

Given: Evaporator temperature = –15°C; Condenser temperature = 30°;

$\dot{m}$ = 5 kg/min; T_2 = 73°C



From table, $h_2' = 1469$ kJ/kg

$$h_4 = h_3 = 323.1 \text{ kJ/kg}$$

$$s_{2'} = 4.984 \text{ kJ/kgK}$$

$$s_3 = 1.204 \text{ kJ/kgK}$$

Now, enthalpy at point 2

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

$$= 1469 + 2.82 \times (73 - 30)$$

$$= 1590.26 \text{ kJ/kg}$$

Process 1-2 is isentropic:

$$s_2 = s_1$$

$$s_{2'} + C_p \ln\left[\frac{T_2}{T_{2'}}\right] = [s_f + x_1(s_g - s_f)]_{@\,-15°C}$$

$$4.984 + 2.82 \times \ln\left[\frac{73+273}{30+273}\right] = 0.457 + x_1 \times [5.549 - 0.457]$$

$$x_1 = 0.9625$$ **Ans.(iii)**

Enthalpy at point 1

$$h_1 = [h_f + x_1(h_g - h_f)]_{@-15°C}$$

$$= 112.3 + 0.9625 \times (1426 - 112.3)$$

$$= 1376.73 \text{ kJ/kg}$$

$$\text{Work done} = h_2 - h_1$$

$$W = 1590.69 - 1376.73 = 213.96 \text{ kJ/kg}$$

$$\text{Refrigerating effect} = h_1 - h_4$$

$$= 1376.73 - 323.1 = 1053.63 \text{ kJ/kg}$$

$$\text{COP} = \frac{R.E.}{W} = \frac{1053.63}{213.96} = 4.924$$ **Ans.(i)**

Amount of heat extracted for producing ice at -6°C from 24°C

$$= C_{pw}(24 - 0) + h_{fg} + C_{pice}[0 - (-6)]$$

$$= 4.187 \times 24 + 336 + 2.1 \times 6$$

$$= 449.08 \text{ kJ/kg}$$

$$\text{Cooling effect produced} = \dot{m} \times (h_1 - h_4)$$
$$= 5 \times 1053.69 = 5268.15 \text{ kJ/min}$$

$$\therefore \quad \text{Mass of ice produced} = \frac{5268.15}{449.08} = 11.73 \text{ kg/min} = 703.8 \text{ kg/hr}$$ **Ans.(ii)**

$$\text{Heat rejected in the condenser} = \dot{m}(h_2 - h_3) = 5 \times (159069 - 3231)$$
$$= 6337.95 \text{ kJ/min or } 105.63 \text{ kW}$$ **Ans.(iv)**

$$\text{Displacement of the compressor} = \dot{m}(v_{g1})$$

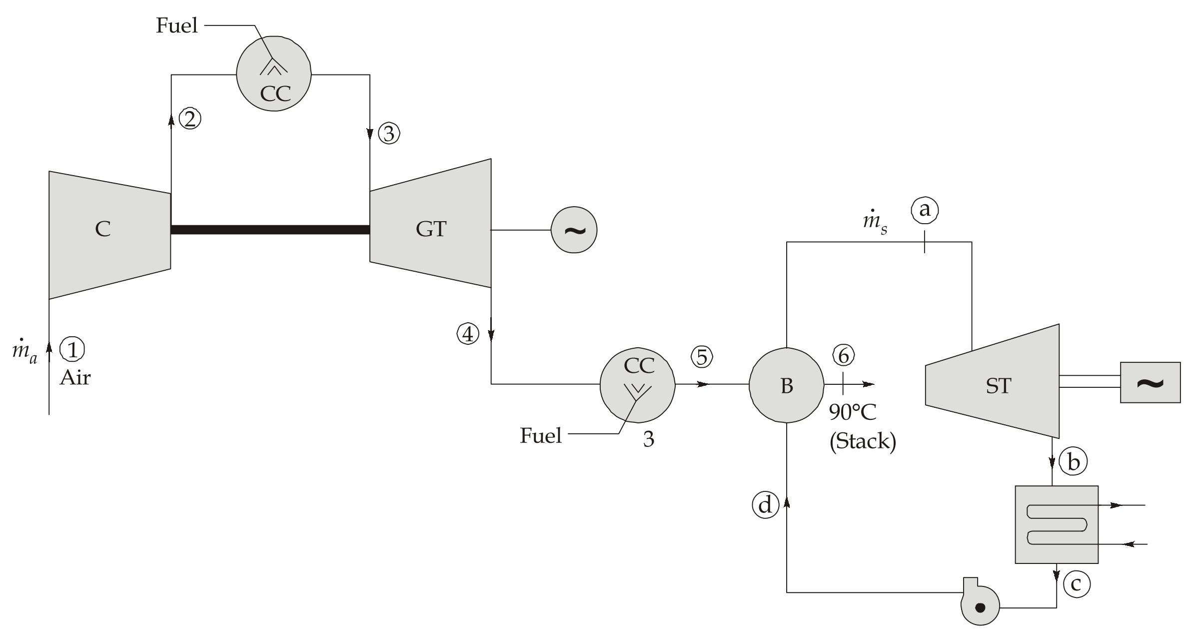
$$v_{g1} = [v_f + x_1(v_g - v_f)]_{@-15°C}$$

