Detailed Solutions

ESE-2025 Mains Test Series

Mechanical Engineering Test No : 5

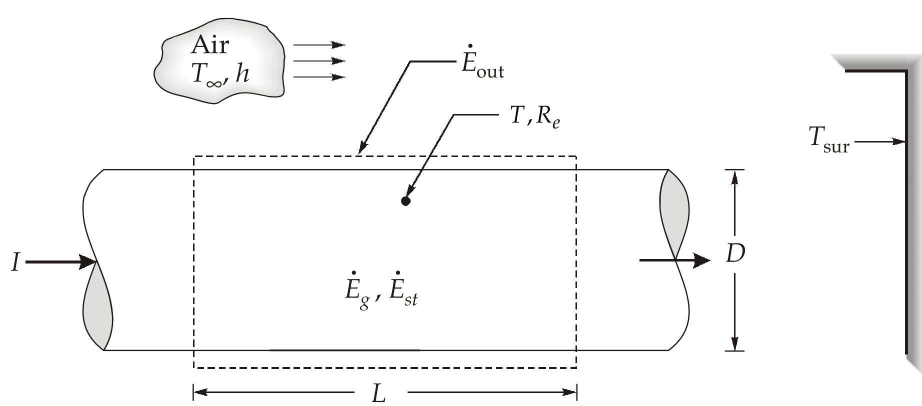
Section A : Heat Transfer + Renewable Sources of Energy

1. (a)

Assumptions :

1. At any time *t* the temperature of the rod is uniform.
2. Constant properties.
3. Radiation exchange between the outer surface of the rod and the surroundings is between a small, diffuse-gray surface and large, isothermal surrounding.

The temperature of a rod changes with time due to passage of an electrical current.



Applying first law of thermodynamics to a system of length L

We get,

Energy generate – Energy out = Energy storage

$$\dot{E}_g - \dot{E}_{out} = \dot{E}_{st} \quad ...(i)$$

Also, the energy generation due to the electric resistance heating is given by

$$\dot{E}_g = I^2 R_e L \quad ...(ii)$$

Energy outflow due to convection and net radiation leaving the surface is given by

$$\dot{E}_{out} = h(\pi DL)(T - T_\infty) + \varepsilon\sigma(\pi DL)\left(T^4 - T_{surr}^4\right) \quad ...(iii)$$

The change in energy storage due to the temperature change is

$$\dot{E}_{st} = \frac{dU}{dt} = \rho c V \frac{dT}{dt} \quad ...(iv)$$

where ρ and c are the density and the specific heat, respectively, of the rod material, and V is the volume of the rod,

Also $$V = \left(\frac{\pi D^2}{4}\right)L,$$

Substituting equation (ii), (iii) and (iv) in equation (i),

We get, $I^2 R_e L - h(\pi DL)(T - T_\infty) - \varepsilon\sigma(\pi DL)\left(T^4 - T_{sur}^4\right) = \rho c\left(\frac{\pi D^2}{4}\right)L\frac{dT}{dt}$

Hence, the time rate of change of the rod temperature is

$$\frac{dT}{dt} = \frac{I^2 R_e - \pi Dh(T - T_\infty) - \pi D\varepsilon\sigma\left(T^4 - T_{sur}^4\right)}{\rho c\left(\frac{\pi D^2}{4}\right)}$$

1. (b)

Break power of engine = 200 kW

80% diesel replacement, now 80% power will be produced by biomass (producer gas).

Power by biomass = 0.8 × total brake power

= 0.8 × 200 = 160 kW

Actual total power of biomass used,

$$\text{Heat supplied} = \frac{\text{Power by biomass}}{\eta_{gasifier} \times \eta_{engine}}$$

$$= \frac{160}{0.75 \times 0.35} = 609.5238 \text{ kW}$$

$$\text{Mass flow rate of biomass required} = \frac{\text{Heat supplied}}{\text{Calorific value of fuel}}$$

$$= \frac{609.5238}{17000} = \frac{609.5238 \times 3600}{17000} = 129.0756 \text{ kg/h}$$ **Ans**

1. (c)

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

Reversible thermochemical reactions of the type A + B + AHC + D may also be used for the same purpose. Some of the possible reactions suitable for thermochemical energy storage are

Reaction	ΔH (kJ/g-mole of reactants or products)	Turning temperature (°C)
$CH_4 + CO_2 \leftrightarrow 2CO + 2H_2$	247.4	960
$CH_4 + H_2O \leftrightarrow CO + 3H_2$	250.31	677

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

Some of the advantages of reversible chemical reaction storage systems are:

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

The temperature above which the equilibrium shifts to forward direction and below that it shifts to reverse direction is known as turning temperature.

1. (d)

Assumptions : Surface a diffuse emitter.

Analysis:

(i) The total emissivity is given by

$$\varepsilon = \frac{\int_0^\infty \varepsilon_\lambda E_{\lambda,b} d\lambda}{E_b} = \frac{\varepsilon_1 \int_0^{2\mu m} E_{\lambda,b} d\lambda}{E_b} + \frac{\varepsilon_2 \int_{2\mu m}^{5\mu m} E_{\lambda,b} d\lambda}{E_b}$$

Also, by using the band emission fractions, we represent the integrals as

$$\varepsilon = \varepsilon_1 F_{(0\to 2\mu m)} + \varepsilon_2 \left[F_{(0\to 5\mu m)} - F_{(0\to 2\mu m)}\right]$$

From table the band emission fractions are:

$$\lambda_1 T = 2\ \mu\text{m} \times 1600\text{K} = 3200\ \mu\text{m}\cdot\text{K}: \qquad F_{(0\to 2\text{ mm})} = 0.318102$$

$$\lambda_2 T = 5\ \mu\text{m} \times 1600\text{K} = 8000\ \mu\text{m}\cdot\text{K}: \qquad F_{(0\to 5\text{ mm})} = 0.856288$$

Hence the total emissivity for this spectrally selective material at 1600 K is

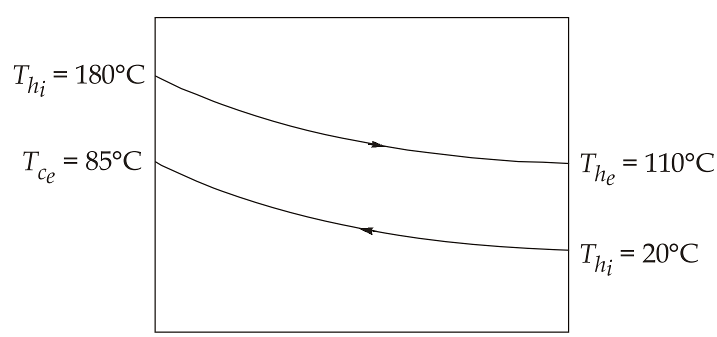
$$\varepsilon = 0.4 \times 0.318102 + 0.8(0.856288 - 0.318102) = 0.558$$

(ii) The total emissive power, $E = \varepsilon E_b = \varepsilon\sigma T^4$

$$= 0.558(5.67 \times 10^{-8})(1600)^4 = 207.35\ \text{kW/m}^2$$

1. (e)

Given : $h_o = 370$ W/m^{2}K; $\dot{m}_c = 3$ kg/s; $N = 12$; $D = 24$ mm



From energy balance,

$$\dot{m}_c \left(c_{p_c}\right)\left(T_{c_e} - T_{c_i}\right) = \dot{m}_h \left(c_{p_h}\right)\left(T_{h_i} - T_{h_e}\right)$$

$$3 \times (4180)(85 - 20) = \dot{m}_h (2300)(180 - 110)$$

$$\dot{m}_h = 5.063\ \text{kg/s}$$

The required length of the tube can be found by

$$Q = UAF\Delta T_m \qquad \text{(where } F \text{ is the correction factor)}$$

The overall heat transfer coefficient in terms of coefficients on the inside (water side) and outside (oil side) of the tube.

$$U = \frac{1}{\left(\frac{1}{h_i}\right)+\left(\frac{1}{h_o}\right)}$$

where, h_i = may be obtained by first calculating Re with $\dot{m}_1 = \frac{m_c}{N} = 0.25$ kg/sec $(N=12)$

$$\text{Re} = \frac{4\dot{m}_1}{\pi D\mu} = \frac{4\times 0.25}{\pi\times 0.24\times 560\times 10^{-6}}$$

$$\text{Re} = 23683.77$$

and $$\text{Pr} = \frac{\mu c_p}{k} = \frac{560\times 10^{-6}\times 4180}{0.65} = 3.6$$

Using the equation given in question for nusselt number.

$$\text{Nu} = 0.023(23683.77)^{0.8}(3.6)^{0.4}$$

$$= 121.3$$

$$h_i = \frac{k}{D}Nu = \frac{0.65}{0.024}\times(121.3) = 3285.27 \text{ W/m}^2\text{K}$$

Hence, the overall heat transfer coefficient

$$U = \frac{1}{\left(\frac{1}{370}\right)+\left(\frac{1}{3285.27}\right)} = 332.55 \text{ W/m}^2\text{K}$$

The log mean temperature difference for counterflow conditions is

$$\Delta T_m = \frac{\left(T_{h_i}-T_{c_e}\right)-\left(T_{h_e}-T_{c_i}\right)}{\ln\left[\frac{\left(T_{h_i}-T_{c_e}\right)}{\left(T_{h_e}-T_{c_i}\right)}\right]}$$

$$\Delta T_m = \frac{95-90}{\ln\left(\frac{95}{90}\right)} = 92.48°\text{C}$$

Now, for finding L

$$Q = UA(\Delta T_m)F$$

where, $$A = N\pi DL$$

$$3 \times 4180(85 - 20) = 332.55(\pi \times 0.024)(12) \times L(92.48)(0.87)$$

$$L = 33.67 \text{ m}$$

2. (a)

Inside temperature $(T_i) > 21°\text{C}$

Submarine can be idealized as a cylinder

$$D = 10 \text{ m}$$

$$L = 70 \text{ m}$$

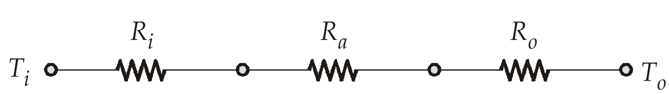
Combined heat transfer coefficient,

$$\text{Inside } \bar{h}_{c_i} = 15 \text{ W/m}^2\text{K}$$

$$\text{Outside } \bar{h}_{c_o} \text{ (not moving)} = 60 \text{ W/m}^2\text{K}$$

$$\text{Top speed} = 880 \text{ W/m}^2\text{K}$$

Sea water temperature (T_o) : $2.2°\text{C} < T_o < 14.5°\text{C}$

(i) 

Total surface area of the idealized submarine is

$$A = \pi dL + \frac{2\pi D^2}{4} = (\pi \times 10 \times 70) + \frac{2 \times \pi \times 10^2}{4}$$

$$= 2356.2 \text{ m}^2$$

$$R_{\text{total}} = \frac{1}{\bar{h}_{c_i} A} + \frac{L_a}{K_a A} + \frac{1}{\bar{h}_{c_o} A}$$

$$= \frac{1}{15 \times 2356.2} + \frac{1.2 \times 10^{-2}}{236 \times 2356.2} + \frac{1}{880 \times 2356.2}$$

The heater requirement will be largest when T_o is at its minimum value and h_{c_o} is at its maximum value.

$$q = \frac{2356.2 \times (21 - 2.2)}{\frac{1}{15} + \frac{1.2 \times 10^{-2}}{236} + \frac{1}{880}} = 652.823 \text{ kW}$$

(ii) For case *(ii)*, the total resistance is

$$R_{total} = \frac{1}{\bar{h}_{c_i}A} + \frac{L_s}{K_s A} + \frac{L_{fg}}{K_{fg}A} + \frac{1}{\bar{h}_{c_o}A}$$

$$q = \frac{2356.2 \times (21 - 2.2)}{\frac{1}{15} + \frac{1.8 \times 10^{-2}}{14} + \frac{2.5 \times 10^{-2}}{0.035} + \frac{1}{880}}$$

$$q = 56.545 \text{ kW}$$

(iii) For total resistance for case (iii) is

$$R_{total} = \frac{1}{\bar{h}_{c_i}A} + \frac{L_s}{K_s A} + \frac{L_{fg}}{K_{fg}A} + \frac{L_a}{K_a A} + \frac{1}{\bar{h}_{c_o}A}$$

$$q = \frac{2356.2 \times (21 - 2.2)}{\frac{1}{15} + \frac{1.8 \times 10^{-2}}{14} + \frac{2.5 \times 10^{-2}}{0.035} + \frac{0.6 \times 10^{-2}}{236} + \frac{1}{880}}$$

$$q = 56.544 \text{ kW}$$

Neither the aluminium nor the stainless steel offers any appreciable resistance to heat loss. Fiberglass or other low conductivity material is necessary to keep the heat loss down to a reasonable level.

