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Leading Institute for ESE, GATE & PSUs

ESE 2025 : Mains Test Series

UPSC ENGINEERING SERVICES EXAMINATION

Mechanical Engineering

Test-5 : ~~Production Engineering & Material Science~~ Heat transfer

\+ ~~Mechatronics and Robotics~~ + Renewable Energy

Name : ....

Roll No :

Test Centres			Student's Signature
Delhi ☑	Bhopal ☐	Jaipur ☐	
Pune ☐	Kolkata ☐	Hyderabad ☐	

Instructions for Candidates

1. Do furnish the appropriate details in the answer sheet (viz. Name & Roll No).
2. There are Eight questions divided in TWO sections.
3. Candidate has to attempt FIVE questions in all in English only.
4. Question no. 1 and 5 are compulsory and out of the remaining THREE are to be attempted choosing at least ONE question from each section.
5. Use only black/blue pen.
6. The space limit for every part of the question is specified in this Question Cum Answer Booklet. Candidate should write the answer in the space provided.
7. Any page or portion of the page left blank in the Question Cum Answer Booklet must be clearly struck off.
8. There are few rough work sheets at the end of this booklet. Strike off these pages after completion of the examination.

FOR OFFICE USE	
Question No.	Marks Obtained
Section-A	
Q.1	43
Q.2	31
Q.3	—
Q.4	41
Section-B	
Q.5	13
Q.6	39
Q.7	—
Q.8	—
Total Marks Obtained	167

Signature of Evaluator .... Cross Checked by ....

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Keep it up. Well done!

IMPORTANT INSTRUCTIONS

CANDIDATES SHOULD READ THE UNDERMENTIONED INSTRUCTIONS CAREFULLY. VIOLATION OF ANY OF THE INSTRUCTIONS MAY LEAD TO PENALTY.

DONT'S

1. Do not write your name or registration number anywhere inside this Question-cum-Answer Booklet (QCAB).
2. Do not write anything other than the actual answers to the questions anywhere inside your QCAB.
3. Do not tear off any leaves from your QCAB, if you find any page missing do not fail to notify the supervisor/invigilator.
4. Do not leave behind your QCAB on your table unattended, it should be handed over to the invigilator after conclusion of the exam.

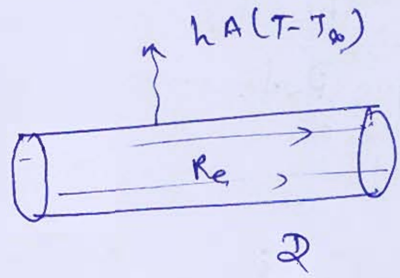
DO'S

1. Read the Instructions on the cover page and strictly follow them.
2. Write your registration number and other particulars, in the space provided on the cover of QCAB.
3. Write legibly and neatly.
4. For rough notes or calculation, the last two blank pages of this booklet should be used. The rough notes should be crossed through afterwards.
5. If you wish to cancel any work, draw your pen through it or write "Cancelled" across it, otherwise it may be evaluated.
6. Handover your QCAB personally to the invigilator before leaving the examination hall.

Section A : Heat Transfer + Renewable Sources of Energy

(a) A long conducting rod of diameter D and electrical resistance per unit length R_e is initially in thermal equilibrium with the ambient air and its surroundings. This equilibrium condition is disturbed when an electrical current I is passed through the rod. Derive an expression for the variation of the rod temperature with time during passage of the current.

[12 marks]



$$\frac{dE}{dt} = (\rho A L) C_p \frac{dT}{dt}$$

$$\dot{q}_{gn} = I^2 R$$

$$\frac{dE}{dt} = I^2 R - hA(T - T_\infty)$$

$$\rho A L C_p \frac{dT}{dt} = I^2 R - hA(T - T_\infty)$$

$$T - T_\infty = \theta$$

$$\frac{dT}{dt} = \frac{d\theta}{dt}$$

$$\frac{d\theta}{dt} = \frac{I^2 R}{mc} - \frac{hA}{mc}\theta$$

$$\int_{\theta=0}^{\theta} \frac{d\theta}{\frac{I^2R}{mc} - \frac{hA}{mc}\theta} = \int_0^t dt$$

$$\frac{1}{-\frac{hA}{mc}} \ln\left[\frac{\frac{I^2R}{mc} - \frac{hA}{mc}\theta}{\frac{I^2R}{mc}}\right] = t$$

$$-\frac{mc}{hA} \ln\left[1 - \frac{hc}{I^2R}\theta_b\right] = t$$

Do not write in this margin

$$\ln\left(1 - \frac{hc}{I^2R}\theta\right) = -\frac{hA}{mc}t$$

$$T - T_\infty = \theta = \frac{I^2R}{hc}\left[1 - e^{-\frac{hA}{mc}t}\right]$$

c → specific heat of Rod.
m = mass of Rod
R = Resistance
I = Current.
h = Convective heat transfer coefficient
t = time

(7)

Q.1 (b) A biomass gasifier is used to run a CI engine in a dual fuel model with 80% diesel replacement. The gasifier engine system produces 200 kW of power at 800 rpm. Calculate the biomass feeding rate of the gasifer if the efficiency of the engine is 35% and the calorific value of the producer gas is 17000 kJ/kg, assuming the efficiency of gasifier to be 75%.

[12 marks]

Ans

$P_{ow\ gasifier} = (200\ kW) \times 0.80 = 160\ kW$

$\eta_{engine} = 35\%$

gasifier. $Q_{supple} = \frac{160}{0.35} = 457.1428\ kW$

$(0.75 \times 17000 \times \dot{m}) = 457.1428$

$\dot{m} = ~~5.1184 \times 10^{-3}~~$ 0.03585 kg/sec

$\dot{m} = ~~18.426~~$ 129.0756 kg/hr

(12)

Do not write in this margin

Q.1 (c) Discuss how energy is stored in reversible chemical reactions. What are their main advantages? What do you understand by turning temperature?

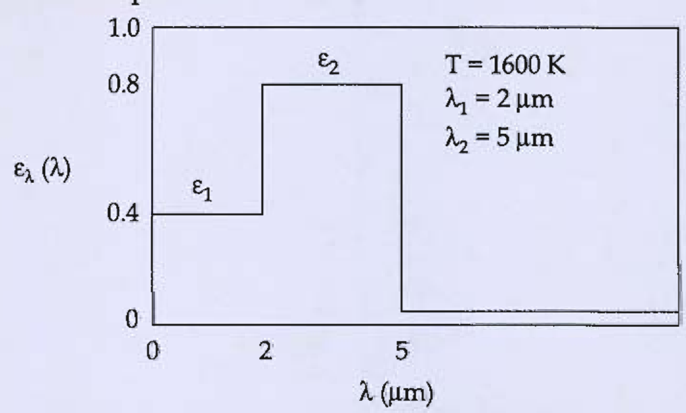
[12 marks]

Ans

(d) A diffuse surface at 1600 K has the spectral emissivity as shown in figure. Determine

(i) the total emissivity.

(ii) the total emissive power.



[Use blackbody radiation band emission fraction table attached at the end]

[12 marks]

12

As table is not attached.