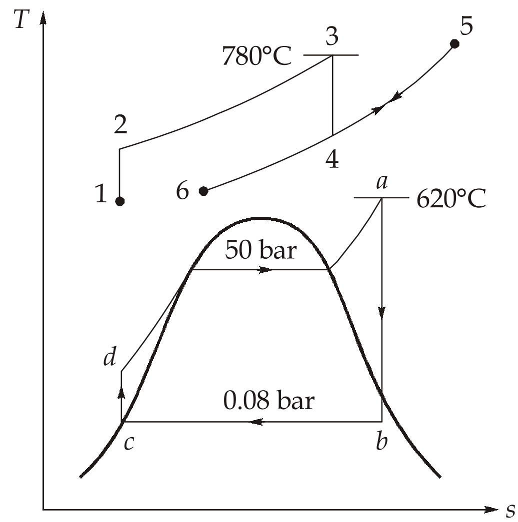
$$v_{g1} = 0.00152 + 0.9625 \times (0.509 - 0.00152)$$

$$v_{g1} = 0.4899 \text{ m}^3/\text{kg}$$

$$\text{Displacement of compressor} = 5 \times 0.4899 = 2.4495 \text{ m}^3/\text{kg}$$ **Ans.(v)**

6. (b) Solution:





(i) For gas turbine,
$$\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}}$$

$$T_2 = (273+20)(8)^{\frac{0.4}{1.4}}$$

$$T_2 = 530.75 \text{ K}$$

$$\frac{T_4}{T_3} = \left(\frac{P_4}{P_3}\right)^{\frac{\gamma-1}{\gamma}}$$

$\Rightarrow$
$$T_4 = \frac{(780+273)}{(8)^{0.33/1.33}} = 628.56 \text{ K}$$

Network done by gas turbine,

$$(W_{net})_{GT} = \dot{m}_a c_{pg}(T_3 - T_4) - \dot{m}_a c_{pa}(T_2 - T_1)$$

$$(W_{net})_{GT} = \dot{m}_a \times 1.11(1053 - 628.56) - \dot{m}_a \times 1.005 \times (530.75 - 293)$$

$$(W_{net})_{GT} = \dot{m}_a \times 232.189 \text{ kW}$$

From steam table,

At 50 bar, $s_a = 7.3131$ kJ/kg

$h_a = 3713.3$ kJ/kgK

At 0.08 bar, $h_f = 173.84$ kJ/kg, $s_f = 0.59249$ kJ/kgK

$h_{fg} = 2402.4$ kJ/kg, $s_{fg} = 7.6348$ kJ/kgK

$$s_a = s_b = s_f + x_b s_{fg}$$

$$7.3131 = 0.59249 + x_b \times 7.6348$$

$$x_b = 0.880$$

$$h_b = 173.84 + 0.88 \times 2402.4$$

$$= 2287.95 \text{ kJ/kg}$$

Word done by steam turbine,

$$W_{ST} = \dot{m}_s (h_a - h_b)$$

$$= \dot{m}_s (3713.3 - 2287.95)$$

$$= \dot{m}_s \times 1425.348 \text{ kW}$$

$$\text{Total output} = 220 \times 10^3 \text{ kW}$$

$$W_{GT} + W_{ST} = 220 \times 10^3 \text{ kW}$$

$$\dot{m}_a \times 232.189 + \dot{m}_s \times 1425.348 = 220 \times 10^3 \quad \text{...(i)}$$

Now, $\dot{m}_a c_{pg} (T_5 - T_6) = \dot{m}_s (h_a - h_d)$

Neglecting pump work, $h_c = h_d$

$$\dot{m}_a \times 1.11(1053 - 363) = \dot{m}_s \times (3713.3 - 173.84)$$

$$\dot{m}_a = 4.621 \times \dot{m}_s \quad \text{...(ii)}$$

On solving equation (i) and (ii),

$$\dot{m}_s = 88.06 \text{ kg/s}$$

and $\dot{m}_a = 4.621 \times 84.085 = 406.93$ kg/s

(ii) $$(W_{net})_{GT} = \frac{406.93 \times 232.189}{10^3} MW = 94.48 \text{ MW}$$ **Ans.**

$$(W_{net})_{ST} = \frac{88.06 \times 1425.348}{10^3} MW = 125.52 \text{ MW}$$ **Ans.**