2. (b)

1. The overall reaction is,

$$C + O_2 \rightarrow CO_2 - 393.5 \text{ MJ per kilo mole}$$

Since for each kilomole of product CO_2, 4 kilomoles of electrons circulate in the load $(n_e = 4)$,

2. Open-circuit voltage, $V_{oc} = \frac{\Delta G}{(-nqN_o)}$

where,
$n = 4$
$q = 1.6 \times 10^{-19}$
$N_o = 6.023 \times 10^{26}$ atoms/kilomole
$\Delta G = -394.5$ MJ/kilomole

$$V_{oc} = \frac{-394.5 \times 10^6}{-(4 \times 1.6 \times 10^{-19} \times 6.023 \times 10^{26})} = 1.0234 \text{ Volt}$$

3. Reactants and products are at the same temperature.

$$\Delta G = \Delta H - T\Delta S$$

$$\Delta S = \left(\frac{\Delta H - \Delta G}{T}\right) = \frac{(-393.5 + 394.5)\times 10^6}{298}$$

$= 3355.70$ J/K/kilomole

Change in entropy, $\Delta S = 3.3557$ kJ/K/kilomole

4. Let N be the number of kilomoles of carbon consumed.

Electric energy generated, $W_e = |\Delta G| N$

Energy lost due to internal resistance = I^2Rt

Total charge flowing through the load = $4NN_o \times 1.6 \times 10^{-19}$ Coulombs

Current flowing through the load, $I = \left(\frac{4NN_o \times 1.6\times 10^{-19}}{t}\right)$ Ampere

Where, t is the duration of the discharge (in seconds).

Energy delivered = (Energy generated) – (Internal losses)

$$1 \text{ MWh} = |\Delta G| N - \left(\frac{4NN_o \times 1.6\times 10^{-19}}{t}\right)^2 Rt$$

$$3.6 \times 10^9 \text{ Joule} = (394.5\times 10^6)N - \frac{(4\times N \times 6.023\times 10^{26}\times 1.6\times 10^{-19})^2 \times 10^{-3}}{t}$$

$$3.6 \times 10^9 \text{ Joule} = (3.945 \times 10^8)N - (1.48588 \times 10^{14})N^2/t$$

$$(1.48588 \times 10^{14})N^2/t = [3.945 \times 10^8 N - 3.6 \times 10^9]$$

$$t = \frac{1.48588\times 10^{14} N^2}{10^8(3.945N - 36)}$$

$$t = \frac{1.48588\times 10^{6} N^2}{(3.945N - 36)}$$

$$\frac{dt}{dN} = 1.48588\times 10^6\left[\frac{2N}{3.945N-36} - \frac{N^2\times 3.945}{(3.945N-36)^2}\right]$$

For, minimum time, $\frac{dt}{dN} = 0$

$$\frac{2N}{(3.945N-36)} - \frac{(N^2)\times 3.945}{(3.945N-36)^2} = 0$$

$$2(3.945N - 36) = 3.945N$$

Kilomoles of carbon consumed, $N = \frac{72}{3.945} = 18.25$ kilomoles

$$\text{Time, } t = \frac{1.48588\times10^6\ N^2}{(3.945N - 36)} = \frac{1.48588\times10^6\times(18.25)^2}{(3.945\times18.25-36)}$$

$= 13.748 \times 10^6$ seconds

Minimum time, $t = 3818.889$ hours $\simeq 159.12$ days

$$\text{Current during the discharge, } I = \left(\frac{4NN_o\times1.6\times10^{-19}}{t}\right)$$

$$= \frac{4\times18.25\times6.023\times10^{26}\times1.6\times10^{-19}}{13.748\times10^6}$$

$I = 511.70$ Ampere

5. Internal resistance, $R = 0.001\Omega$

Total resistance $= R + R_L$

We know that, $R + R_L = \frac{V_{oc}}{I} = \frac{1.0234}{511.70}$

$R + R_L = 0.002\ \Omega$

Load resistance, $R_L = 0.002 - 0.001 = 0.001\Omega$

Alternative:

For transferring 3.6×10^9 J(1 MWh) in minimum time, means using maximum power.

For this, $R_L = R = 0.001\Omega$

Now, Current, $I_L = \left(\frac{V_{oc}}{R+R_L}\right) = \frac{1.0234}{0.002} = 511.70$ Ampere

Load voltage, $V_L = (I_L) \times R_L = (511.70) \times (0.001)$

$V_L = 0.5117$ Volt

Power, $P = V_L \times I_L = 0.5117 \times 511.70$

$P = 261.837$ Watt

Time necessary to deliver 3.6×10^9 J at the rate of 261.837 Watt.

$$t = \frac{3.6\times10^9}{261.837} = 13.75 \times 10^6 \text{ seconds}$$

Now, the energy that the fuel cell must deliver $= 2 \times 3.6 \times 10^9$ J

($\because$ Internal losses are equal to the power in the load).

$\because$ Electricity produced by 1 kilomole of carbon = 394.5 MJ

$$\text{Kilomoles of carbon required, } N = \frac{2\times3.6\times10^9}{394.5\times10^6}$$

$$N = 18.250 \text{ kilomoles}$$

Results:

1. Overall reaction, $C + O_2 \rightarrow CO_2 - 393.5$ MJ
2. Ideal open circuit voltage is 1.0234 Volts.
3. The entropy change in the reaction is 3.355 kJ/K/K-mole of CO_2.
4. To deliver 1 MWh, 18.25 kilomole of carbon is required.
5. The load resistance must be 1 milli-ohm.

2. (c)

$$\text{Velocity of air, } U_\infty = 30 \text{ m/s}$$

$$\text{Reynolds number, } Re_L = \frac{U_\infty L}{\nu} = \frac{30\times L}{18.97\times10^{-6}} = 1.5814 \times 10^6 L \quad \text{...(i)}$$

As we know,

$$\text{Drag force, } F_D = C_D \times \frac{1}{2}\rho U_\infty^2 \times A$$

$$10.5 = \frac{0.0742}{(1.5814\times10^6 L)^{1/5}} \times \frac{1}{2} \times 1.06 \times 30^2 \times L^2$$

$$10.5 = 2.0376\, L^{(2-0.2)}$$

$$L^{1.8} = 5.1532$$

$$\therefore \quad L = (5.1582)^{1/1.8}$$

$$\Rightarrow \quad L = 2.486 \text{ m}$$

From (i)

$$Re_L = 1.5814 \times 10^6 \times 2.486$$

$$Re_L = 3.932 \times 10^6$$

$$C_D = \frac{0.0742}{(3.932\times10^6)^{1/5}}$$

$$\Rightarrow \quad C_D = 3.5602 \times 10^{-3}$$

By Colburn analogy,

$$St\,Pr^{2/3} = \frac{C_D}{2}$$

$$\frac{\bar{h}}{\rho U_\infty c_p}\text{Pr}^{2/3} = \frac{C_D}{2}$$

$$\Rightarrow \quad \bar{h} = \frac{3.5602\times10^{-3}}{2}\times1.06\times30\times1.005\times1000\times\frac{1}{(0.696)^{2/3}}$$

Heat transfer coefficient, $\bar{h} = 72.438 \text{ W/m}^2\text{K}$

Heat loss from plate surface,

$$Q = \bar{h}A(T - T_\infty)$$

$$= 72.438 \times (2.486)^2 \times (95 - 25) = 31337.55 \text{ W}$$

$$Q = 31.337 \text{ kW}$$

3. (a)

Insulated cylinder tank with hemispherical ends

$$D_t = 1.5 \text{ m}$$

$$L_t = 6 \text{ m}$$

$$T_{bp} = -179.4°\text{C}$$

$$h_{fg} = 282 \text{ kJ/kg}$$

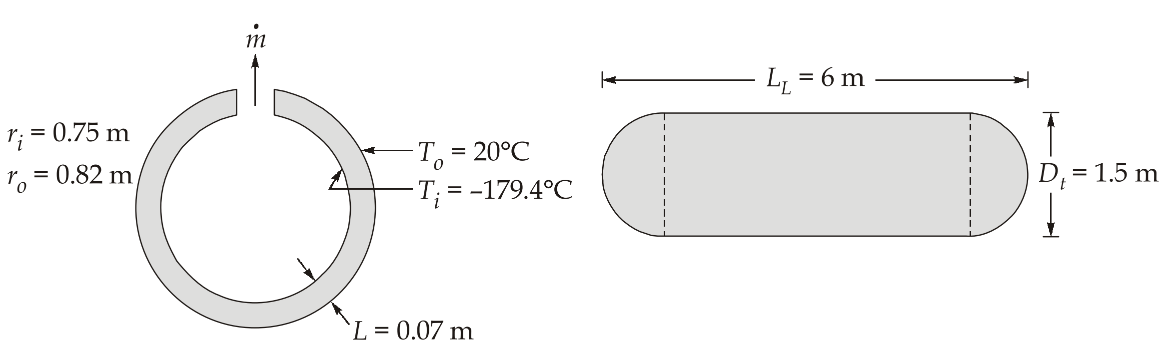
$$\dot{m} = 12 \text{ kg/hr} = 3.33 \times 10^{-3} \text{ kg/sec}$$

Maximum thickness of insulation (L) = 7 cm = 0.07 m

Outside temperature = 20°C

Assumptions:

- Length given includes the hemispherical ends.
- The thermal resistance of the tank is negligible compared to the insulation.
- The thermal resistance at the interior surface of the tank is negligible.