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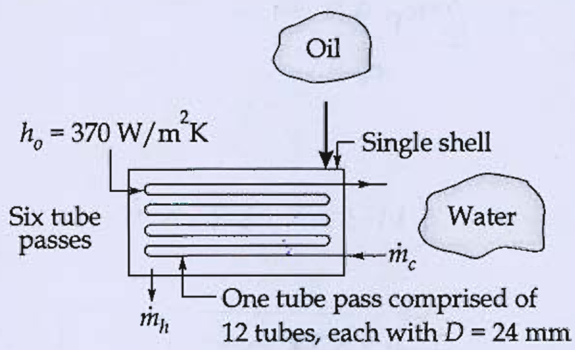
(e) A shell and tube exchanger must be designed to heat 3 kg/s of water from 20 to 85°C. The heating is to be accomplished by passing hot oil, which is available at 180°C, through the shell and tube side of the heat exchanger. The oil is known to provide an average convection coefficient $h_0 = 370\ \text{W/m}^2\text{K}$ on the outside of the tube. Twelve tubes pass the water through the shell. Each tube is thin walled, of diameter $D = 24$ mm, and makes six passes through the shell. If the oil leaves the exchanger at 110°C. Determine

(i) The required oil flow rate in kg/s.

(ii) The required tube length to accomplish the desired heating.



Use the equation $\text{Nu} = 0.023\,(\text{Re})^{0.8}(\text{Pr})^{0.4}$

Correction factor for the heat exchanger to be 0.87

Properties of oil, $c_p = 2300$ J/kgK; Properties of water, $c_p = 4180$ J/kgK;

$\mu = 560 \times 10^{-6}\ \text{Ns/m}^2$; $k = 0.65$ W/mK

[12 marks]

(1) $\dot{m} = 3$ kg/sec

total no of tube $= 6 \times 12 = 72$

~~$n \rho A V = \dot{m}$~~

~~$72 \times 1000 \times \pi \times 0.012^2 \times$~~

$(\dot{m} c_p \Delta T)_{water} = (\dot{m} c_p \Delta T)_{oil}$

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

$\dot{m}_{oil} = 5.0627$ kg/sec

(2) $0.87 \times UA\,(\text{LMTD}) = (\dot{m} c_p \Delta T)$

$n \rho A V = \dot{m}_{water}$

~~$h = 0.023 \times$~~

$v \times 1000 \times \pi \times 0.012^2 \times 12 = 3$

$\Pr = \frac{\mu c_p}{k} = 3.6012$

$v = 0.5526$ $\quad V = 6 \times 0.0921$ m/sec

$h = \frac{k}{d} \times Nu \Rightarrow 783.486 \times 4.1929$

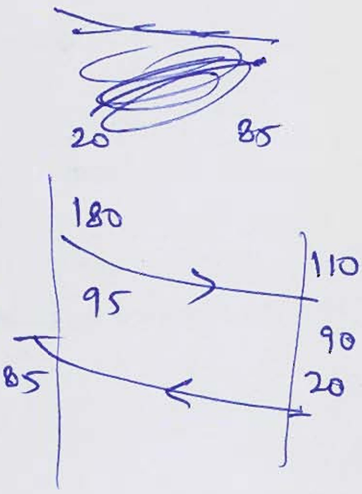
$Re_d = \frac{\rho V D}{\mu} = 3947.14 \times 6 = 23682.84$

$\frac{1}{U} = \frac{1}{h_1} + \frac{1}{h_2}$

$= \frac{1}{763.49} + \frac{1}{370} \Rightarrow U = 332.545$ ~~251.317~~

4.1929 ×

0.87 × 332.545 ~~251.317~~ × 2πr² × L × 92.477



h × ~~h~~UA (LMTD) ⁄⁄ $= \left(\frac{mc_p \Delta T}{12}\right)$

$= mc_p \Delta T$

LMTD ≈ 92.477

$L = (11320.833 \times 6)$

~~L = 7.42538 m~~

L = 33.6717 m

length of each tube

12

(a) A submarine is to be designed to provide a comfortable temperature for the crew of not less than 21°C. The submarine can be idealized as a cylinder 10 m in diameter and 70 m in length. The combined heat transfer coefficient on the interior is 15 W/m²K, while on the outside surface the heat transfer coefficient is vary from 60 W/m²K (not moving) to 880 W/m²K (top speed). For the following wall constructions, determine the minimum size in kilowatts of the heating unit required if the sea water temperatures vary from 2.2°C to 14.5°C during operation.

(i) 1.2 cm aluminium

(ii) 1.8 cm stainless steel with a 2.5 cm thick layer fiberglass insulation on the inside

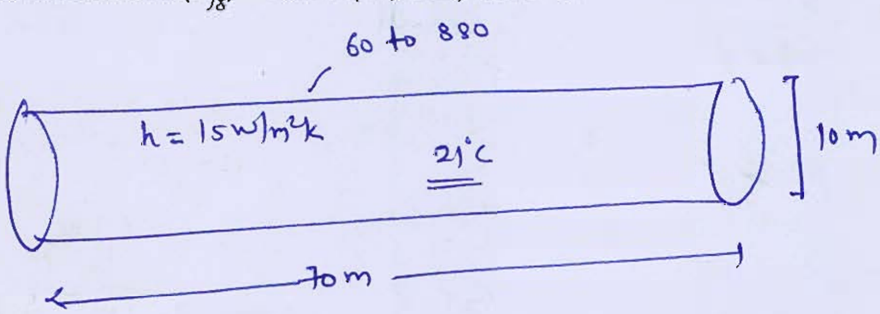
(iii) of sandwich construction with a 1.8 cm thickness of stainless steel, a 2.5 cm thick layer of fiberglass insulation, and a 0.6 cm thickness of aluminium on the inside. What conclusions can you draw?

Take, for aluminium (K_a) = 236 (W/mK) at 0°C

for stainless steel (K_s) = 0.035 (W/mK) at 20°C

for fiberglass insulation (K_{fg}) = 0.035 (W/mK) at 20°C

[20 marks]



2.2 to 14.5°C

taking worst condition for maxi heat loss

$h_{out} = 880$ W/m²k

$T_{sea} = 2.2°C$

Area = 2πrh + 2πr² = 750π

(i) $q_{max} = \dfrac{T_1 - T_2}{R_{th}}$

$4.8228 \times 10^{-7} = \dfrac{1}{hA}$ $\dfrac{L}{KA}$ Rcell $\dfrac{1}{hA} = 2.829 \times 10^{-5}$

circumferent $R_1 = \left(\dfrac{\ln(r_2/r_1)}{2\pi K L}\right)$

$= \dfrac{\ln(5.012/5)}{2\pi \times 236 \times 70}$

$= 2.3094 \times 10^{-8}$

sides $R = \left(\dfrac{L}{KA}\right) \times \dfrac{1}{2}$

$R_2 = 3.237 \times 10^{-7}$

$R_{eq} = \dfrac{R_1 R_2}{R_1 + R_2} = 1.3478 \times 10^{-8}$

$R_{total} = R_1 + R_2 + R_3$

$= 2.878\,~~3~~ \times 10^{-5}$

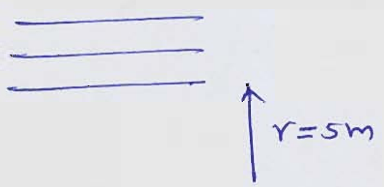
$\dot{q}_{loss} = \dfrac{\Delta T}{R_{tot}} = \dfrac{21 - 2.2}{2.878\,~~3~~ \times 10^{-5}} =$ ~~653 835~~ kW

653,100.