(iii) Total heat added, $\dot{Q}_1 = \dot{m}_a c_{pg} (T_3 - T_2 + T_5 - T_4)$

$$\dot{Q}_1 = \frac{406.93 \times 1.11}{10^3} \times (1053 - 530.75 + 1053 - 628.56) \text{MW}$$

$$\dot{Q}_1 = 427.613 \text{ MW}$$

$$\text{Efficiency, } \eta_{cycle} = \frac{\dot{W}_{net}}{\dot{Q}_1} = \frac{220}{427.613} = 0.5147$$

$$\eta_{cycle} = 51.45\%$$ **Ans.**

(iv)

$$Q_1 = \dot{m}_f \times 44 \times 10^3 = \dot{m}_a \times c_{pg} \times (T_3 - T_2 + T_5 - T_4)$$

$$\frac{\dot{m}_f}{\dot{m}_a} = \frac{1.11 \times (1053 - 530.75 + 1053 - 628.56)}{44 \times 10^3}$$

$$\text{Air fuel ratio, } \frac{m_a}{m_f} = 41.872$$ **Ans.**

6. (c) (i) Solution:

Concentration ratio for compound parabolic concentrator (CPC) is given as

$$CR = \frac{1}{\sin\theta_A} \quad (\text{where } 2\theta_A = \text{acceptance angle} = 20°)$$

$$CR = \frac{1}{\sin 10°} = 5.76$$ **Ans.**

$$\text{Aperture, } W = CR \times \text{width of absorber plate}$$

$$= 5.76 \times 15 = 86.4 \text{ cm}$$

The ratio of height to aperture can be expressed as

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

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

$$H = 3.328 \times W = 3.328 \times 86.4 = 287.54 \text{ cm}$$ **Ans.**

The surface area of the concentrate can be given as (for $CR > 3$)

$$\frac{\text{Concentrator area}}{\text{aperture area}} = \frac{A_{conc}}{A_a} = 1 + c$$

$$\frac{A_{conc}}{WL} = 1 + 5.76 = 6.76$$

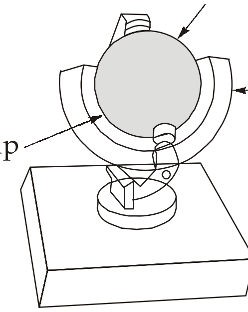
$$A_{conc} = 6.76 \times 0.864 \times 1.5 = 8.76 \text{ m}^2$$ **Ans.**

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

Sunshine Recorder : A sunshine recorder is a device used to measure the "hours of bright sunshine in a day".

The description of a sunshine recorder is given below:

Construction: It consist of a "glass-sphere" installed in a section of "spherical metal bowl" having grooves for holding a "recorder card strip" and the glass sphere.

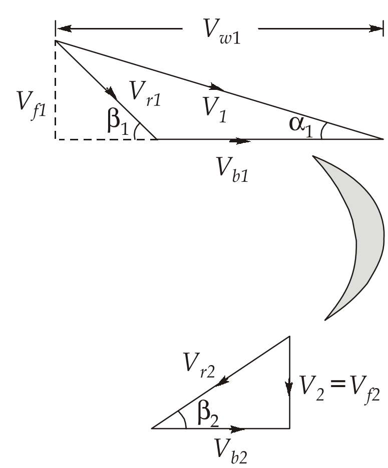


Sunshine recorder

Working: The glass-sphere, which acts as a convex lens, focusses the sun's rays/beams to a point on the card strip held in a groove in the spherical bowl mounted concentrically with the sphere.

Whenever there is a bright sunshine, the image formed is intense enough to burn a spot on the card strip. Through the day, the sun moves across the sky, the image moves along the strip. Thus a burnt space whose length is proportional to the duration of sunshine is obtained on the strip.

7. **(a) Solution:**



Flow ratio: $\dfrac{V_{f1}}{\sqrt{2gH}} = 0.22$

$$V_{f1} = \sqrt{2\times 9.81\times 80}\times 0.22 = 8.716 \text{ m/s} = V_{f2}$$

$$A_b = 0.94\ \pi D_1 B_1$$

Since discharge at outlet is radial,

$$V_{w2} = 0,\ V_{f2} = V_2 = 8.716 \text{ m/s}$$

$$\text{Overall efficiency, } \eta_0 = \frac{\text{Shaft power}}{\text{Water power}} = \frac{360}{9.81 \times Q \times 80}$$

$$Q = \frac{360}{9.81 \times 80 \times 0.82} = 0.5594 \text{ m}^3/\text{s}$$

$$\text{Width ratio, } \frac{B}{D} = 0.1,\ D_1 = D_2 \times 2$$

$$Q = 0.94\ \pi D_1 B_1 \times V_{f1}$$

$$0.5594 = 0.94 \times \pi D_1 \times 0.1 D_1 \times 8.716$$

$$D_1 = 0.4662 \text{ m}$$ **Ans. (iii)**

$$B_1 = 0.1 \times 0.4662 = 0.04662 \text{ m or } 4.662 \text{ cm}$$ **Ans. (iv)**

$$D_2 = \frac{D_1}{2} = \frac{0.4662}{2} = 0.2331 \text{ m}$$ **Ans. (iii)**

$$V_{bl} = \frac{\pi D_1 N}{60} = \frac{\pi \times 0.4662 \times 800}{60} = 19.53 \text{ m/s}$$