The tank can be thought of as a sphere (the ends) separated by a cylindrical section, therefore the total heat transfer is the sum of that through the spherical and cylindrical sections. The steady state conduction through a spherical shell with constant thermal conductivity is

$$q_s = \frac{4\pi k r_o r_i (T_o - T_i)}{(r_o - r_i)}$$

The rate of steady state conduction through a cylindrical shell is

$$q_c = \frac{2\pi L_c k (T_o - T_i)}{\ln\left(\frac{r_o}{r_i}\right)}$$

$$L_c = 6 - 1.5 = 4.5 \text{ m}$$

The total heat transfer through the tank is the sum of these.

$$q = q_s + q_c$$

$$= \frac{4\pi k r_o r_i (T_o - T_i)}{(r_o - r_i)} + \frac{2\pi L_c k (T_o - T_i)}{\ln\left(\frac{r_o}{r_i}\right)}$$

$$= 2\pi k (T_o - T_i)\left[\frac{2r_o r_i}{(r_o - r_i)} + \frac{L_c}{\ln\left(\frac{r_o}{r_i}\right)}\right]$$

The rate of heat transfer required to evaporate the liquid oxygen at m is m_{hfg},

$$\therefore \quad \dot{m}_s h_{fg} = 2\pi k (T_o - T_i)\left[\frac{2r_o r_i}{r_o - r_i} + \frac{L_c}{\ln\left(\frac{r_o}{r_i}\right)}\right]$$

$$k = \frac{\dot{m} h_{fg}}{2\pi (T_o - T_i)\left[\frac{2r_o r_i}{r_o - r_i} + \frac{L_c}{\ln\left(\frac{r_o}{r_i}\right)}\right]}$$

$$k = \frac{3.33 \times 10^{-3} \times 282 \times 10^{3}}{2\pi(20-(-179.4))\left[\frac{2\times 0.82\times 0.75}{0.82-0.75} + \frac{4.5}{\ln\left(\frac{0.82}{0.75}\right)}\right]}$$

$$k = \frac{939.06}{1252.867\left[\frac{123}{7} + 50.43\right]}$$

$$k = 0.011 \text{ W/mK}$$

3. (b)

Gas required for lighting lamps = 10 × 0.126 × 6 = 7.56 m^3/day

Electrical energy required for ten computers = (10 × 250 × 6) × 3600 Joule/day
= 54 MJ/day

Thermal energy input for producing 54 MJ electrical energy = $\frac{54}{(0.25\times 0.8)}$ = 270 MJ/day

Energy required for water pump = (2 × 746 × 2) × 60 × 60 = 10.7424 MJ/day

Thermal energy input for water pumping = $\frac{10.7424}{0.25}$ = 42.9696 MJ/day

Total thermal energy input = 270 + 42.9696 = 312.9696 MJ/day

Required volume of biogas for both engines = $\frac{312.9696}{23}$ = 13.6074 m^3/day

Total requirement of biogas = 13.6074 + 7.56 = 21.1674 m^3/day

Assume: Number of cows required for the plant = n

Total collectable cow dung = 7n kg/day

Total dry matter = (7n) × 0.18 = (1.26 n) kg/day

Gas produced per day = (Biogas yield) × (Total dry matter)
= (0.34 × 1.26 n)
= (0.4284 n)m^3/day

Now,Gas produced per day = Total requirement of biogas per day

(0.4284 n) = 21.1674

n = 49.410

Thus, 50 cows are required to feed the plant.

Daily feeding of cowdung into the plant = 7 × 50 = 350 kg.

∵ Equal amount of water is added for making slurry.

So, Daily slurry produced = (350 + 350) = 700 kg

$$\text{Volume of slurry} = \frac{\text{Mass of slurry}}{\text{Density of slurry}}$$

$$= \frac{700}{1090} = 0.6422 \text{ m}^3/\text{day}$$

Volume of slurry in digester = (Volume of slurry per day) × (Retention period)

$$= (0.6422 \times 50) = 32.11 \text{ m}^3$$

∵Only 90% of the digester volume is occupied by the slurry.

$$\text{Net volume of the digester} = \left(\frac{32.11}{0.9}\right) = 35.678 \text{ m}^3$$

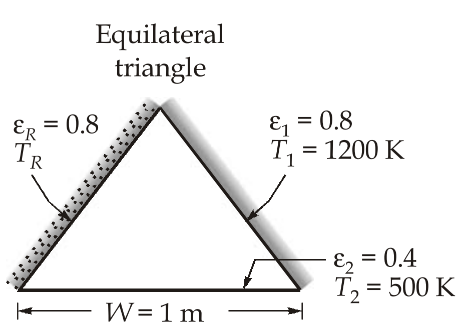
Result: Number of cows required = 50

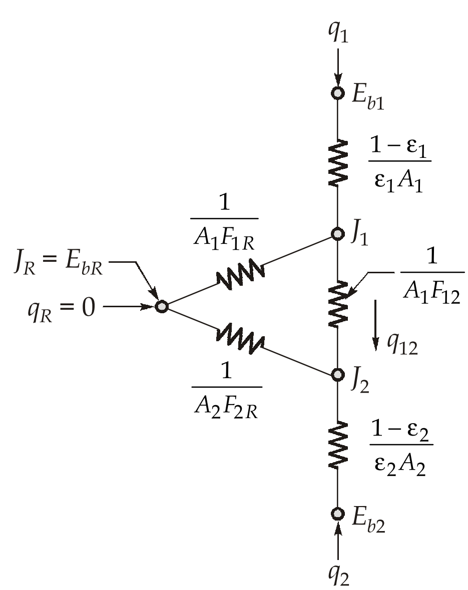
Volume of the digester = 35.678 m^3

3. (c)

Assumptions:

1. Steady-state conditions exist.
2. All surfaces are opaque, diffuse, gray, and of uniform radiosity.
3. Convection effects are negligible.
4. Surface R is reradiating.
5. End effects are negligible.





The rate at which energy must be supplied to the heated surface is

$$q_1 = \frac{E_{b_1} - E_{b_2}}{\dfrac{1-\varepsilon_1}{\varepsilon_1 A_1} + \dfrac{1}{A_1F_{12} + \left[\left(\dfrac{1}{A_1F_{1R}}\right) + \left(\dfrac{1}{A_2F_{2R}}\right)\right]^{-1}} + \dfrac{1-\varepsilon_2}{\varepsilon_2 A_2}}$$

From symmetry, $F_{12} = F_{1R} = F_{2R} = 0.5$

Also, $A_1 = A_2 = W \cdot L$, where L is the duct length.

The heat transfer to the duct per unit length as

$$q_1' = \frac{q_1}{L} = \frac{5.67 \times 10^{-8} \times \left(1200^4 - 500^4\right)}{\dfrac{1-0.8}{0.8 \times 1} + \dfrac{1}{1 \times 0.5 + (2+2)^{-1}} + \dfrac{1-0.4}{0.4 \times 1}}$$

$$q_1' = 36.982 \text{ kW/m}$$ **Ans.**

Applying the surface energy balance, to surface 1 and 2, and recognizing from the network that $q_2' = -q_1'$,

$$J_1 = E_{b_1} - \frac{1-\varepsilon_1}{\varepsilon_1 W} q_1'$$

$$= 5.67 \times 10^{-8} (1200)^4 - \frac{1-0.8}{0.8 \times 1} \times 36982 = 108327.62 \text{ W/m}^2$$

$$J_2 = E_{b_2} - \frac{1-\varepsilon_2}{\varepsilon_2 W} q_2'$$

$$= 5.67 \times 10^{-8} (500)^4 - \frac{1-0.4}{0.4 \times 1} \times (-36982) = 59016.75 \text{ W/m}^2$$

From the energy balance for the reradiating surface,

We get, $$\frac{108327.62 - J_R}{\dfrac{1}{W \times L \times 0.5}} - \frac{J_R - 59016.75}{\dfrac{1}{W \times L \times 0.5}} = 0$$

Hence, the radiosity of the reradiating surface is

$$J_R = 83672.19 \text{ W/m}^2$$

Also, $J_R = E_{bR} = \sigma T_R^4$ for the reradiating surface, its temperature is

$$T_R = \left(\frac{J_R}{\sigma}\right)^{1/4} = \left(\frac{83672.19}{5.67 \times 10^{-8}}\right)^{1/4} = 1102.2 \text{ K}$$

4. (a)

Insulated rod with internal heat generation,

$$L = 0.4 \text{ m}$$

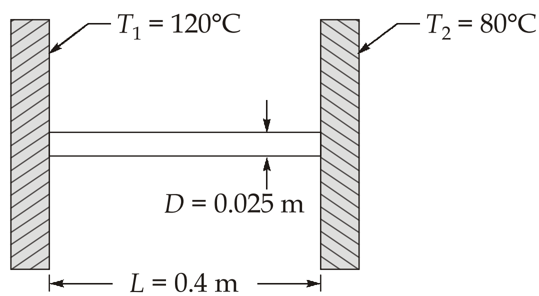
$$D = 2.5 \text{ cm} = 0.025 \text{ m}$$

Internal heat generation $(\dot{q}_{GV}) = 15 \text{ W}$

End temperature of the rod, $T_1 = 120°C$; $T_2 = 80°C$

Assumptions:

- The system has reached steady state.
- The heat loss through the insulation in negligible.
- Constant thermal conductivity.
- The plate temperatures are constant.
- Heat is generated uniformly throughout the rod.



The heat generation per unit volume of the rod is

$$\dot{q}_G = \frac{\dot{q}_{GV}}{V} = \frac{\dot{q}_{GV}}{V}$$

$$\dot{q}_G = \frac{15}{\frac{\pi}{4}D^2L} = \frac{15}{\frac{\pi}{4}(0.025)^2 \times (0.4)}$$

$$\dot{q}_G = 76394.373 \text{ W/m}^3$$

(i) The temperature distribution in the rod will be evaluated from the conduction equation,

The one dimensional conduction equation is,

$$k\frac{\partial^2 T}{\partial x^2} + \dot{q}_G = \rho c \frac{\partial T}{\partial t}$$

For steady state, $$\frac{\partial T}{\partial t} = 0$$

$$\therefore \qquad \frac{d^2T}{dx^2} = \frac{-\dot{q}G}{k}$$

This is subject to the following boundary condition

$$T = T_1 \text{ at } x = 0 \text{ and } T = T_2 \text{ at } x = L$$

Integrating the conduction equation,

$$\frac{dT}{dx} = \frac{-\dot{q}_G}{k}x + c_1$$

Integrating a second time, $T = \dfrac{-\dot{q}_G x^2}{2k} + c_1 x + c_2$

The constant c_2 can be evaluated using the first boundary condition,

$$T_1 = \frac{-\dot{q}_G}{2k}(0)^2 + c_1(0) + c_2; \;\; c_2 = T_1$$

$\therefore$ The temperature distribution becomes

$$T = \frac{-\dot{q}_G}{2k}(x)^2 + c_1 x + T_1$$

The secondary boundary condition can be used to evaluate the constant c_1

$$T_2 = \frac{-\dot{q}_G}{2k}(L)^2 + c_1 L + T_1$$

$$\Rightarrow \qquad c_1 = \frac{1}{L}(T_2 - T_1) + \frac{\dot{q}_G L}{2k}$$

The temperature distribution in the rod is

$$T = \frac{-\dot{q}_G}{2k}x^2 + \left[\frac{1}{L}(T_2 - T_1) + \frac{\dot{q}_G L}{2k}\right]x + T_1$$

The maximum temperature in the rod occurs where the first derivative of the temperature distribution is zero.

$$\frac{dT}{dx} = \frac{-\dot{q}_G}{k}x_m + \frac{1}{L}(T_2 - T_1) + \frac{\dot{q}_G L}{2k} = 0$$

$$x_m = \frac{k}{Lq_G}(T_2 - T_1) + \frac{L}{2}$$

$$= \frac{43}{0.4 \times 76394.373}(80 - 120) + \frac{0.4}{2} = 0.1437 \text{ m}$$

$$x_m = 0.1437 \text{ m}$$

Evaluating the temperature at this value of x,

$$T_{max} = \frac{\dot{q}_G}{2k}x_m^2 + \left[\frac{1}{L}(T_2 - T_1) + \frac{\dot{q}_G L}{2k}\right]x_m + T_1$$

$$= \frac{76394.373}{2\times 43}\times(0.1437)^2 + \left[\frac{80-120}{0.4} + \frac{76394.373\times 0.4}{2\times 43}\right](0.1437) + 120$$

$$= 18.34 + [-100 + 355.3] \times 0.1437 + 120$$

$$= 18.34 + 36.72 + 120$$

$$T_{max} = 175.06°C$$

(ii) The heat flow from the rod at $x = 0$ can be calculated as,

$$q_0 = -kA\left.\frac{dT}{dx}\right|_{x=0}$$

$$= -kA\left[\frac{1}{L}(T_2 - T_1) + \frac{\dot{q}_{GL}}{2k}\right] = -5.389\,\text{W}$$

Heat flow from the rod at $x = L$

$$q_L = \frac{\pi}{4}\times D^2\left[\frac{\dot{q}_G}{2}L - \frac{k(T_2 - T_1)}{L}\right]$$

$$q_L = \frac{\pi}{4}\times(0.025)^2\left[\frac{76394.373\times 0.4}{2} - \frac{43\times(80-120)}{0.4}\right]$$

$$= \frac{\pi}{4}\times(0.025)^2[15278.875 + 4300]$$

$$q_L = 9.611\text{ W}$$

Positive sign indicates, heat is flowing to the right, out of rod.