(ii)

1.8 cm stainless steel

2.5 cm fiberglass



$R = \dfrac{\ln\left(\frac{5.018}{5}\right)}{2\pi \times 0.035 \times 70} + \dfrac{\ln\left(\frac{5.025}{5}\right)}{2\pi \times 0.035 \times 70}$

$R =$ ~~6.5034 × 10⁻⁴~~ 5.57437×10^{-4}

$\text{side wall} = \dfrac{d_1}{k_1 A} + \dfrac{d_2}{k_2 A}$

$= \dfrac{0.018}{0.035 \times \pi \times 5^2} + \dfrac{0.025}{0.035 \times \pi \times 5^2}$

$= 0.01564$

$R_{total} = \dfrac{R_1 R_2}{R_1 + R_2} =$ ~~6.4377 × 10⁻⁴~~ 5.3825×10^{-4}

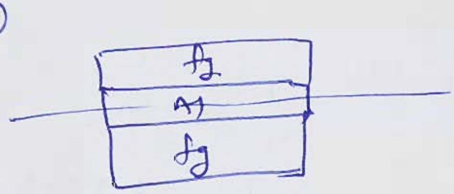
$R_{out} = \dfrac{1}{hA} =$ ~~4.8228 × 10⁻⁷~~ 4.8228×10^{-7}

$R_{in} = 2.829 \times 10^{-5}$

$R_{total} = R_1 + R_2 + R_3 =$ ~~6.5315 × 10⁻⁷~~ 5.67025×10^{-7}

$\dot{q}_{supp} = \dfrac{\Delta T}{R} = \dfrac{21 - 2.2}{R} =$ ~~28.783~~ 33.155 kW

(3)



$R = \sum \dfrac{\ln(r_2/r_1)}{2\pi k L}$

$R_{shell} = 5.574486 \times 10^{-4}$

$R_{side\ wall} = \sum \dfrac{d}{kA} = 0.01564$

$R_{total} = \dfrac{R_{sh} \times R_{wall}}{R_{shell} + R_{wall}} = 5.38366 \times 10^{-4}$

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$R_{total} = 5.38366 \times 10^{-4} + 4.8228 \times 10^{-7} + 2.829 \times 10^{-5}$

$= 5.6713828 \times 10^{-4}$

$i = \frac{\Delta T}{R_T} = \frac{21-2.2}{R_T}$

$= 33.148$ kW

min heat loss is in 3rd case

So power ~~supplied~~ requirement will be less

⇓

Best option.

(3.)

(b) A fuel cell has the following reactions:

Anode: $C + 2O^{--} \rightarrow CO_2 + 4e^-$

Cathode: $4e^- + O_2 \rightarrow 2O^{--}$

At reference temperature and pressure (298 K and 1 bar), the changes of enthalpy and of free energy, per kilomole of CO_2, are:

$$\Delta\bar{h}_f^\circ = -393.5 \text{ MJ}$$

$$\Delta\bar{g}_f^\circ = -394.5 \text{ MJ}$$

What is the overall reaction? What is the ideal emf? What is the difference in entropy between reactants and products? Assume that the internal resistance of the cell is 1 milli-Ohm. Otherwise, the cell behaves as an ideal voltage source. How much carbon is needed to deliver 1 MWh of electricity to the load in minimum possible time? What is the load resistance under such conditions?

[20 marks]

overall Rxn: $C + O_2 \rightarrow CO_2$

ideal emf $= \frac{\Delta G}{\Delta H} = \frac{394.5}{393.5}$

$= 1.0025$ Volt

~~$\Delta g = \Delta h - \Delta s T$~~.

Const Temp: $G = H - TS$

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

$-394.5 = -393.5 - 298 \times \Delta S$

differen in entropy. $\Delta S = 3.3557 \times 10^{-3}$ MJ/K

1 Carbon ⇒ $4e^-$

Work = ΔG = 394.5 MJ/kg of CO_2

(3)

$1 \times 10^6 \times 3600$ Jule = $394.5 \times 10^6 \times x$ kg CO_2

$x =$

Q.2 (c) A square plate maintained at 95°C experiences a force of 10.5 N when air at 25°C flows over it at a velocity of 30 m/s. Assuming the flow to be turbulent and using Colburn analogy, calculate (a) heat transfer coefficient and (b) heat loss from the plate surface. Properties of air at the mean film temperature are:

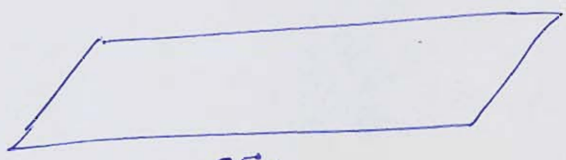
$\rho = 1.06\ kg/m^3$, $c_p = 1.005\ kJ/kgK$, $\nu = 18.97 \times 10^{-6}\ m^2/s$, $Pr = 0.696$

For turbulent flow, take drag coefficient

$$C_D = \frac{0.0742}{Re_L^{1/5}}$$ ← Assuming It avg drag coefficient,

[20 marks]

Ans



95°C

F = 10.5 N

$$Re_L = \frac{\rho V_\infty L}{\mu} = 1.581444 \times 10^6 L$$

Avg ← $$C_D = \frac{0.0742}{Re_L^{0.2}} = \frac{4.271625 \times 10^{-3}}{x^{0.2}}$$

Colburn analogy

$$St\ Pr^{2/3} = \frac{f'}{2} = \frac{2.1358 \times 10^{-3}}{x^{0.2}}$$

$$\frac{Nu}{Re_x\ Pr}$$

$$\overline{Nu}_x = \frac{2.1358 \times 10^{-3}}{x^{0.2}} \times Re_x\ Pr^{1/3}$$

$$\nu = \frac{\mu}{\rho}$$

$$\overline{Nu}_x = 3377.648\ x^{0.4} \times 0.8862$$

$$\overline{Nu}_x = 2993.3\ x^{0.4}$$

$$\frac{\mu C_p}{k} = Pr.$$

$$\frac{\bar{h} x}{k} = Nu_x$$

$$k = 0.029\ \frac{W}{mK}$$

$$\bar{h}_x = \frac{86.9121}{x^{0.2}}$$

$$\bar{h}_L = \frac{86.9121}{L^{0.2}}$$

Assuming air flow over one side of the plate

$$\text{drag force} = C_d \times \frac{1}{2} \rho A V_\infty^2$$

$$10.5 = \frac{4.271625 \times 10^{-3}}{L^{0.2}} \times \frac{1}{2} \times 1.06 \times L^2 \times 30^2$$

$$\boxed{L = 2.4865\ m} \leftarrow \text{size of plate} = L \times L$$

$$C_d = \frac{\int_0^L f'\,dx}{L}$$

$$C_d = \frac{\int_0^L \frac{A}{x^{0.2}}\,dx}{L}$$

$$= \frac{1}{0.4} \frac{A}{L^{0.2}}$$

$$\boxed{C_d = \frac{5}{4} C_{fx}}$$

(a) Heat transfer coefficient

$$\bar{h}_L = \frac{86.9121}{2.4865^{0.2}}$$

$$= 72.4373\ W/m^2K$$

(b) Heat loss

$$\bar{h} A (T_s - T_\infty)$$

$$\Rightarrow 72.4373 \times 2.4865^2 \times 70$$

$$= 31.349\ kW$$

20

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Q.3 (a) A cylindrical liquid oxygen (LOX) tank has a diameter of 1.5 m, a length of 6 m, and hemispherical ends. The boiling point of LOX is -179.4°C. An insulation is sought which will reduce the boil-off rate in the steady state 12 kg/hr. The heat of vapourization of LOX is 282 kJ/kg. If the thickness of the insulation 7 cm, then determine the value of its thermal conductivity?