$$\text{Hydraulic efficiency, } \eta_h = \frac{V_{w1} V_{bl}}{gH}$$

$$V_{w1} = \frac{gH\eta_h}{V_{bl}} = \frac{9.81 \times 80 \times 0.92}{19.53} = 36.97 \text{ m/s}$$

$$\tan\alpha_1 = \frac{V_{f1}}{V_{w1}} = \frac{8.716}{36.97} = 0.23576$$

$$\alpha_1 = 13.2657°$$ **Ans. (i)**

$$\tan\beta_1 = \frac{V_{f1}}{V_{w1} - V_{bl}} = \frac{8.716}{36.97 - 19.53} = 0.49977$$

$$\beta_1 = 26.554°$$ **Ans. (ii)**

$$\tan\beta_2 = \frac{V_{f2}}{V_{b2}}$$

$$\frac{V_{bl}}{r_1} = \frac{V_{b2}}{r_2} = \omega = \frac{2\pi N}{60}$$

$$V_{b2} = \frac{D_2}{D_1} \times V_{bl} = \frac{19.53}{2} = 9.765 \text{ m/s}$$

$$\tan\beta_2 = \frac{8.716}{9.765} = 0.8926$$

$$\beta_2 = 41.75°$$ **Ans. (ii)**

7. (b) Solution:

Given : $\Delta G° = -177.40$ kJ/mol; $\Delta H° = -250.42$ kJ/mol

The electrical work output per mole of fuel (methanol) consumed:

$$\Delta W = -\Delta G = 177.40 \text{ kJ}$$

That means, 177.40 kJ electrical work is produced from 1 mole (i.e., 32 g) of methanol and $\frac{3}{2}$ mole (i.e., 1.5 × 32 g) of oxygen.

In other words, 177..40 kW electrical power is produced from flow rate of 32 g/s of methanol and 48 g/s of oxygen.

Required flow rate of methanol for electrical output of 100 kW is

$$= \frac{32 \times 100}{177.40} = 18.038 \text{ g/s} = 64.93 \text{ kg/h}$$

Required flow rate of oxygen for electrical output of 100 kW

$$= \frac{48 \times 100}{177.40} = 27.057 \text{ g/s} = 97.406 \text{ kg/h}$$

The heat transferred is given by

$$\Delta Q = T\Delta S,$$

which from, may be written as

$$\Delta Q = \Delta H° - \Delta G°$$
$$= -250.42 + 177.40 = -73.02 \text{ kJ/mol}$$

The negative sign indicates that heat is removed from the cell and transferred to the surroundings.

Thus 1 mole (i.e., 32 g) of methanol produces 73.02 kJ of heat.

As calculated above, the fuel consumption rate for 100 kW electrical power generation is 18.038 g/s.

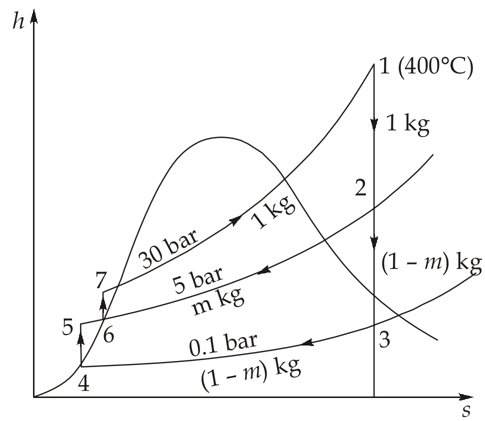
Consumption of fuel at the rate 18.038 g/s produces heat at the rate of

$$\frac{73.02 \times 18.038}{32} = 41.16 \text{ kJ/s}$$

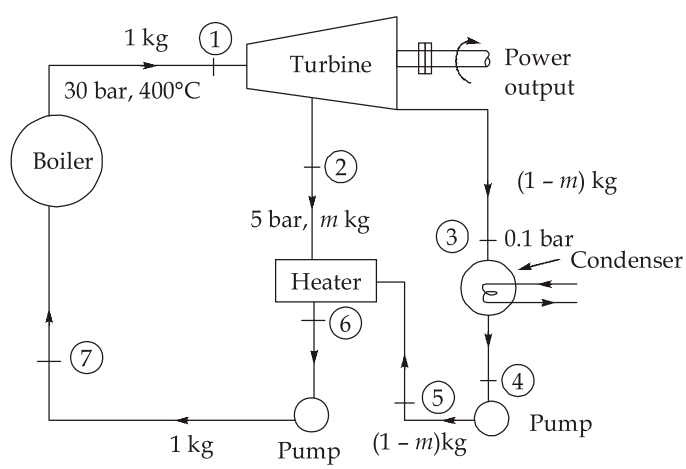
Thus, the required heat removal rate from the cell at electrical output of 100 kW is 41.16 kJ/s or 41.16 kW.