The net heat flow rate is

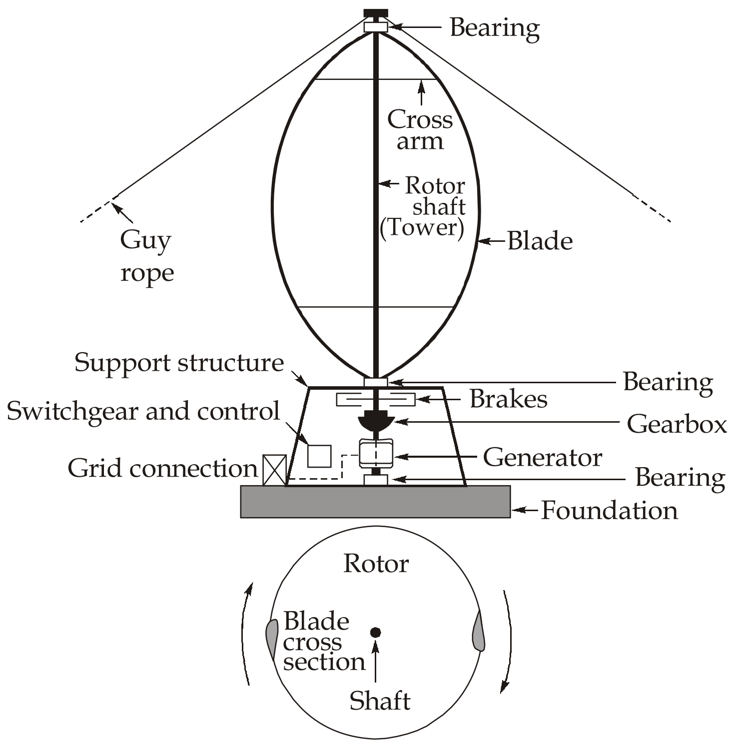
$$q_{total} = |q_0| + |q_L|$$

$$= 5.389 + 9.611 = 1500\text{ W} \simeq 15\text{ W}$$

The net heat flow rate is equal to the rate of heat generation within the rod.

4. (b) (i)

The constructional details of a vertical axis wind turbine (Darrieus type rotor) are shown in figure below. The details of main components are as follows:



Vertical axis wind (Darrieus) turbine

(a) Tower (or Rotor Shaft): The tower is a hollow vertical rotor shaft, which rotates freely about vertical axis between top and bottom bearings. It is installed above a support structure. In the absence of any load at the top, a very strong tower is not required, which greatly simplifies its design. The upper part of the tower is supported by guy ropes. The height of the tower of a large turbine is around 100 m.

(b) Blades : It has two or three thin, curved blades shaped like an eggbeater in profile, with blades curved in a form that minimizes the bending stress caused by centrifugal forces-the so-called 'Troposkien' profile. The blades have airfoil cross-section with constant chord length. The pitch of the blades cannot be changed. The diameter of the rotor is slightly less than the tower height. The first large Darrieus type, Canadian machine has rotor height as 94 m and diameter as 65 m with a chord of 2.4 m.

(c) Support Structure : Support structure is provided at the ground to support the weight of the rotor. Gearbox, generator, brakes, electrical switchgear and controls are housed within this structure.

VAWTs are in the development stage and many models are undergoing field trial.

Main advantages of a VAWT are:

(i) it can accept wind from any direction, eliminating the need of yaw control.

(ii) gearbox, generator etc. are located at the ground, thus eliminating the heavy nacelle at the top of the tower. This simplifies the design and installation of the whole structure, including tower.

(iii) the inspection and maintenance also gets easier and

(iv) it also reduces the overall cost.

4. (b) (ii)

From given data : $U_4 = 15$ m/s; $H = 10$ m; $Z = 120$ m; $\rho = 1.23$ kg/m^3; $\alpha = 0.15$; $D = 85$ m;

$$A_1 = \frac{\pi \times (85)^2}{4} = 5674.5 \text{ m}^2;\ U_1 = 0.75U_0;\ \eta_{gen} = 0.9$$

$$U_z = U_H\left(\frac{Z}{H}\right)^{\alpha} = 15\times\left(\frac{120}{10}\right)^{0.15} = 21.775 \text{ m/s} = U_0$$

$$U_1 = 0.75U_0 = 0.75 \times 21.775 = 16.33 \text{ m/s}$$

and

(i)

$$\frac{P_0}{A} = \frac{1}{2}\rho U_0^3$$

$$P_0 = 5674.5\times\frac{1}{2}\times 1.23\times(21.775)^3$$

$$P_0 = 36.031 \text{ MW}$$

(ii) The interference factor, $a = \dfrac{(U_0 - U_1)}{U_0} = \dfrac{21.775 - 16.33}{21.775} = 0.25$

The power coefficient, $c_p = 4a(1 - a)^2$

$$= 4 \times 0.25(1 - 0.25)^2 = 0.5625$$

(iii) Electrical power generated = 0.9 × 0.5625 × 36.031 = 18.241 MW

(iv) Axial thrust on the turbine

$$F_A = 4a(1-a)\left(A_1\frac{\rho U_0^2}{2}\right)$$

$$= 4\times 0.25(1-0.25)\left(5674.5\times 1.23\times\frac{(21.775)^2}{2}\right)$$

$$= 12.41 \times 10^5 \text{ N}$$

(v) Maximum axial thrust occurs when

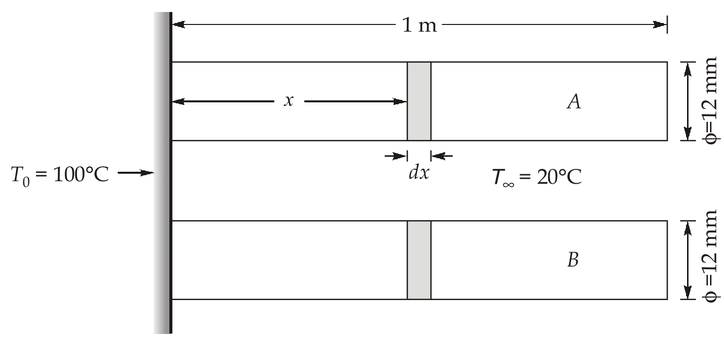
$$a = 0.5 \text{ and } c_p = 1$$

$$F_{A,\max} = A_1 \frac{\rho U_0^2}{2}$$

$$= 5674.5 \times 1.23 \times \frac{(21.775)^2}{2}$$

$$= 16.55 \times 10^5 \text{ N}$$

4. (c)



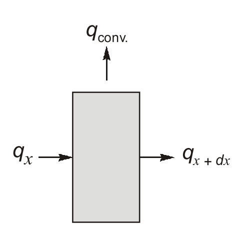
Base of both the rods is maintained at the same temperature as shown in figure.

Assumption:

(i) Since the length of the rods is very large 1 m as compared to their diameter, they can be assumed to be infinitely long with temperature at tip approaching surrounding temperature.

(ii) Heat transfer is purely one dimensional conduction in the rods and convection from rod surface.

Consider an element of thickness dx at a distance x from the base on any rod.



Energy balance for this section

$$q_x - q_{x+dx} = q_{\text{conv}}$$

$$\Rightarrow k.A_c.\frac{d^2T}{dx^2}.dx - h(Pdx)(T - T_\infty) = 0$$

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$$\Rightarrow \qquad \frac{d^2\theta}{dx^2} - m^2\theta = 0$$

General solution is of form:

$$\theta = C_1 e^{mx} + C_2 e^{-mx} \qquad ...(1)$$

where, $\theta = T - T_\infty$ and $m = \sqrt{\frac{hP}{kA_c}}$

Constant C_1 and C_2 are evaluated with following boundary conditions:

(i) $T|_{x=0} = T_0$

(ii) Infinitely long rod assumption due to which $T|_{x=L} = T_\infty$

At $x = 0$, $\quad T = T_0$

$$\theta = T_0 - T_\infty = \theta_0$$

From eq. (1)

$$\theta_0 = C_1 e^{m(0)} + C_2 e^{-m(0)}$$

$$\theta_0 = C_1 + C_2 \qquad ....(2)$$

At $x = \infty$, $\quad T = T_\infty$

$$\theta = T_\infty - T_\infty = 0$$

Again, from eq. (1)

$$0 = C_1 e^{m\infty} + C_2 e^{-m\infty}$$

$$\Rightarrow \qquad C_1 = 0$$

From eq. (2)

$$\theta_0 = 0 + C_2$$

So, From eq. (1) $\quad \theta = \theta_0\, e^{-mx}$

Given: $h = 5\ \text{W/m}^2\text{K}$, $k_A = 60\ \text{W/mK}$, $A_c = \frac{\pi d^2}{4} = \frac{\pi \times (0.012)^2}{4} = 1.131 \times 10^{-4}\ \text{m}^2$,

$P = \pi d = \pi \times 0.012 = 0.0377$ m

For rod A:

$$m_A = \sqrt{\frac{hP}{k_A A_c}} = \sqrt{\frac{5 \times 0.0377}{60 \times 1.131 \times 10^{-4}}} = 5.270\ \text{m}^{-1}$$

Temperature at 15 cm from base

$$\frac{T - T_\infty}{T_0 - T_\infty} = \frac{T - 293}{373 - 293} = e^{-mx} = e^{-5.270 \times 0.15}$$

$$\Rightarrow \quad T = 329.29 \text{ K}$$

This temperature is equal to temperature of rod B at a distance 7.5 cm from base.

For rod B:

$$\frac{T - T_\infty}{T_0 - T_\infty} = e^{-m_B \times 0.075}$$

$$\Rightarrow \quad \frac{329.29 - 293}{373 - 293} = e^{-m_B \times 0.075}$$

$$\Rightarrow \quad m_B = 10.5398 \text{ m}^{-1}$$

We know,

$$m_B = \sqrt{\frac{hP}{k_B A_C}} = 10.5398$$

$$\Rightarrow \quad k_B = 15 \text{ W/mK}$$

Heat transfer for a rod in this case= $\sqrt{hP\,kA_C}\,(T_b - T_\infty)$

∴ Ratio of heat transfer for rod A and B

$$\frac{Q_A}{Q_B} = \frac{\sqrt{hP\,k_A\,A_c}\,(T_b - T_\infty)}{\sqrt{hPk_B\,A_c}\,(T_b - T_\infty)}$$

$$\Rightarrow \quad \frac{Q_A}{Q_B} = \sqrt{\frac{k_A}{k_B}} = 2$$

Section B : Heat Transfer + Renewable Sources of Energy

5. (a)

The molten carbonate fuel cell has a high operating temperature with molten carbonate mixture as electrolyte. It offers the prospect of the use of a variety of fossil fuels including coal. The special feature of these cells is that they can oxidise carbon monoxide to carbon dioxide as well as hydrogen to water during their operation. Hence, the cell can use inexpensive mixture of hydrogen and carbon monoxide, which is called synthetic gas. Also, the presence of carbon dioxide in fuel and air does not have any adverse effect on the working of the cell.