[Assume surrounding temperature to be 20°C]

[20 marks]

Q.3 (b) A school in a remote place has the following energy requirements:

- Ten lamps each of 100 CP, that operate for 6 hours daily.
- Ten computers each of 250W, that operate for 6 hours daily by a dual fuel engine driven generator.
- 2 hp water pump driven by dual fuel engine for two hours daily.

Use the following data:

Gas required for lighting a 100 Candle power lamp = 0.126 m^3/hour

Thermal efficiency of both the engines = 25%

Conversion efficiency of generator = 80%

Collectable cow dung per cow = 7 kg

Percentage of dry matter in cow dung = 18%

Biogas yield = 0.34 m^3/kg of dry matter

Retention period = 50 days

Density of slurry = 1090 kg/m^3

Heating value of biogas = 23 MJ/m^3

Volume occupied by gas = 10% of digester volume

Equal amount of water is added in cowdung for producing slurry.

Calculate the size of digester and the number of cows required to feed the plant.

[20 marks]

3 (c) A paint baking oven consists of a long, triangular (equilateral) duct in which a heated surface is maintained at 1200 K and another surface is insulated. Painted panels, which are maintained at 500 K, occupy the third surface. The triangle is of width $W = 1$ m, and the heated and insulated surfaces have an emissivity of 0.8. The emissivity of the panels is 0.4. Determine:

(i) During steady-state operation, the rate at which energy is supplied to the heated side per unit length of the duct to maintain its temperature at 1200 K?

(ii) The temperature of the insulated surface?

[20 marks]

4 (a) Two large steel plates at temperature of 120°C and 80°C are separated by a steel rod 0.4 m long and 2.5 cm in diameter. The rod is welded to each plate. The space between the plates is filled with insulation, which also insulates the circumference of the rod. Due to voltage difference between the two plates, an electric current flows through the rod, dissipating electrical energy at a rate of 15 W. Determine:

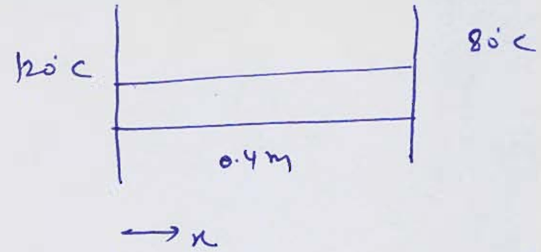
(i) The maximum temperature in the rod.

(ii) The heat flow rate at each end of the rod.

Take thermal conductivity of steel as 43 W/mK at 20°C. Also, compare the net heat flow rate at the two ends with the total rate of heat generation.

[20 marks]

Ans



$d = 2.5\,cm \quad r = 1.25\,cm$

$\dot{q}_{total} = 15\,W$

$\dot{q}_{gen}/\text{volume} = \frac{15}{\pi r^2 h}$

$\dot{q}_{gen} = 76394.37\ \frac{W}{m^3}$

Conduction equation (onedirection)

Steady state.

$$\frac{d}{dx} k \frac{dT}{dx} + \dot{q}_{gen} = 0$$

$k = 43\ W/mK$

$$\frac{d^2T}{dx^2} = -\frac{\dot{q}_{gen}}{k}$$

$$\frac{dT}{dx} = -\frac{\dot{q}_{gen}}{k}x + C_1$$

$$T = -\frac{\dot{q}_{gen} x^2}{2k} + C_1 x + C_2$$

at $x = 0$ $T = 120°$ $120 = C_2$

at $x = 0.4$

(1) $T = 80° = -142.129 + 0.4\,C_1 + 120$

$C_1 = 255.3225$

$$T = -888.3067\,x^2 + 255.3225\,x + 120$$

for T_{max}

$$\frac{dT}{dx} = 0$$

$$-888.3067 \times 2x + 255.3225 = 0$$

$x = 0.1437\,m$ — (1)

$T_{max} = 138.34°C$

(2) Heat flow rate at each end

$$q_1 = +kA \frac{dT}{dx}\bigg|_{x=0} = 43 \times \pi \times 0.0125^2 \times (255.3225)$$

-ve x direction $= 5.389\ W$

$$q_2 = -kA \frac{dT}{dx}\bigg|_{x=0.4} = -43 \times \pi \times 0.0125^2 \times \left[-868.3067 \times 2 \times 0.4 + 255.3225\right]$$

$$= 9.6107\ W$$

Total heat flow rate $= q_1 + q_2 = 5.389 + 9.6107$

$= 14.999\ W$

$= \underline{15\ W}$ } Both are same

total heat generation $= 15\ W$.

~~Hotal~~

⇓

Conservation of Energy

Total Energy loss	=	Total Energy Generated

4

Q.4 (b) **(i)** With the help of a neat sketch, explain the working of a Vertical Axis Wind Turbine (VAWT). Describe the function of its main components. Also, discuss the key advantages of VAWTs.

(ii) A propeller type wind turbine has following data

Speed of free wind at a height of 10 m = 15 m/s ; Air density = 1.23 kg/m^3;
α = 0.15; Height of tower = 120 m; Diameter of rotor = 85 m;

Wind velocity at the turbine reduces by 25%; Generator efficiency = 90%

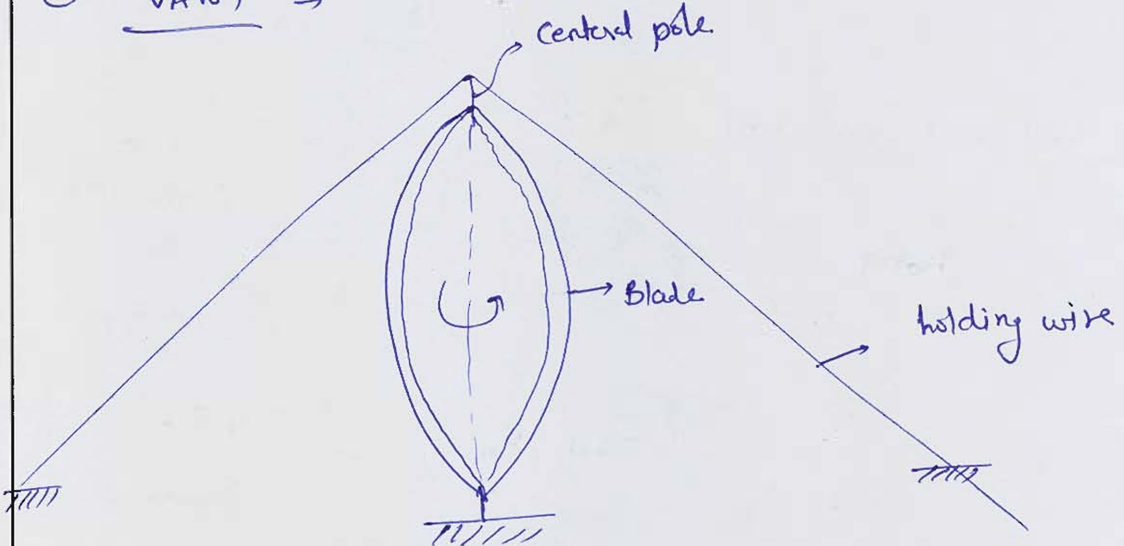
Find :

(i) Total power available in wind.
(ii) Power extracted by the turbine.
(iii) Electrical power generated.
(iv) Axial thrust on the turbine.
(v) Maximum axial thrust on the turbine.