7. (c) Solution:

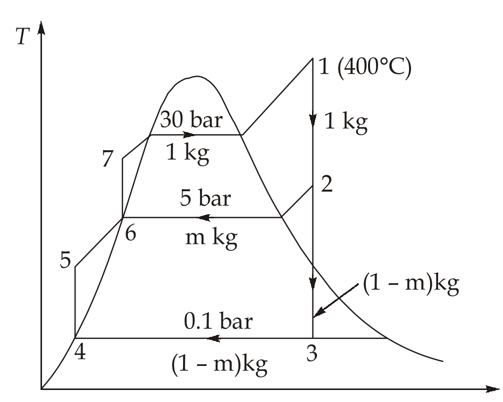
(i) Processes on h-s plane can be shown as below:



(ii) Schematic of power plant is shown below:



(iii) T-s diagram,



For process 2–3 : $s_2 = s_1$

$$6.921 = s_{f3} + x_3 s_{fg3} = 0.649 + x_3 \times 7.501$$

$$x_3 = \frac{6.921 - 0.649}{7.501} = 0.836$$

$$h_3 = h_{f3} + x_3 h_{fg3} = 191.8 + 0.836 \times 2392.8 = 2192.2 \text{ kJ/kg}$$

Since pump work is neglected,

$$h_{f4} = 191.8 \text{ kJ/kg} = h_{f5}$$

$$h_{f6} = 640.1 \text{ kJ/kg (at 5 bar)} = h_{f7}$$

Energy balance for heater gives

$$m(h_2 - h_{f6}) = (1 - m)(h_{f6} - h_{f5})$$

$$m(2796 - 640.1) = (1 - m)\ (640.1 - 191.8) = 448.3\ (1 - m)$$

$$2155.9 \text{ m} = 448.3 - 448.3 \text{ m}$$

$$m = \frac{448.3}{(2155.9 + 448.3)} = 0.172 \text{ kg}$$

Turbine work, $W_T = (h_1 - h_2) + (1 - m)\ (h_2 - h_3)$

$$= (3230.9 - 2796) + (1 - 0.172)\ (2796 - 2192.2)$$

$$= 434.9 + 499.9 = 934.8 \text{ kJ/kg}$$

Heat supplied, $Q_1 = h_1 - h_{f6}$

$$= 3230.9 - 640.1 = 2590.8 \text{ kJ/kg}$$

$$\eta_{cycle} = \frac{W_T}{Q_1} = \frac{934.8}{2590.8} = 0.3608 \text{ or } 36.08\ \%$$ **Ans.**

$$\text{Steam rate} = \frac{3600}{934.8} = 3.85 \text{ kg/kWh}$$ **Ans.**

(iv) Mean temperature of heat addition (with regeneration)

$$T_{m1} = \frac{h_1 - h_{f7}}{s_1 - s_7} = \frac{3230.9 - 640.1}{6.921 - 1.8604} = 511.9 \text{ K or } 238.9°\text{C}$$

Mean temperature of heat addition (without regeneration)

$$T_{m1} = \frac{h_1 - h_{f4}}{s_1 - s_4} = \frac{3230.9 - 191.8}{6.921 - 0.649} = \frac{3039.1}{6.272}$$

$$= 484.5 \text{ K or } 211.5°\text{C}$$

Increase in T_{m1} due to regeneration

$$= 238.9 - 211.5 = 27.4°\text{C}$$ **Ans.**

Work output (without regeneration)

$$= h_1 - h_3 = 3230.9 - 2192.2 = 1038.7 \text{ kJ/kg}$$

Steam rate without regeneration

$$= \frac{3600}{W_T} = \frac{3600}{1038.7} = 3.46 \text{ kg/kWh}$$

Increase in steam rate due to regeneration

$$= 3.85 - 3.46 = 0.39 \text{ kg/kWh}$$ **Ans.**

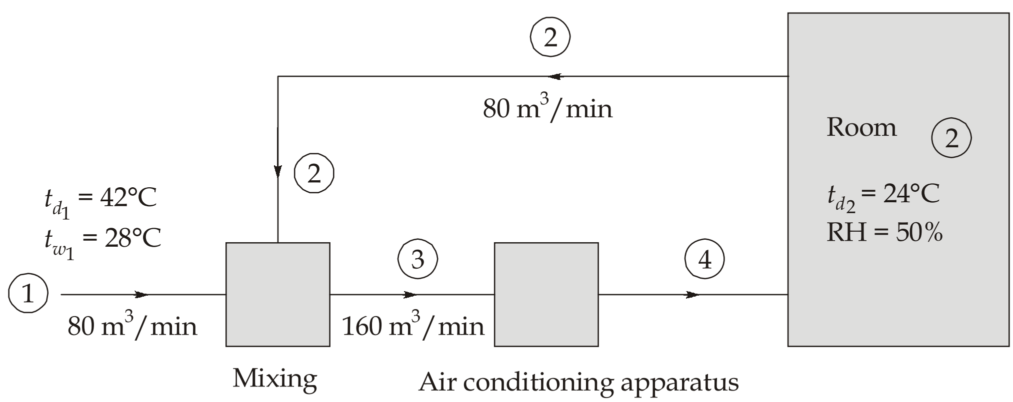
$$\eta_{cycle} \text{ (without regeneration)} = \frac{h_1 - h_3}{h_1 - h_{f4}} = \frac{1038.7}{3230.9 - 191.8} = 0.3418 \text{ or } 34.18\%$$