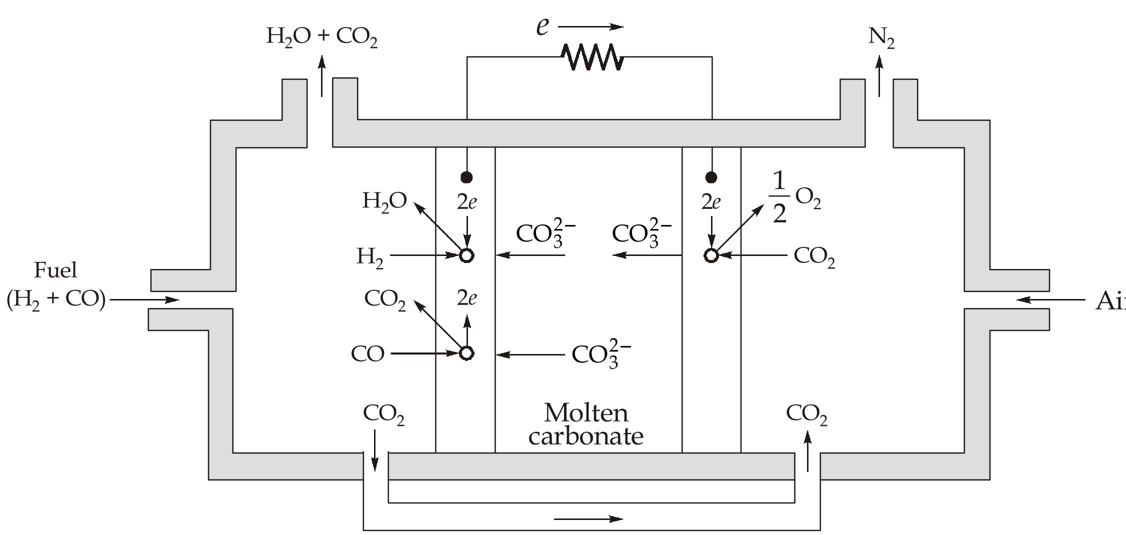
The carbonate of alkali metals (Na, K and Li) in molten state is used as the electrolyte. This necessity makes the cell to operate at a temperature above the melting point of carbonates (range of 600-700°C). The porous nickel and silver are used as the anode and the cathode electrode respectively which are separated by electrolyte held by a sponge-like ceramic matrix. The synthetic gas (H_2 + CO) is used as the fuel and air is used as the oxidant. The synthetic gas is passed through the anode, where the hydrogen and carbon monoxide are oxidised with CO_3^{2-} ions, thereby liberating electrons. The electrons move to cathode from the external circuit. At the cathode, oxygen gets reduced in the presence of carbon dioxide and electrons, thereby forming CO_3^{2-} ions. The reactions are as follows:

$$H_2 + CO_3^{2-} \rightarrow H_2O + CO_2 + 2e^- \quad \text{(anode)}$$

$$CO + CO_3^{2-} \rightarrow 2CO_2 + 2e^- \quad \text{(anode)}$$

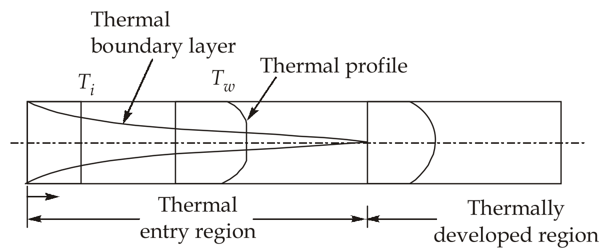
$$O_2 + CO_2 + 4e^- \rightarrow 2CO_3^{2-} \quad \text{(cathode)}$$

The emf generated by the cell is about 1 V at 700°C. Any fuel which can be converted into a mixture of hydrogen and carbon monoxide can be used. However, the mixture has to disulphurized as sulphur can poison the electrodes or reduce their effectiveness as a catalyst. The discharge from the reactants consists of steam, carbon dioxide and nitrogen and the discharge has temperature of 540°C. This hot discharge can be used to generate power using waste heat boiler with steam turbine to run generator.

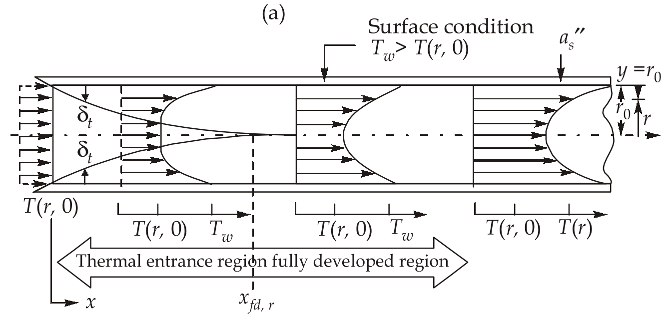


Molten carbonate fuel cell

5. (b)

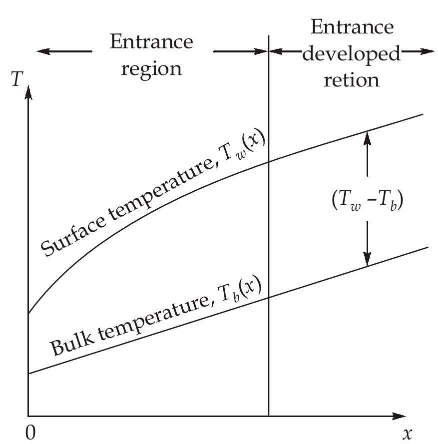


(a)

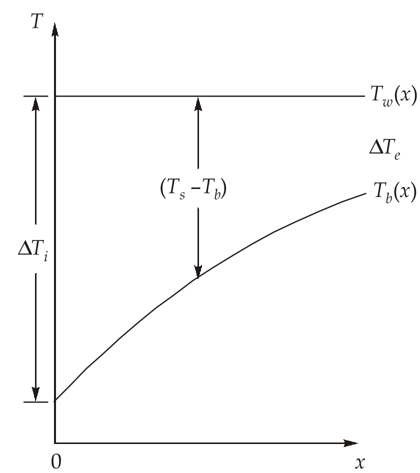


(b)

Development of thermal boundary layer in a tube (a) when $T > T_w$ and (b) when $T_w > T$



Distance from entrance
(a)



Distance from entrance
(b)

Let us consider that a fluid at a uniform temperature enters a circular tube with its wall at a different temperature. The fluid particles in the layer in contact with the surface of the tube will assume the tube surface or wall temperature T_w. This will initiate convection heat transfer in the tube followed by development of the thermal boundary layer along the tube. The thickness of this thermal boundary layer reaches the tube center and thus fills the entire tube. The region of flow over which the thermal boundary layer develops and reaches the tube centre is called the thermal entry region. The region beyond the thermal entry region in which the temperature profile remains unchanged is called the thermally developed region/zone.

The dimensionless temperature profile $\left(\frac{T - T_w}{T_c - T_w}\right)$ does not also change upstream of thermal entry length. The zone in which the flow is both hydrodynamically and thermally developed is called the fully developed differs according to whether a uniform wall temperature (T_w) or a uniform heat flux is maintained. For both surface conditions, however, the amount by which fluid temperatures exceed the entrance temperature increase with increasing x.

Nusselt number for fully developed laminar flow in a tube is given as

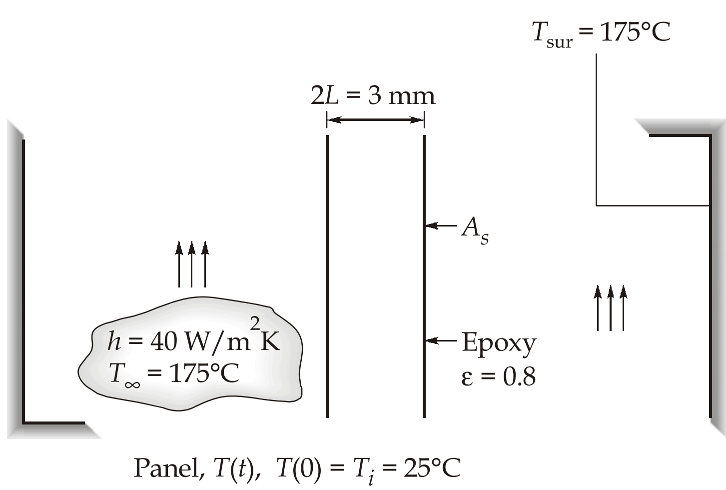
$$Nu_d = \frac{hD}{k} = \frac{48}{11} = 4.364 \text{ (for constant heat flux)}$$

$$Nu_d = \frac{hD}{k} = 3.66 \text{ (for } T_w = \text{constant)}$$

5. (c)

Assumptions:

1. Panel temperature is uniform at any instant.
2. Thermal resistance of epoxy is negligible.
3. Radiation exchange with the surroundings can be characterized by an effective linearized radiation coefficient, h_{rad}.
4. Constant properties



During the cure operation, the panel surface experiences convection with the fluid at T_∞ and radiation exchange with the surrounding at T_∞.

The total heat rate from the panel surface is

$$\therefore \quad q = q_{conv} + q_{rad} = (h + h_{rad})A_s(T - T_\infty)$$

where h and h_{rad} are the convection and effective radiation coefficients, respectively, and $(h + h_{rad})$ represents the combined convection-radiation coefficient.

Also,
$$Bi = \frac{(h+h_{rad})L}{k}$$
$$= \frac{(40+12)\times(0.0015)}{177} = 4.41\times10^{-4} \qquad \left[\text{As } L_c = \frac{V}{A}\right]$$

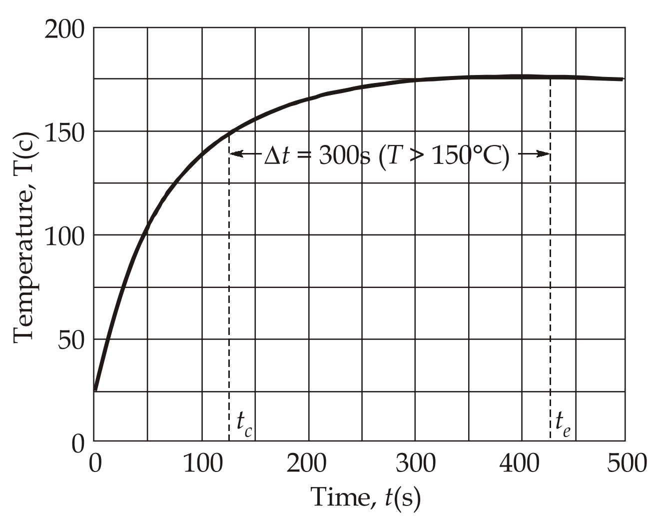
Since $Bi < 0.1$,

The time required for the panel to reach the cure temperature is

$$\therefore \quad t_c = \frac{\rho Vc}{hA_s}\ln\frac{\theta_i}{\theta} = \frac{\rho Lc}{(h+h_{rad})}\ln\frac{T_i - T_\infty}{T_c - T_\infty}$$
$$= \frac{2770\times0.0015\times875}{(40+12)}\ln\frac{25-175}{150-175} = 125.27 \text{ sec}$$

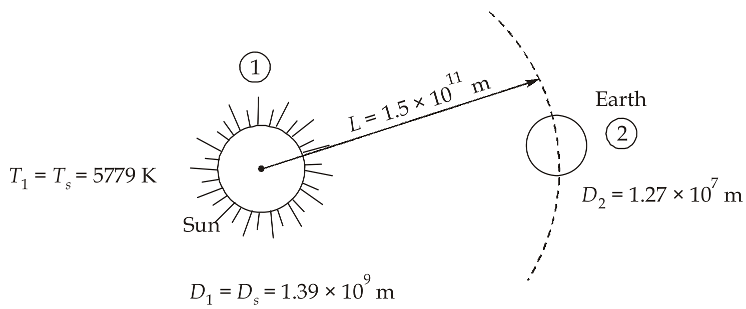
The panel reaches the cure temperature of 150°C in 125s, hence the total time to complete the 5-min duration cure is

$$t_e = t_c + 5\times60\text{s}$$
$$= (125 + 300)\text{s} = 425\text{s}$$



Variation of temperature with time during curing process

5. (d)



Rate at which the sun emits energy is

$$Q_{\text{emit-sun}} = A_s \sigma T_s^4$$
$$= (\pi D_s^2)\sigma T_s^4$$
$$= \pi \times (1.39 \times 10^9)^2 \times 5.67 \times 10^{-8} \times (5779)^4$$
$$= 3.84 \times 10^{26} \text{ W} \quad \text{....Answer (1)}$$