[10 + 10 marks]

Ans

(1) VAWT →



→ Rotation axis is vertical

- ~~Agle~~ Angle of attack changes continuously at const wind velocity also.

- No need to rotate it in the wind direction as in case of HAWT.
It will work whether wind is coming from any direction.

→ chances of Resonance occures that's why hight cannot be increased as high as HAWT.

— Low power output

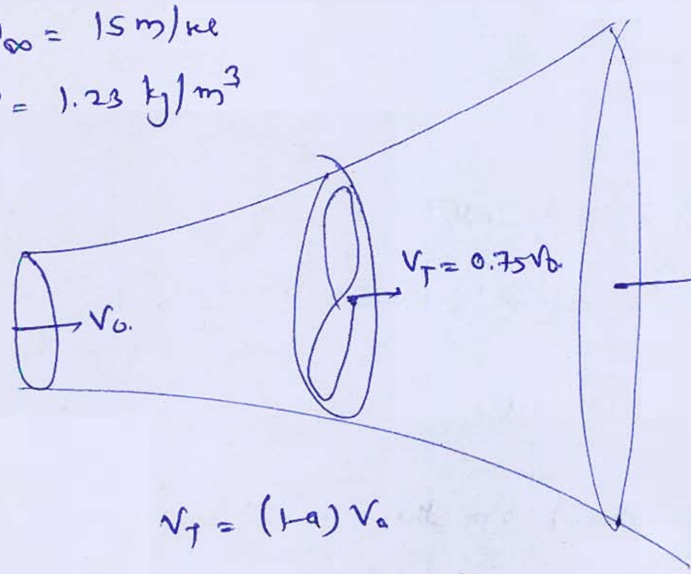
Do not write in this margin

→ low wind energy available ~~at~~ due to low height

→ ~~Gen~~ Installation cost is less.

(2) $U_\infty = 15\ m/sec$

$\rho = 1.23\ kg/m^3$



$V_T = (1-a)\,V_0$

$0.75 V_0 = (1-a) V_0$

$a = 0.25$

(1) Total power available in wind

$P_0 = \left(\frac{1}{2} \rho A V_0^3\right)$

$= \frac{1}{2} \times 1.23 \times \pi \times \frac{85^2}{4} \times 15^3$

$= 11778.137\ kW$

Total useful ~~work~~ power avaible in wind

$= \frac{16}{27} \times P_0 = 6979.637\ kW$

(2) Power Extracted by the turbine

$= 4a(1-a)^2 \times \frac{1}{2} \rho A V^3$

$= (4 \times 0.25 \times 0.75^2) \times P_0$

$= 0.5625 \times P_0$

$= 6625.125\ kW$

(3) Electrical power generated

$= \eta_g \times 6625.125$

$= 0.9 \times 6225.125$

$= 5962.61$ kW

(iv) Axial thrust

$F_T = 4a \times (1-a) \times \frac{1}{2} \rho A V_0^2$

$= 4 \times 0.25 \times 0.75 \times \frac{1}{2} \times 1.23 \times \pi \times \frac{85^2}{4} \times 15^2 \times 10^{-3}$ kN

$= 588.906$ kN

(v) Maximum axial thrust on the turbine

$F_{T_{max}} = \frac{1}{2} \rho A V_0^2$

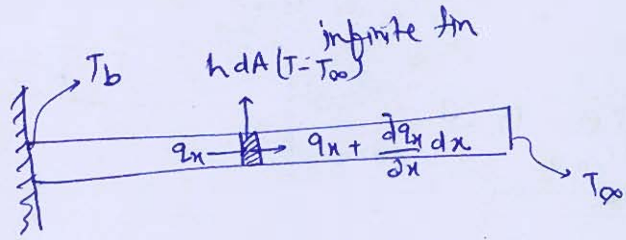
$= \frac{1}{2} \times 1.229 \times \pi \times \frac{85^2}{4} \times 15^2 \times 10^{-3}$ kN

$=$ ~~78520~~ 785.209 kN

Q4 (c) Derive an expression for temperature distribution in case of infinite fin.

Two long slender rods A and B, made of different materials having same diameter of 12 mm and length 1 m, are attached to a surface maintained at a temperature of 100°C. The surfaces of the rods are exposed to ambient still air at 20°C. By traversing along the length of the rods with a temperature sensor, it is found that the surface temperatures of rods A and B are equal at positions 15 cm and 7.5 cm respectively away from the base surface. If material of A is carbon steel with thermal conductivity 60 W/mK, what is the thermal conductivity of rod B? List the assumptions made. Assume that the average convection coefficient of air is 5 W/m^{2}K. Find the ratio of the rate of heat transfer for rods A and B.

[20 marks]



T_∞

No heat generation

Energy balance for small element

$$E_{in} - E_{out} = 0$$

$$q_x - \left(q_x + \frac{\partial q_x}{\partial x}.dx\right) - h\,dA\,(T-T_\infty) = 0$$

$$\frac{dq_x}{dx}dx + hP\,dx\,(T-T_\infty) = 0$$

A_c & k constant with x

$$\frac{d}{dx}\left(-kA_c\frac{dT}{dx}\right) + hP(T-T_\infty) = 0$$

$$\frac{d^2T}{dx^2} - \frac{hP}{kA_c}(T-T_\infty) = 0$$

Assume

$$\theta = T - T_\infty$$

$$\frac{d\theta}{dx} = \frac{dT}{dx}$$

$$\frac{d^2\theta}{dx^2} = \frac{d^2T}{dx^2}$$

$$\frac{d^2\theta}{dx^2} - \frac{hP}{kA_c}\theta = 0$$

$$m = \sqrt{\frac{hP}{kA_c}}$$

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

⇓ solution of this differential eqn

$$\theta = C_1e^{mx} + C_2e^{-mx} \quad \text{--- (3)}$$

Boundary Condition at $x = L$ $\theta = 0$

$$0 = C_1e^{mL} + C_2e^{-mL}$$

~~at $x = 0$ $\theta = \theta_b$~~

~~$\theta_b = C_1 + C_2$~~

~~$0 = C_1 e^{mL} + C_2 e^{-mL}$~~

~~$C_1 e^{mL} = -C_2 e^{-mL}$~~

~~$C_1 = -C_2 e^{-2mL}$~~

~~$\theta_b =$~~

$L \to \infty$

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

$\boxed{C_1 = 0}$ — (1)

at $x = 0$

$\theta = \theta_b$

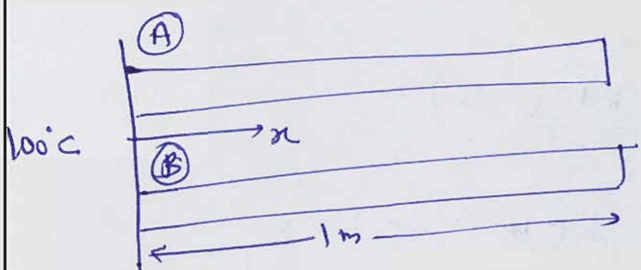
$\theta_b = C_2 e^{-m \times 0}$

$\boxed{\theta_b = C_2}$ — (2)

By putting eq (1) & (2) in (3)

$$\theta = 0 \, e^{+mx} + \theta_b e^{-mx}$$

$$\boxed{\frac{\theta}{\theta_b} = e^{-mx}}$$



$d = 12\,mm$

$\theta_b = 100 - 20 = 80°C$

$$m = \sqrt{\frac{hP}{kA}} = \sqrt{\frac{5 \times \pi d}{k \pi d^2/4}} = \sqrt{\frac{20}{kd}} = \frac{40.8248}{\sqrt{k}}$$

$$\theta_A \Big|_{x=15cm} = \theta_B \Big|_{x=7.5cm}$$

$$\theta_0 e^{-m_1 x_1} = \theta_0 e^{-m_2 x_2}$$

$$e^{-\frac{40.8248}{\sqrt{60}} \times 0.15} = e^{-\frac{40.8248}{\sqrt{k_2}} \times 0.075}$$

$$\boxed{k_2 = 15 \; W/mK}$$

Assumptions

(1) tip end there is no heat transfer as long fin $T_{x=1m} = T_\infty$

(2) No temp gradient along the radial direction

(3) Unidirection heat flow through the fin.