Increase in cycle efficiency due to regeneration

$$= 36.08 - 34.18 = 1.9\%$$ **Ans.**

8. (a) Solution:

Given : t_{d1} = 42°C, t_{w1} = 28°C, t_{d2} = 24°C, RH = 50%; RSHF = 0.8, ρ_a = 1.2 kg/m^3



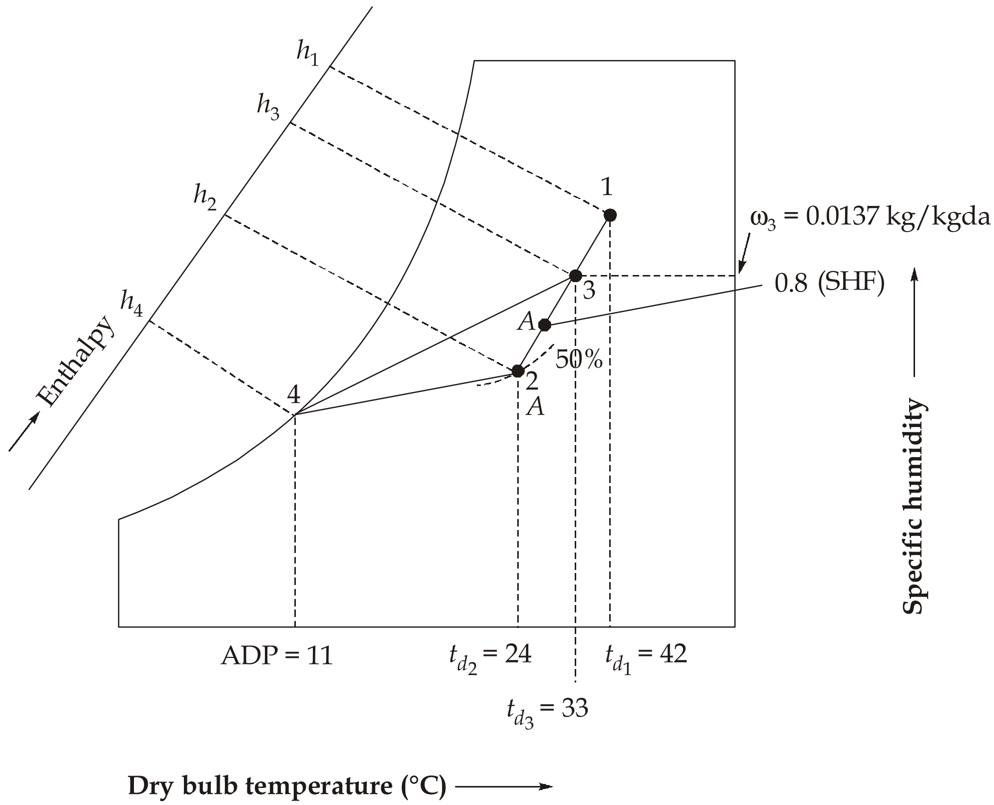
Mark inside and outside condition on psychrometric chart as point (2) and (1) respectively. Since 50% of the room air and 50% of fresh air is added before entering the air conditioning apparatus, mark point 3 on the line 1-2 such that

$$\text{Length 2 - 3} = \frac{\text{Length 1-2}}{2}$$

which gives t_3 = 33°C

Now, mark the given value of RSHF (0.8) on the room sensible heat factor scale and join this with the alignment circle (i.e. 26°C DBT and 50% RH). From point 2 draw a line 2-4 parallel to this line. This line is called RSHF line.

From psychrometric chart,



$h_2 = 48$ kJ/kg; $h_1 = 90$ kJ/kg; $h_3 = 69$ kJ/kg; $h_4 = 32$ kJ/kg

(i) Mass of air supplied to the room,

$$m_a = v_3 \times \rho_a$$
$$= (80 + 80) \times 1.2$$
$$= 192 \text{ kg/min}$$

$$\text{RSH} = m_a c_{pm}(t_{d_2} - t_{d_4})$$
$$= 192 \times 1.005 \times (24 - 11) = 2508.48 \text{ kJ/min} = 41.81 \text{ kW}$$

$$\text{Room total heat load, RTH} = m_a(h_2 - h_4)$$
$$= \frac{192}{60} \times (48 - 32) = 51.2 \text{ kW}$$

$$\text{Room Latent heat} = \text{RTH} - \text{RSH}$$
$$= 51.2 - 41.81 = 9.39 \text{ kW}$$

(ii) Mass of fresh air = $v_1 \times \rho_a$

$$\dot{m}_f = 80 \times 1.2 = 96 \text{ kg/min}$$

Sensible heat load due to fresh air

$$= \dot{m}_f c_{pm} \left(t_{d_1} - t_{d_2}\right)$$

$$= 96 \times 1.005 \times (42 - 24) = 1736.64 \text{ kJ/min} = 28.94 \text{ kW}$$