Radiation from the sun (1) spreads out evenly in all directions and we imagine that it falls on the inside of a hollow sphere of radius (revolving radius) L (the earth sun distance). It follows that the proportion of the total radiation falling on the earth (2) from sun (1) is the ratio of the projected area of the earth (2) (which will be a circle of diameter D_2) to the total area of the sphere (of radius L). Then the fraction of radiation emitted by the sun and intercepted by the earth is

$$F_{S-E} = F_{1-2} = \frac{(\pi D_2^2/4)}{4\pi L^2} = \frac{D_2^2}{16L^2} = \left(\frac{D_2}{4L}\right)^2$$

$$F_{1-2} = \left(\frac{1.27 \times 10^7}{4 \times 1.5 \times 10^{11}}\right)^2 = \left(\frac{1.27}{6 \times 10^4}\right)^2$$
$$= 4.48 \times 10^{-10} \quad \text{Answer (2)}$$

The amount of energy from the sun intercepted by the earth is

$$\dot{Q}_{\text{read, earth}} = \dot{Q}_{\text{emit, sun}} \times F_{12}$$
$$= 3.84 \times 10^{26} \times 4.48 \times 10^{-10}$$
$$= 1.72 \times 10^{17} \text{ W} \quad \text{Answer (3)}$$

5. (e)

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

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

$$CR = \frac{1}{\sin 10°} = 5.76 \qquad \text{Answer}$$

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

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

The ratio of height to aperture can be expressed as

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

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

$$H = 3.328 \times W = 3.328 \times 86.4 = 287.54 \text{ cm} \qquad \text{Answer}$$

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

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

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

$$A_{conc} = 6.76 \times 0.864 \times 1.5 = 8.76 \text{ m}^2 \qquad \text{Answer}$$

6. (a)

Agra (27.167° N, 78.1°E)

n for 10th June = 31 + 28 + 31 + 30 + 31 + 10 = 161

Declination angle,

$$\text{Using Copper's relation, } \delta = 23.45° \times \sin\left\{\frac{360}{365}(284+n)\right\}^{\circ}$$

$$= 23.45° \times \sin\left\{\frac{360}{365}(284+161)\right\}^{\circ}$$

$$\delta = 23.01°$$

For horizontal orientation:

$$I_n = I_{sc}\left\{1+0.033\cos\left(\frac{360\times n}{365}\right)^{\circ}\right\}$$

$$= 1367\left\{1+0.033\cos\left(\frac{360\times161}{365}\right)^{\circ}\right\}$$

$$I_n = 1324.943 \text{ W/m}^2$$

Sunrise angle, $\omega_s = \cos^{-1}(-\tan\phi \times \tan\delta)$

$$= \cos^{-1}(-\tan(27.167)^{\circ} \times \tan 23.01^{\circ})$$

$$\omega_s = 102.59^{\circ}$$

One day radiation, $H_o = \left(I_n \times \dfrac{3600}{1000}\right)\displaystyle\int_{-\omega_s}^{\omega_s}(\cos\theta)\,dt \text{ kJ/m}^2\text{day}$

$$= (I_n \times 3.6)\times\frac{12}{\pi}\times 2\int_0^{\omega_s}(\cos\theta)\,d\omega \text{ kJ/m}^2\text{-day}$$

$$H_o = 1324.943\times3.6\times\frac{24}{\pi}\int_0^{\omega_s}(\sin\phi\times\sin\delta+\cos\phi\cos\delta\cos\omega)\,d\omega$$

$$= 36438.548[(\omega_s)\sin\phi\cdot\sin\delta + \cos\phi\cdot\cos\delta\cdot\sin\omega_s]$$

[where, $\omega_s = 102.59^{\circ}$]

$$= 36438.548\left[\left(102.59\frac{\pi}{180}\right)\sin 27.167^{\circ}\cdot\sin 23.01^{\circ}+\cos 27.167^{\circ}\cos 23.01^{\circ}\sin 102.59^{\circ}\right]$$

$$= 36438.548[0.319566 + 0.7992] \text{ kJ/m}^2 \text{ day}$$

$$H_o = 40766.2 \text{ kJ/m}^2\text{-day}$$

$$H_o = 40.7662 \text{ MJ/m}^2\text{-day}$$

Total extraterrestrial radiation, $\bar{H}_o = H_o \times A_c$

$$= (40.7662 \times 10) \text{ MJ/day} = 407.662 \text{ MJ/day}$$

(II) If collector is inclined by 15°:

$$I_n = 1324.943 \text{ W/m}^2,\ \beta = 15^{\circ}$$

$$\omega_s = \cos^{-1}[-\tan(\phi-\beta)\tan\delta]$$

$$= \cos^{-1}[-\tan(27.167-15)^{\circ}\tan 23.01^{\circ}]$$

$$\omega_s = 95.25^{\circ}$$

$$(H_o)_1 = 1324.943\times3.6\times\frac{24}{\pi}\int_0^{\omega_s}[\sin(\phi-\beta)\sin\delta+\cos(\phi-\beta)\cos\delta\cos\omega]\,d\omega$$

$$= 36438.548[\omega_s\sin(\phi-\beta)\sin\delta+\cos(\phi-\beta)\cos\delta\sin\omega_s]$$

$$= 36438.548\left[\left(95.25\times\frac{\pi}{180}\right)\sin(27.167-15)^\circ\sin 23.01^\circ+\cos(27.167-15)^\circ\cos 23.01^\circ\sin 95.25^\circ\right]$$

$= 36438.548(0.136959 + 0.895986)$

$$(H_o)_1 = 37639.01 \text{ kJ/m}^2\text{-day} = 37.63901 \text{ MJ/m}^2 \text{ day}$$

Total extraterrestrial radiation, $(\bar{H}_o)_1 = H_o \times A_c$

$$= (37.63901 \times 10) = 376.3901 \text{ MJ/day}$$

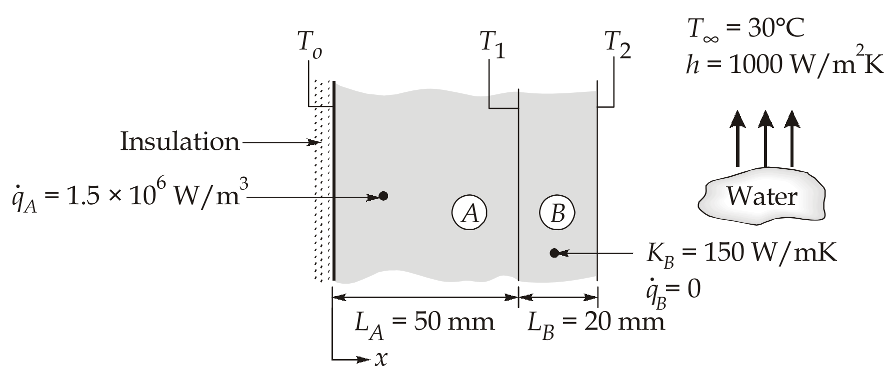
$$\text{Change in extraterrestrial radiation} = \frac{(\bar{H}_o)_1 - \bar{H}_o}{\bar{H}_o} = \left(\frac{376.3901 - 407.662}{407.662}\right)$$

$$= -0.07671 = -7.671\%$$

6. (b)

Assumptions:

1. Steady-state conditions.
2. One-dimensional conduction in x-direction.
3. Negligible contact resistance between walls.
4. Inner surface of A is adiabatic.
5. Constant properties for materials A and B.

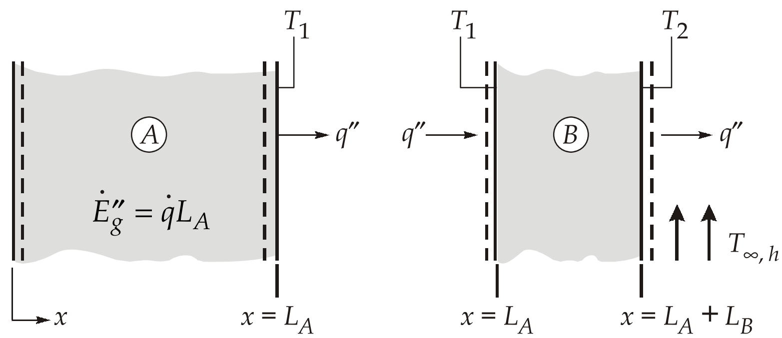


The outer surface temperature T_2 can be obtained by performing an energy balance on a system about material B. Since there is no generation in this material, it follows that, for steady-state conditions and a unit surface area, the heat flux into the material at $x = L_A$ must equal the heat flux from the material due to convection at $x = L_A + L_B$.

$\therefore$ $$q'' = h(T_2 - T_\infty) \quad \text{...(i)}$$

The surface at $x = 0$ is adiabatic, there is no inflow and the rate at which energy is generated must equal the outflow. Therefore for a unit surface area

$$q'' = \dot{q}L_A \quad \text{...(ii)}$$



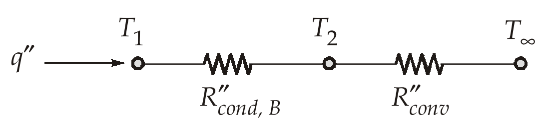
Energy balance on material A | Energy balance on material B

From equation (i) and (ii), the outer surface temperature is

$$T_2 = T_\infty + \frac{\dot{q}L_A}{h} = 30 + \frac{1.5\times 10^6 \times 0.05}{1000} = 105°\text{C}$$

Also, the temperature at the insulated water is

$$T_0 = \frac{\dot{q}L_A^2}{2K_A} + T_1 \quad \text{...(iii)}$$



Thermal circuit representing wall B conduction and convection processes

From thermal circuit shown in figure,

$$T_1 = T_\infty + \left(R''_{cond,B} + R''_{conv}\right)q''$$

or

$$T_1 = T_\infty + \left(\frac{L_B}{k_B} + \frac{1}{h}\right)q''$$

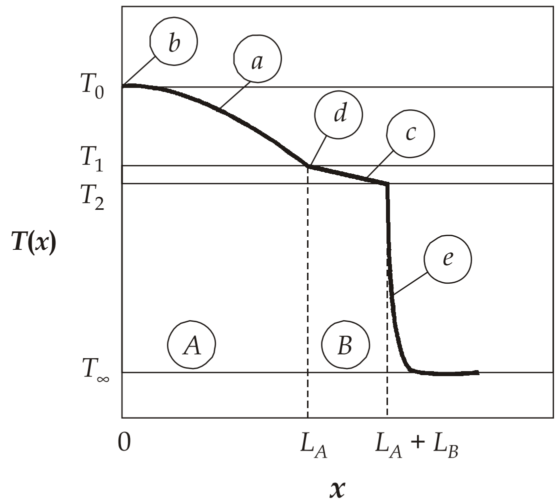
$$T_1 = 30 + \left(\frac{0.02}{150} + \frac{1}{1000}\right)\times\left(1.5\times 10^6\right)0.05$$

$$T_1 = 30 + 85 = 115°\text{C}$$

Substituting into equation (iii), the inner surface temperature of the composite is

$$T_0 = \frac{1.5\times 10^6 \times (0.05)^2}{2\times 75} + 115 = 25°\text{C} + 115°\text{C} = 140°\text{C}$$

(ii) The temperature distribution in the composite has the following features, as shown:



(a) Parabolic in material A.

(b) Zero slope at insulated boundary.

(c) Linear in material B.

(d) Slope change = k_B/k_A at interface

The temperature distribution in the water is characterized by large gradients near the surface (e).

6. (c)

The following are the advantages of tidal power:

1. About two-third of earth's surface is covered by water, there is scope to generate tidal energy on large scale.
2. Techniques to predict the rise and fall of tides as they follow cyclic fashion and prediction of energy availability is well established.
3. The life of tidal energy power plant is very long.
4. Tidal energy is a clean source of energy and does not require much land or other resources as in harnessing energy from other sources.
5. It is an inexhaustible source of energy.
6. It is an environment friendly energy and does not produce greenhouse effects.
7. Despite the fact that capital investment of construction of tidal power is high, running and maintenance costs are relatively low.

The following are the disadvantages of tidal power.

1. Capital investment for construction of tidal power plant is high.
2. Only a very few ideal locations for construction of plant are available and they too are localized to coastal regions.
3. Unpredictable intensity of sea waves can cause damage to power generating units.
4. Aquatic life is influenced adversely and can disrupt the migration of fish.
5. The energy generated is not much as high and low tides occur only twice a day and continuous energy production is not possible.
6. The actual generation is for a short period of time. The tides only happen twice a day so electricity can be produced only for that time, approximately for 12h and 25 min.
7. This technology is still not cost effective and more technological advancements are required to make it commercially viable.