Ratio of Heat transfer

$$\frac{H_A}{H_B} = \frac{(\sqrt{K P K A}\ \theta_b)_1}{(\sqrt{K P K A}\ \theta_b)_2}$$

$$= \sqrt{\frac{k_1}{k_2}}$$

$$= \sqrt{\frac{60}{15}}$$

$$\boxed{\frac{H_A}{H_B} = 2}$$

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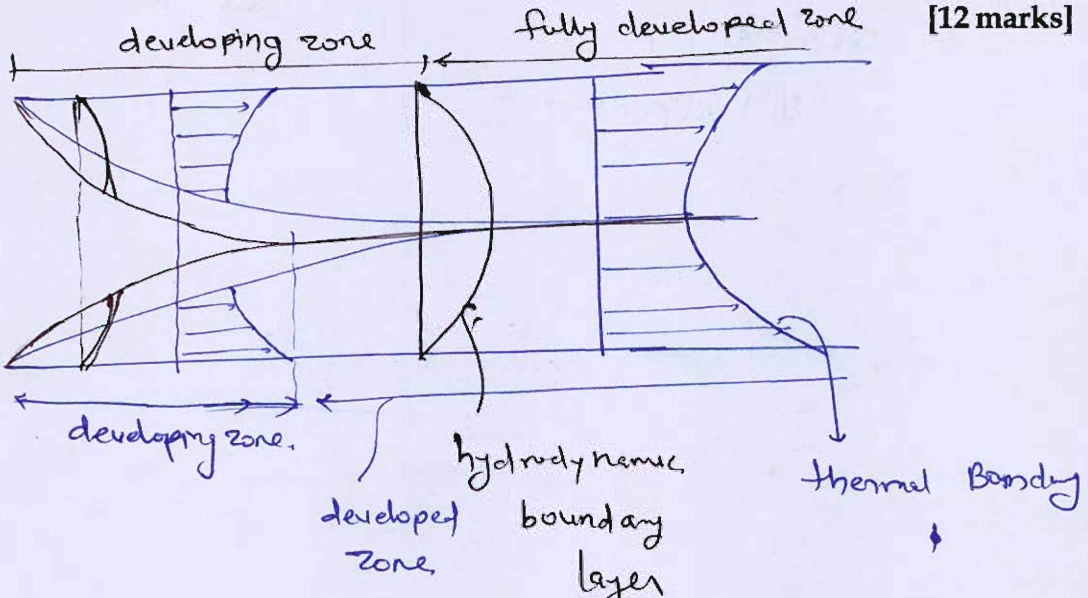
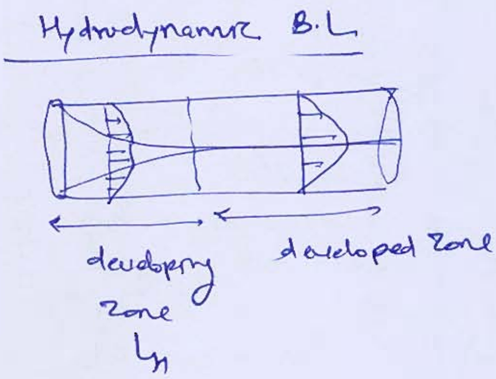
Section B : Heat Transfer + Renewable Sources of Energy

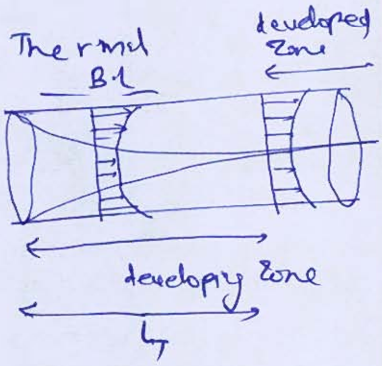
Q.5 (a) Explain the working of molten carbonate fuel cell using appropriate diagram and write the various chemical reactions involved in this type of fuel cell.

[12 marks]

Q.5 (b) Explain clearly what is "thermally developed zone" in case of laminar flow through a tube and compare it to hydrodynamically developed zone. Draw the temperature distribution for (i) constant wall temperature (ii) constant heat flux. **[12 marks]**







$$\frac{L_H}{D} = 0.05\, Re_D$$

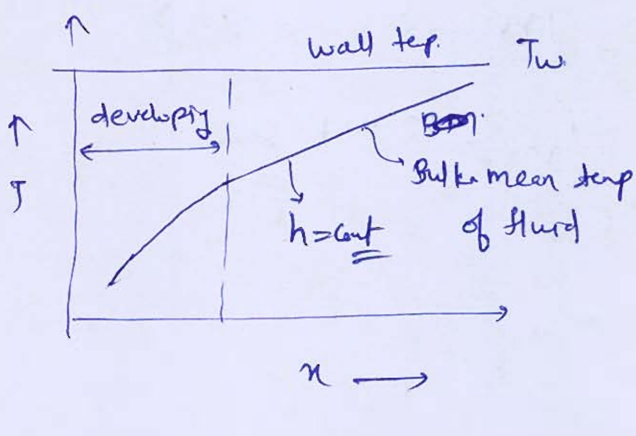
$$\frac{L_H}{L_T} = 1.025\, Pr^{1/3}$$

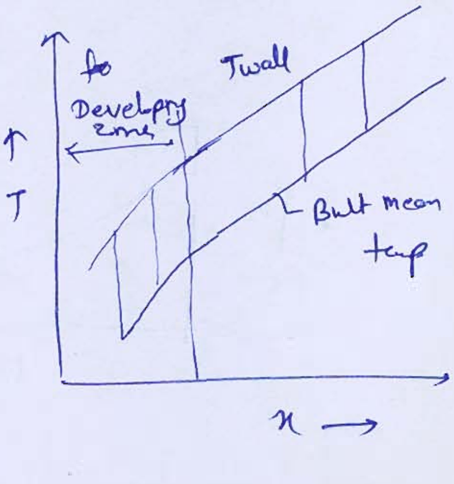
↓ prandtl No

$$\frac{L_H}{D} = 0.05\, Re_D \cdot Pr^{1/3}$$

Temperature distribution

(1) Constant Wall temp. (heating) (2) Const heat flux





for laminar flow

$\bar{h} = 3.66$ Cost wall temp. in full developed region

$\bar{h} = 4.36$ Cost heat flux

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Q.5 (c) A 3 mm-thick panel of aluminum alloy (ρ = 2770 kg/m^3, c = 875 J/kgK and k = 177 W/mK is finished on both sides with an epoxy coating that must be cured at or above T_c = 150°C for at least 5 min. The curing operation is performed in a large oven with air at 175°C and convection coefficient of h = 40 W/m^{2}K. The coating has an emissivity of ε = 0.8, and the temperature of the oven walls is 175°C, providing an effective radiation coefficient of h_{rad} = 12 W/m^2 K. If the panel is placed in the oven at an initial temperature of 25°C, at what total elapsed time, t, will the cure process be completed? Also show the variation of temperature with time during the curing process.