Total heat load due to fresh air $= \dot{m}_f \times (h_1 - h_2) = \dfrac{96}{60} \times (90 - 48) = 67.2 \text{ kW}$

Latent heat load due to fresh air = Total heat load – Sensible heat load

= 67.2 – 28.94

= 38.26 kW

(iii) Apparatus dew point, t_{d4} = 11°C

Humidity ratio and dry bulb temperature of air entering air conditioning apparatus

$$\omega_3 = 0.0137 \text{ kg/kg of dry air}$$

$$t_{d3} = 33°\text{C}$$

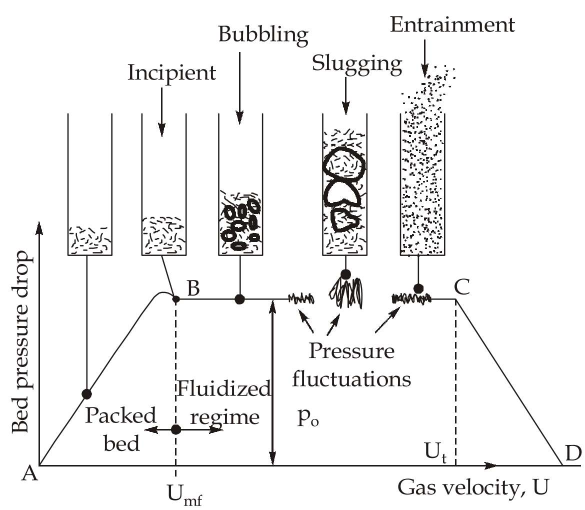
8. **(b) (i) Solution:**

Working of bubbling bed fluidized boiler:

When an evenly distributed air or gas is passed upward through a finely divided bed of solid particles such as sand supported on a fine mesh, the particles are undisturbed at low velocity. As air velocity is gradually increased, a stage is reached when the individual particles are suspended in the air stream – the bed is called "fluidized". With further increase in air velocity, there is bubble formation, vigorous turbulence, rapid mixing and formation of dense defined bed surface. The bed of solid particles exhibit the properties of a boiling liquid and assumes the appearance of a fluid – "bubbling fluidized bed". At higher velocities, bubbles disappear, and particles are blown out of the bed. Therefore, some amounts of particles have to be recirculated to maintain a stable system – "circulating fluidized bed". Fluidization depends largely on the particle size and the air velocity.

The mean solids velocity increases at a slower rate than does the gas velocity. The difference between the mean solid velocity and mean gas velocity is called as slip velocity. Maximum slip velocity between the solids and the gas is desirable for good heat transfer and intimate contact. If sand particles in a fluidised state is heated to the ignition temperatures of coal, and coal is injected continuously into the bed, the coal will burn rapidly and bed attains a uniform temperature. The fluidised bed combustion (FBC) takes place at about 840°C to 950°C. Since this temperature is much below the ash fusion temperature, melting of ash and associated problems are avoided.

The lower combustion temperature is achieved because of high coefficient of heat transfer due to rapid mixing in the fluidised bed and effective extraction of heat from the bed through in-bed heat transfer tubes and walls of the bed. The gas velocity is maintained between minimum fluidisation velocity and particle entrainment velocity. This ensures stable operation of the bed and avoids particle entrainment in the gas stream.



Variation of bed pressure drop with superficial velocity

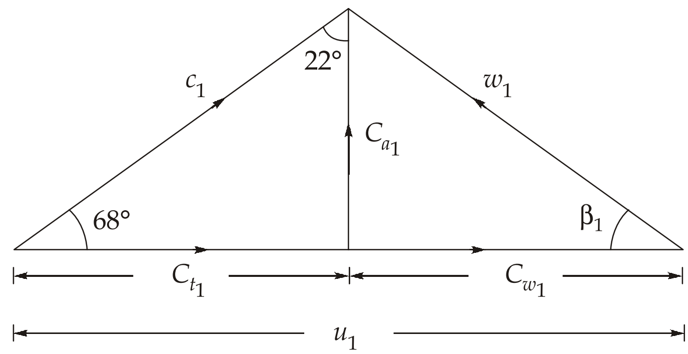
Combustion process requires the three "T"s that is Time, Temperature and Turbulence. In FBC, turbulence is promoted by fluidisation. Improved mixing generates evenly distributed heat at lower temperature. Residence time is many times greater than conventional grate firing.

Thus an FBC system releases heat more efficiently at lower temperatures.

Since limestone is used as particle bed, control of sulphur dioxide and nitrogen oxide emissions in the combustion chamber is achieved without any additional control equipment. This is one of the major advantages over conventional boilers. There are three basic types of fluidised bed combustion boilers:

1. Atmospheric classic Fluidised Bed Combustion System (AFBC)
2. Atmospheric circulating (fast) Fluidised Bed Combustion system(CFBC)
3. Pressurised Fluidised Bed Combustion System (PFBC).