Difficulties in tidal power developments:

1. Usually the places where tidal energy is produced are far away from the places where it is consumed. This transmission is expensive and difficult.
2. **Intermittent supply**: Cost and environmental problems, particularly barrage systems are less attractive than some other forms of renewable energy.
3. **Cost**: Before jumping to conclusion that this renewable, clean resource is the answer to all our problems, the disadvantages of using tidal and wave energy must be considered. The main disadvantage is the cost of those plants.
4. Altering the ecosystem at the bay: Damages such as reduced fishing, winter icing, and erosion can change the vegetation of the area and disrupt the balance. Similar to other ocean energies, tidal energy has several prerequisites that make it only available in a small number of regions.

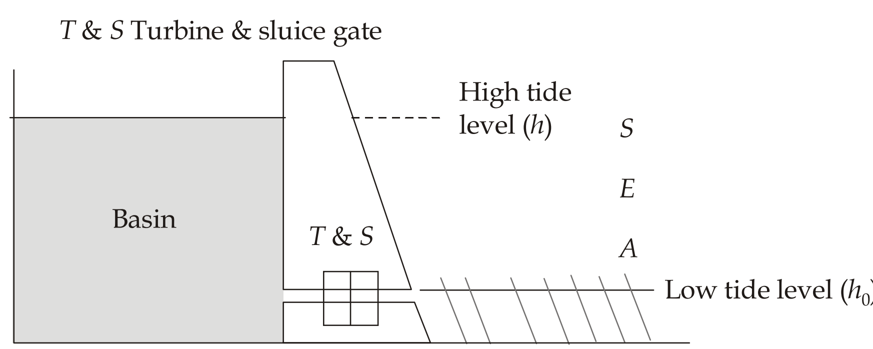


Figure: Single Basin tidal plant

Potential tidal power can be reckoned based on a mathematical calculation. Let us assume that the surface area of the reservoir as stable between the full stored water level and the emptied floor, the energy produced by the ebbing water can be expressed as

$$d(W) = \rho g h d(V) = \rho g A h \, dh$$

Here $d(W)$ = energy unit; ρ = density of seawater; g = acceleration due to gravity; A = surface area of the reservoir assumed as a constant from high tide to low tide; h = instant water level height (m); V = volume of reservoir, R = tidal range, h_0 = minimum head below which turbine cannot work.

1. Total work done in filling or emptying the basin (h to h_0)

$$W = \int dw = \int \rho g A h \, dh$$

$$= \frac{1}{2}\rho g A\left(R^2 - h_0^2\right)$$

$$= \frac{1}{2} \times 1025 \times 9.81 \times 25 \times 10^6 (10^2 - 2^2)$$

$$W = 12.0663 \times 10^{12} \text{ Nm or J}$$ Answer

2. Average power,

$$P_{average} = \frac{W}{t} = \frac{12.0663 \times 10^{12}}{22350} = 539.879 \times 10^6 \text{ W}$$ Answer

Also, average power of plant $= \eta_g \times P_{avg} = 0.75 \times 539.879 = 404.91$ MW

[As t = 6 hour and 12.5 min = 6 × 3600 + 60 × 12.5 = 22350 s]

3. Energy generated (in one filling)

$$E = \frac{0.75 \times 539.879 \times 10^6 \times 3600}{1000} = 1.458 \times 10^9 \text{ kWh}$$

7. (a) (i)

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.

7. (a) (ii)

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

$$P_a = \frac{18.76 \times 10^3}{(9.7 \times 3)} \text{ (for the battery recharging)} + \frac{67}{0.6} \text{ (for the load during 9.7 h)} + \frac{67(24-9.7)}{(9.7 \times 0.6)}$$

(to carry the daily load through night)

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

$$\text{Daily average insolation } D_1 = \frac{181}{(9.7 \times 30)} = 0.622 \text{ kW/m}^2$$

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

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

$$= \frac{0.921 \times 10^3}{(0.622 \times 10^3 \times 0.10 \times 0.5)} = 29.61 \text{ m}^2$$

7. (b)

Given : Air flow over a flat plate,

Plate surface temperature = 80°C

Air velocity (u_∞) = 50 m/s

Plate length (L) = 45 cm = 0.45 m

Plate width = 60 cm = 0.6 m

The transition to turbulence occurs at

$$Re_x = \frac{u_\infty x_c}{\nu} = 4 \times 10^5$$

$$x_c = \frac{Re_x \nu \times 10^5}{u_\infty} = \frac{4 \times 10^5 \times 18.1 \times 10^{-6}}{50}$$

$$x_c = 0.1448 \text{ m}$$

The Reynold number at the end on the plate is

$$Re_L = \frac{u_\infty L}{\nu} = \frac{50 \times 0.45}{18.1 \times 10^{-6}} = 1.243 \times 10^6$$

(i) For the laminar region, h_{c_L} is given by

$$h_{c_L} = \frac{1}{x_c} \int_0^{x_c} \frac{k}{x} 0.332 \text{Re}_x^{1/2} P_r^{1/3} dx$$

$$= \frac{k}{x_c} 0.664 \text{Re}_x^{1/2} P_r^{1/3}$$

$$h_{c_L} = \frac{0.0269}{0.1448} \times 0.664 \times \left(4 \times 10^5\right)^{1/2} (0.71)^{1/3}$$

$$h_{c_L} = 69.599 \text{ W/m}^2\text{K}$$

For the turbulent region, h_{c_T} is

$$h_{c_T} = \frac{1}{L - x_c}\int_{x_c}^{L}\frac{k}{x}0.0296(\text{Re}_x)^{0.8}(\text{Pr})^{1/3}dx$$

$$= \frac{k}{L - x_c}0.037\left((\text{Re}_L)^{0.8} - (\text{Re}_{x_c})^{0.8}\right)(P_r)^{1/3}$$

$$h_{c_T} = 130.263 \text{ W/m}^2\text{K}$$

(ii) The total heat transfer is the sum of the heat transfer from both regions

$$q = q_{\text{lan}} + q_{\text{turb}}$$

$$= (h_{CL}A_L + h_{CT}A_T)(T_s - T_\infty)$$

$$q = [(69.599 \times 0.1448 \times 0.6) + (130.263)(0.45 - 0.1448)(0.6)][80 - 0]$$

$$= 2392.04 \text{ W}$$

For both sides, $q_{\text{Total}} = 2 \times q$

$$= 4784.08 \text{ W}$$

7. (c)

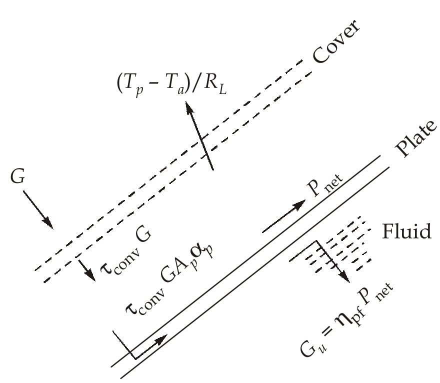


Figure: Heat transfer from solar radiation to a fluid in a collector

Answer (iii)

All solar collectors include an absorbing surface which may be called as the collector plate. In the above figure, the radiant flux striking the plate is $\tau_{\text{conv}} A_p G$, where G is the irradiance on the collector, A_p is the exposed area of the plate and τ_{conv} is transmittance of any transparent cover that may be used to protect the plate from the wind. Only a faction α_p of heat influx is actually absorbed. Since the plate is hotter than its surroundings, it loses heat at a rate $(T_p - T_a)/R_L$, where R_L is the resistance to heat loss from the plate (temperature T_p) to the outside environment (temperature T_a). The net heat flow into the plate is

$$P_{net} = \tau_{con}\, \alpha_p\, A_p\, G - [(T_p - T_a)/R_L]$$
$$= A_p[\tau_{conv}\, \alpha_p G - U_L(T_p - T_a)] = \eta_{sp}\, A_p G$$

where η_{sp} is the capture efficiency and $U_L = \dfrac{1}{R_L A_p}$ is the overall heat loss coefficient.

Useful output power from the collector is

$$P_u = \eta_{pf}\, P_{net}$$

where η_{pf} = transfer efficiency

$$P_u = \frac{\rho c Q(T_2 - T_1)}{A_p} = \eta_{pf}\left[\tau_{conv}.\alpha_p G - \frac{(T_p - T_a)}{r_L}\right] \quad ..(i)$$

Here
$\rho c = 4.2575 \times 10^6\ J/m^3K$
$A_p = 2 \times 0.8 = 1.6\ m^2$
$\Delta T = T_2 - T_1 = 4°C$
$\eta_{pf} = 0.85,\ \tau_{conv} = 0.9,$
Assume, $\alpha_p = 0.9$ (Given)
$r_L = 0.13\ m^2KW^{-1}$
$T_p = 42°C,\ T_a = 20°C$

$$\frac{4.2575\times 10^6 \times Q}{1.6}\times 4 = 0.85\left[0.9\times 0.9\times 750 - \frac{42-20}{0.13}\right]$$

$$\frac{4.2575\times 10^6}{0.4}\times Q = 0.85(607.5 - 169.23)$$

$$Q = 3.5 \times 10^{-5}\ m^3/s$$

$$Q = 126\ \text{litre/hour}$$ Answer (i)

If we put G = 0, in equation (i), we get

$$\frac{\rho c Q(T_2 - T_1)}{A_p} = \eta_{pf}\times\left(-\frac{T_p - T_a}{r_L}\right)$$

$$T_2 - T_1 = \frac{A_p \eta_{pf}}{\rho c Q}\times\frac{-(T_p - T_a)}{r_L}$$

$$= \frac{1.6\times 0.85}{4.2575\times 10^6 \times 3.5\times 10^{-5}}\times\frac{-(38-20)}{0.13}$$

$$T_2 - T_1 = -1.2637°C$$ Answer (ii)

Here –ve sign indicates temperature fall.

8. (a)

Condition I: $P_1 = 1$ atm = 101.325 kPa, $T_1 = 30 + 273 = 303\,\text{K}$

$$u_1 = 24 \text{ kmph} = 24\times\frac{5}{18} = 6.667 \text{ m/s}$$

Now, Density of air, $\rho_1 = \dfrac{P_1}{RT_1} = \dfrac{101.325}{0.287\times 303}$

$$\rho_1 = 1.165 \text{ kg/m}^3$$

Power developed, $P_1 = \eta_0 \times\left(\dfrac{1}{2}\rho_1 A u_1^3\right)$

$$1500 = 0.45 \times (0.5 \times 1.165 \times A \times (6.667)^3)$$

Cross-sectional area of rotor, $A = 19.31 \text{ m}^3$

Condition II: $P_2 = 0.88\, P_{atm} = 0.88 \times 101.325 = 89.166$ kPa

$T_2 = 10 + 273 = 283\,\text{K}$

$$u_2 = 30 \text{ kmph} = \left(30\times\frac{5}{18}\right) = 8.333 \text{ m/s}$$

Density of air, $\rho_2 = \dfrac{P_2}{RT_2} = \dfrac{89.166}{0.287\times 283} = 1.0978 \text{ kg/m}^3$

$$\rho_2 = 1.10 \text{ kg/m}^3$$

Power developed, $P_2 = \eta_0 \times\left(\dfrac{1}{2}\rho_2 A u_2^3\right)$

$$= 0.45 \times 0.5 \times 1.1 \times 19.31 \times (8.333)^3$$

$$P_2 = 2765.42 \text{ Watt}$$

% change in power output $= \left(\dfrac{P_2 - P_1}{P_1}\right)\times 100\%$

$$= \left(\frac{2765.42 - 1500}{1500}\right)\times 100\%$$

%Change in power output = 84.361%

Solidity: Solidity is defined as the ratio of the blade area to the circumference of the rotor. It determines the quantity of blade material required to intercept a certain wind area.

$$\text{Solidity, } \sigma = \frac{Nb}{2\pi R}$$

where, N = Number of blades

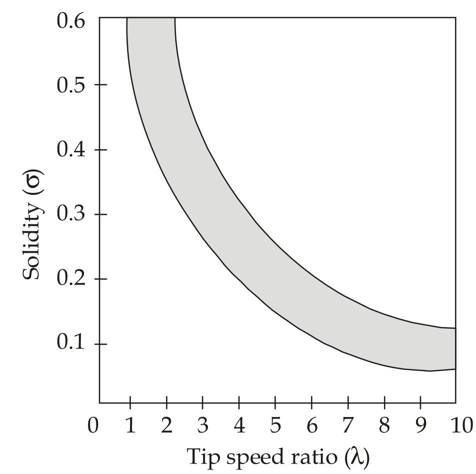
b = Blade width

R = Blade radius

It represents the fraction of the swept area of the rotor which is covered with metal.