[12 marks]

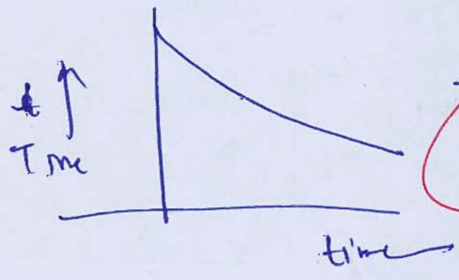
Ans

$$\frac{\theta}{\theta_b} = e^{-\frac{hA}{\rho V c_p} t}$$

1

$$\frac{V}{A} = \frac{t \times b \times h}{2(b \times h)} = \frac{t}{2}$$

$$\frac{150 - 25}{175 - 25} = e^{-\frac{52 \times 0.1 \times t}{2770 \times 0.0015 \times 875}}$$



t_{min} = 12.747 sec

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Q.5 (d) Assuming the sun's surface as black and an equivalent black body temperature of 5779 K,

1. Estimate the rate at which the sun emits radiant energy
2. What fraction of this energy is intercepted by the earth?
3. What is the amount intercepted?

Given: Diameter of sun = 1.39×10^9 m

Diameter of earth = 1.27×10^7 m

Distance between the sun and the earth = 1.5×10^{11} m **[12 marks]**

Ans

(1) $E = \sigma A T^4 = 5.67 \times 10^{-8} \times \frac{4\pi \times (1.39 \times 10^9)^2}{4} \times 5779^4$

$= 3.8386 \times 10^{26}$ Watt.

(2)

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5 (e) A compound parabolic concentrator (CPC), 1.5 m long has an acceptance angle of 20°. The surface of the absorber is flat with a width of 15 cm. Evaluate the concentration ratio, the aperture height and the surface area of the concentrator.

[12 marks]

Q.6 (a) A roof top collector is installed in a building at Agra (27.167°N, 78.1°E). Determine the total extra-terrestrial radiation falling on the collector on 10[th] June. If the collector are installed horizontally and area covered by the collector is 10 m^2. Calculate the change in the total extra-terrestrial radiation incident on the collector if it is inclined by 15°.

[20 marks]

Ans

$$I_0 = I_{ext}\left(1 + 0.033\cos\left(\frac{360}{365}n\right)\right)$$

$$\delta = 23.45 \sin\left(\frac{360}{365}(284+n)\right)$$

$$\theta_i = \cos(\phi-\beta)\cos\delta\cos\omega + \sin(\phi-\beta)\sin\delta$$

on 10th Jun $\quad n = 31+28+31+30+31+10$

$$= 161$$

$$\delta = 23.0116^\circ$$

$$\phi = 27.167^\circ$$

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

$$\omega_s = 102.589^\circ$$

$$t_d = \frac{2\omega_s}{15} = 13.678\ hr$$

Do not write in this margin

(a)

$H_0 = 2\left[3600\ I_{ext}\left(1 + 0.033\cos\left(\frac{360}{365}n\right)\right) \times \right.$

$\cos(\phi)\cos\delta\ \sin\omega_s + \sin\phi\ \sin\delta \times \omega_s\Big] \times \frac{2}{15}$

$\sin\omega_s \to 102.529$, $\omega_s \to 1.7905$

$= 1312320 \times 0.96923 \times$ ~~6.761779×10^6~~ 1.11877

$=$ ~~8.5624 ... kJoule~~

$= 1423.008$ KJule

if $\beta = 15^\circ$

(b)

$H_1 = 1312320 \times 0.96923 \times \left[\cos(\phi - \beta)\cos\delta\ \sin\omega_s + \sin(\phi-\beta)\sin\delta\ \omega_s\right]$

1.0256

$= 1304.551$ KJule

(a-b)

change in total extra terrestrial radiation

$= 1423.008 - 1304.551$

$= 118.457$ KJule

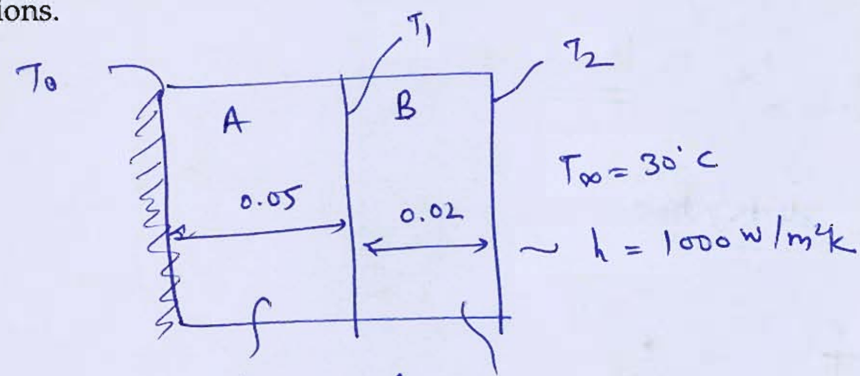
Do not write in this margin

6 (b) A plane wall is composed of two materials, *A* and *B*. The wall of material *A* has uniform energy generation $\dot{q} = 1.5\times10^6$ W/m³, K_A = 75 W/mK and thickness L_A = 50 mm. The wall of material *B* has no internal heat generation, with K_B = 150 W/mK and thickness L_B = 20 mm. The inner surface of material *A* is well insulated, while the outer surface of material *B* is cooled by a water stream T_∞ = 30°C and *h* = 1000 W/m²K.

(i) Determine the temperature T_o of the insulated surface and the temperature T_2 of the cooled surface.

(ii) Sketch the temperature distribution that exists in the composite under steady-state conditions.

[20 marks]



$\dot{q} = 1.5\times10^6 \frac{W}{m^3}$ $k_B = 150$

$k_A = 75$

$$q_{total\ gen} = \frac{kA(T_1 - T_2)}{0.02} = hA(T_2 - T_\infty)$$

$$1.5\times10^6 \times A \times 0.05 = \frac{150\ A(T_1 - T_2)}{0.02} = 1000\times A(T_2 - 30°)$$