8. (b) (ii) Solution:



$$\frac{T_{02}}{T_{01}} = \left(\frac{p_{02}}{p_{01}}\right)^{\frac{\gamma-1}{\gamma}}$$

$$T_{02} = 290 \times \left(\frac{4}{1}\right)^{\frac{0.4}{1.4}} = 430.94 \text{ K}$$

Isentropic temperature rise

$$T_{02} - T_{01} = 430.94 - 290 = 140.94 \text{ K}$$

$$\text{Actual temperature rise, } \Delta T = \frac{\text{Isentropic temperature rise}}{\text{Isentropic efficiency}}$$

$$= \frac{140.94}{0.82} = 171.88 \text{ K}$$

Power input per unit mass flow rate

$$= C_p \times \Delta T = 1.005 \times 171.88 = 172.74 \text{ kJ/kg}$$

$$c_1 = 160 \text{ m/s}$$

$$u_1 = \frac{\pi \times \text{Mean diameter of eye} \times 16000}{60}$$

$$= \frac{\pi \times 0.240 \times 16000}{60} = 201.06 \text{ m/s}$$

$$c_{t1} = c_1 \sin 22° = 160 \times \sin 22° = 59.94 \text{ m/s}$$

At exit,

Gas Turbines, $$u_2 = \frac{\pi \times \text{Impeller tip dia} \times 16000}{60}$$

$$= \frac{\pi \times 0.62 \times 16000}{60} = 519.41 \text{ m/s}$$

Power input unit mass flow rate = $u_2 c_{t2} - u_1 c_{t1}$

$$177.74 \times 10^3 = 519.41 \times c_{t2} - 201.06 \times 59.94$$

$$c_{t2} = 355.77 \text{ m/s}$$

$$\text{Slip factor, } \mu = \frac{c_{t2}}{u_2} = \frac{355.77}{519.41} = 0.685$$ **Ans.**

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

Plastic solar cells with the help of nanotechnology:

Photovoltaic devices will be used more and more in the near future as the production cost goes down. The fabrication of a simple semiconductor cell is a complex process and requires controlled conditions of high vacuum with temperature between 400°C and 1400°C.

Ever since the discovery of conducting plastic in 1977, there has been a constant quest to use these materials for the fabrication of solar cells. Plastic solar cells can be made in bulk quantities with lower cost, though their efficiency to convert solar radiation into electricity is low compared to semiconductor cells. A new generation solar cell that combines nanotechnology with plastic electronics has been launched with the development of a semiconductor polymer photovoltaic device. Such hybrid solar cells will be cheaper and easier to make in a variety of shapes.

Semiconductor nano-rods are used to fabricate energy efficient hybrid solar cells together with polymers. Hybrid materials, i.e., semiconductors and polymers provide a double advantage. Inorganic semiconductors with excellent electronic properties are good for solar cells. Organic polymers can be suitably processed at room temperature which is economical, and also allows to use fully flexible substrates like plastics.

In a semiconductor solar cell, the two poles are made from n-type and p-type semiconductors. In a plastic solar cell they are made from hole-acceptor and electron-acceptor polymers.

To fabricate such a hybrid solar cell, a semi-crystalline polymer known as poly (3-hexylth iophene) is used for the hole-acceptor, i.e., negative pole, and nanometre (nm) sized (7 nm diameter and 60 nm length) cadmium salenide (CdSe) rods for positive pole. The use of rod-shaped nano crystals provides a direct path for electron transport and is a basic requirement to improve the performance of the solar cell. This type of hybrid solar cell (plastic PV device) has achieved a monochromatic power conversion efficiency of 6.9%. To attain a higher efficiency, an important step is to increase the amount of sunlight absorbed in the red part of the spectrum.

8. (c) (ii) Solution:

The required array output is composed of the load and the battery recharge current as given.

The average load given is 67 W for 24 h. For continuous seven days under cloudy weather condition, we get 67 × 24 × 7 = 11.256 kWh.

Therefore, input power required for battery charging is $\frac{11.256}{0.6} = 18.76$ kWh

To recharge the battery in 3 days, each day having 9.7 h of sunshine in winter, the array must provide the following output.

Thus, the array output capability (P_a) is

$$P_a = \frac{18.76\times10^3}{(9.7\times3)} \text{ (for the battery recharging)} + \frac{67}{0.6} \text{ (for the load during 9.7 h)} + \frac{67(24-9.7)}{(9.7\times0.6)}$$

(to carry the daily load through night)

$$P_a = 644.67 + 111.67 + 164.62 = 920.96 \text{ W} = 0.921 \text{ kW}$$

$$\text{Daily average insolation } D_1 = \frac{181}{(9.7\times30)} = 0.622 \text{ kW/m}^2$$

The required area of solar array (S.A.) is,

$$\text{S.A.} = \frac{P_a}{(D_1 \eta F)}$$

$$= \frac{0.921\times10^3}{(0.622\times10^3\times0.10\times0.5)} = 29.61 \text{ m}^2$$

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