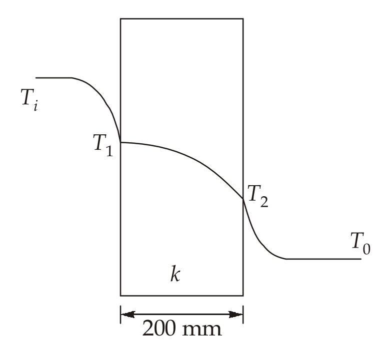
i. A two or three-blade turbine has a low solidity and so needs to rotate faster to intercept and capture wind energy. Otherwise the major part of wind energy would be lost through the large gaps between the blades. High speed wind turbines have a low starting torque.

ii. Rotors having a high value of solidity, operates at low tip speed ratio. Such rotors need a high starting torque.



A high solidity rotor rotates slowly and uses the drag force while a low solidity rotor uses lift forces.

8. (b)



Assumptions:

1. Steady state
2. One dimensional heat transfer
3. Radiation exchange is negligible

Heat transfer coefficient on hot side, $h_i = 40\ \text{W/m}^2\text{K}$

Heat transfer coefficient on cold side, $h_o = 10\ \text{W/m}^2\text{K}$

Average thermal conductivity of wall,

$$k_{avg} = k_o\left(1+\beta T_{avg}\right)$$

$$= k_o\left[1+\beta\left(\frac{T_1+T_2}{2}\right)\right]$$

$$= 0.85\left[1+7\times10^{-4}\left(\frac{T_1+T_2}{2}\right)\right]$$

$$k_{avg} = (0.85 + 2.975 \times 10^{-4}(T_1 + T_2)) \text{ W/mK}$$

Heat transfer rate per unit area,

$$q = \frac{T_i - T_1}{\frac{1}{h_i}} = \frac{T_1 - T_2}{\frac{L}{k_{avg}}} = \frac{T_2 - T_o}{\frac{1}{h_o}}$$

$$\Rightarrow \quad \frac{1800 - T_1}{\frac{1}{40}} = \frac{T_1 - T_2}{\frac{0.2}{\left[0.85 + 2.975\times10^{-4}(T_1+T_2)\right]}} = \frac{T_2 - 300}{\frac{1}{10}}$$

$$0.2 \times 40[1800 - T_1] = [0.85 + 2.975 \times 10^{-4}(T_1 + T_2)](T_1 - T_2)$$

$$14400 - 8T_1 = 0.85T_1 - 0.85T_2 + 2.975 \times 10^{-4}(T_1^2 - T_2^2)$$

$$2.975 \times 10^{-4}(T_1^2 - T_2^2) + 8.85T_1 - 0.85T_2 = 14400 \quad \text{...(1)}$$

Also, $40[1800 - T_1] = 10[T_2 - 300]$

$\Rightarrow \quad 7200 - 4T_1 = T_2 - 300$

$\Rightarrow \quad T_2 = 7500 - 4T_1$ ...(2)

Putting this value in eq. (1):

$$2.975\times10^{-4}\left[T_1^2 - (7500 - 4T_1)^2\right] + 8.85T_1 - 0.85(7500 - 4T_1) = 14400$$

$$2.975\times10^{-4}\left[T_1^2 - 7500^2 - 16T_1^2 + 60000T_1\right] + 12.25T_1 = 20775$$

$$2.975\times10^{-4}\left[-15T_1^2 + 60000T_1 - 7500^2\right] + 12.25T_1 = 20775$$

$$-4.4625\times10^{-3}T_1^2 + 17.85T_1 - 16734.375 + 12.25T_1 = 20775$$

$$4.4625\times10^{-3}T_1^2 - 30.1T_1 + 37509.375 = 0$$

On solving,

$$T_1 = 1649.579 \text{ K}$$

(Discarding other solution 5095.52K which is unrealistic)

From (2) $\quad T_2 = 7500 - 4 \times 1649.579 = 901.684 \text{ K}$

So, heat transfer rate per unit area,

$$q = \frac{1800 - T_1}{\frac{1}{40}} = \frac{1800 - 1649.579}{\frac{1}{40}}$$

$$q = 6016.84 \text{ W/m}^2$$

Heat lost per unit area, $q = 6.016 \text{ kW/m}^2$

8. (c) (i)

Tidal power plants can be broadly classified into the following four categories:

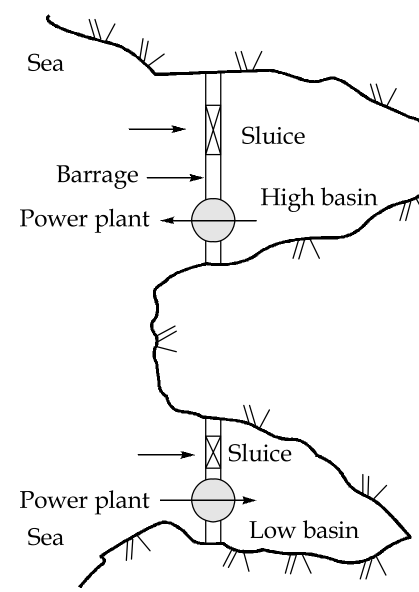
(1) Single-basin single-effect plant

(2) Single-basin double-effect plant

(3) Double-basin with linked-basin operation

(4) Double-basin with paired-basin operation

Double-basin with paired-basin operation : The paired basin scheme consists of two single-basin single-effect separate schemes located at a distance from each other. The locations are so selected that there is a difference in tidal phase between them. Both the schemes never exchange water, but are interconnected electrically. Both the basins operate in single-basin single effect mode. One basin generates electrical energy during the 'filling' process while the other during the 'emptying' process. The scheme is shown in figure below.



Double-basin with paired-basin operation

This arrangement affords a little more flexibility in operation of the plants to meet power demands. More benefit can be derived if there is a difference in tidal phase of the sea near the two basins. In case where there is no difference in tidal phase, variations in power output can be evened out by resorting to ebb tide operation in one plant and flood tide operation in the other.

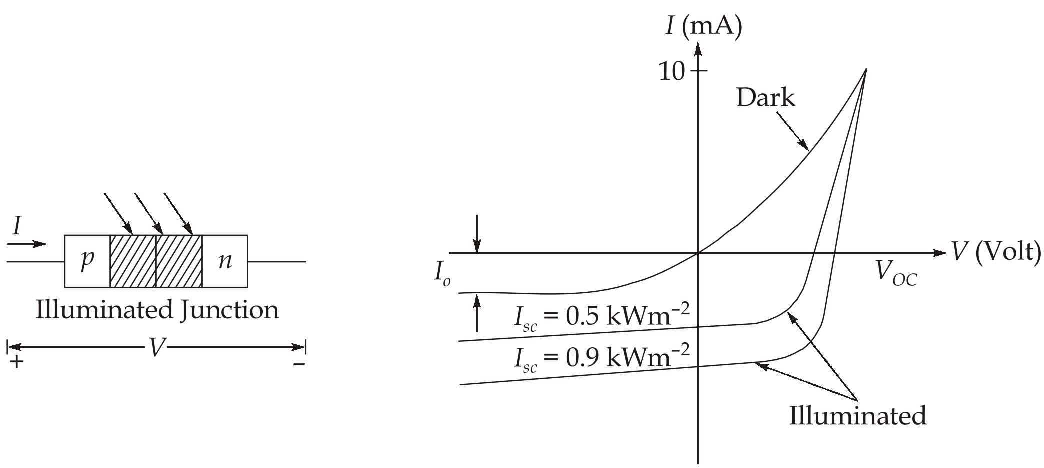
The paired-basin operation leads to a continuous output, still its power supply remains irregular and there is no solution for equalizing the great difference in output between the spring and the neap tide operation. Further, it is difficult to find two tidal sites within reasonable distance of each other having the requisite difference in time of high water.

8. (c) (ii)

Mathematical representation of characteristic of an ordinary silicon *pn*-junction is given by

$$I = I_o\left\{\exp\left(\frac{V}{V_T}\right)-1\right\}$$

where,
I_o = Reverse saturation current
V_T = Voltage equivalent of temperature



$$V_T = \frac{kT}{q}$$

where,
k = Boltzman's constant
T = Temperature in K
q = Charge of an electron

When the *pn* junction is illuminated, the characteristic gets modified in shape and shift downwards as the photon-generated component is added with reverse leakage current. Modified equation is,

$$I = -I_{sc} + I_o\left\{\exp\left(\frac{V}{V_T}\right)-1\right\}$$

When the junction is short-circuited at its terminals, V becomes zero and a finite current $I = -I_{sc}$ flows through external path emerging from the *p*-side. I_{sc}-short circuit current and its magnitude depends on solar insolation V_{oc}-open circuit voltage (current becomes zero).

$$V_{oc} = V_T.\ln\left\{\left(\frac{I_{sc}}{I_o}\right)+1\right\}$$

Hence, I-V characteristic of a solar cell may be written as,

$$I = I_{sc} - I_o\left\{\exp\left(\frac{V}{V_T}\right) - 1\right\} - I_{sc}$$

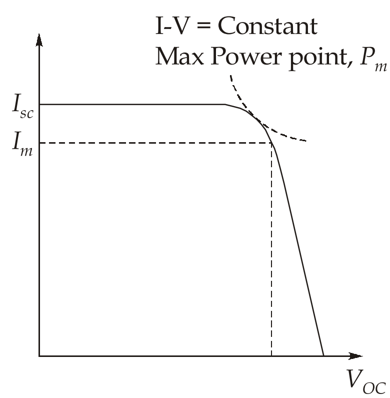
In order to obtain as much energy as possible from the rather costly PV-cell, it is desirable to operate the cell to produce maximum power. Maximum power point can be obtained by plotting the hyperbola, which is tangential to the IV characteristics. The voltage and current corresponding to the point are peak-point voltage and peak point current. There is only one point on the characteristic at which it will produce the maximum electrical power.

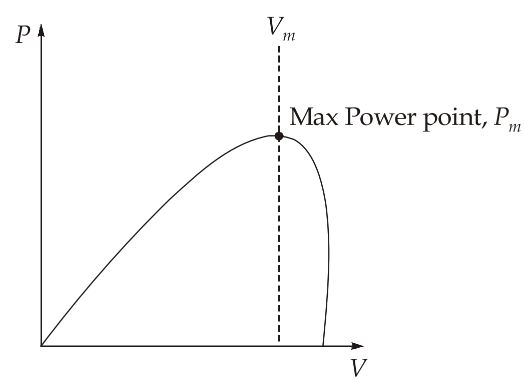
Fill Factor : Closeness of the characteristics curve to the rectangular shape is a measure of the quality of the cell.

Fill factor is defined as the ratio of the peak power to the product of open circuit voltage and short circuit current.

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

An ideal cell will have a fill factor of unity. In order to maximize the fill factor, the ratio of the photocurrent to reverse saturation current should be maximized while minimizing internal series resistance and maximizing the shunt resistance. Its value for a commercial silicon cell is in the range of 0.5 to 0.83.





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