$$T_2 = 105°C$$

$$T_1 = T_2 + 10 = 115° C$$

Steady state eq

$$k\frac{d^2T}{dx^2} + \dot{q}_g = 0$$

$$T = -\frac{\dot{q}_{gn}}{2k}x^2 + C_1x + C_2$$

$$\left.\frac{dT}{dx}\right|_{x=0} = 0 \rightarrow C_1 = 0$$

$$kA\left(\frac{dT}{dx}\right)\Big|_{x=0.05} = \frac{kA(T_1 - T_2)}{0.02}.$$

$$-\frac{\dot{q}_{gen}}{2k} \times 2x \times kA \Big|_{x=0.05} = 75000\ A$$

$$75000 = 75000.$$

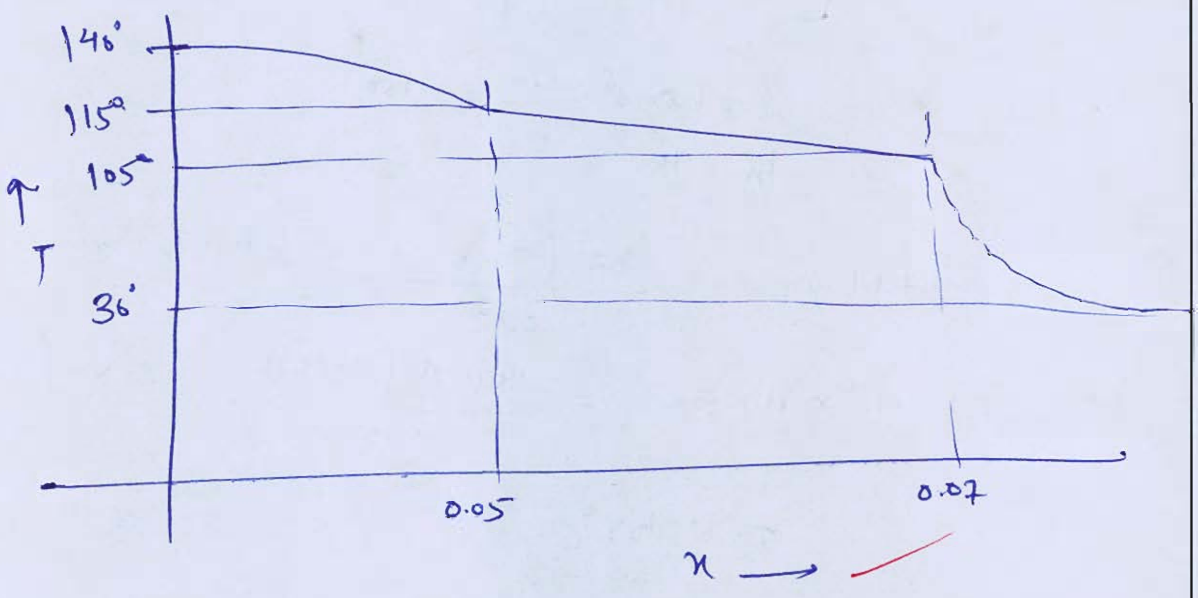
$$T\Big|_{x=0.05} = 115^\circ C = -25 + C_2$$

$$C_2 = 140^\circ C$$

$$T_1\Big|_{x=0} = C_2 = 140^\circ C$$

(iii)

Temp. distribution



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6 (c) Discuss the relative merits and limitations of tidal power. What are the difficulties in tidal power developments? For a typical tidal power plant shown below, the basin area is 25×10^6 m^2. The tide has a range of 10 m. However, turbine stops working when the head on it falls below 2 m. Assume that density of seawater is 1025 kg/m^3, acceleration due to gravity is 9.81 m/s^2, combined efficiency of turbine and generator is 75% and period of energy generation is 6h and 12.5 min.

Determine:

1. Work done in filling or emptying the basin
2. Average power
3. The energy generated in one filling process (in kWh)

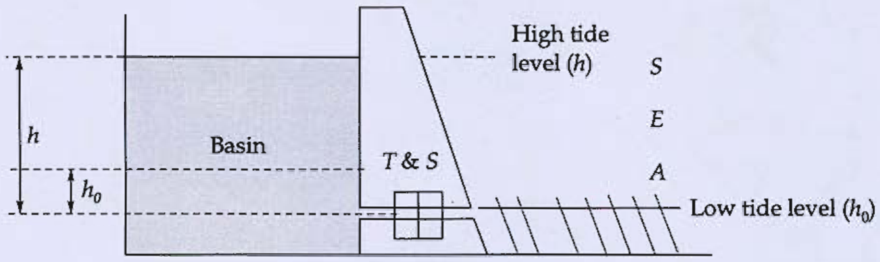

Figure: Single Basin tidal plant

[20 marks]

tidel power

* Merits
→ low maintance cost
→ No pollution to the environment
→

limitation
(1) large area near the costal region is required
(2) difficult to maintain constant heet
> Intermittent power supple
(3) Initial investment is very high

$A = 25\times10^6$ m^2 $\quad \rho = 1025$ kg/m^3

$H_1 = 10$ m $\quad g = 9.81$

$H_2 = 2$ m $\quad \eta_c = 0.75$ $\quad$ time = 6h 12.5 min

3

(1) Work done $= \frac{1}{2}\rho A g(H_1^2 - H_2^2)$

$= 1.20663\times10^{13}$ Joule

(2) Average power $= \eta_c \times \frac{\text{workdone}}{\text{time}} = 404909.396$ kW

~~= 404.9 MW~~

(B) Energy Generated in one filling period

$\Rightarrow \eta \times$ Workdone

$= \dfrac{1.20663 \times 10^{13} \times 0.75}{3.6 \times 10^{6}}$ kWH

$= 2513812.5$ kWH

$= 25.14 \times 10^{5}$ kWH

7 (a) (i) Briefly explain how plastic solar cells with the help of nanotechnology can popularize the use of solar cells in the near future.

(ii) Determine the solar array area and battery size for the average load of 67 W for 24 h. Solar cell efficiency is 10% and sum total of all array design and degrade array factor is 0.5. Battery charging efficiency is 60%. The load is to be supported for seven continuous days of cloudy weather (no sunshine) and the battery is to be fully recharged in 3 days. Average monthly insolation is 181 kWh/m^2 and it is assumed that each winter day receives 9.7 hour of sunshine.

[10 + 10 marks]

Q.7 (b) The surface temperature of a thin, flat plate placed parallel to an air stream is 80°C. The free stream velocity is 50 m/s and the temperature of the air is 0°C. The plate is 60 cm wide and 40 cm long in the direction of the air stream. Neglecting the end effect of the plate and assuming that the flow within the boundary layer changes abruptly from laminar to turbulent at a transition Reynolds number of $Re_{tr} = 4 \times 10^5$, find:

(i) the average heat transfer coefficient in the laminar and turbulent regions.

(ii) the rate of heat transfer for the entire plate, considering both sides.

Also plot the heat transfer coefficient and local friction coefficient as a function of the distance from the leading edge of the plate.

Take, kinematic viscosity (ν) = 18.1×10^{-6} m²/s

Thermal conductivity (k) = 0.0269 W/mK

Prandtl number (Pr) = 0.71

Density (ρ) = 1.075 kg/m³

[20 marks]

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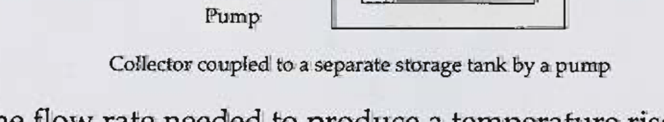
Q.7 (c) A flat plate collector (2 m × 0.8 m) has a loss resistance $r_L = 0.13\ m^2KW^{-1}$ and a plate transfer efficiency $\eta_{pf} = 0.85$. The glass cover has transmittance, $\tau = 0.9$ water enters at a temperature $T_1 = 40°C$. The ambient temperature is $T_a = 20°C$ and irradiance in the plane of the collector is $G = 750\ W/m^2$. Mean temperature of fluid is $T_p = 42°C$. Volumetric heat capacity may be taken as $4.2575 \times 10^6\ J/m^3K$.
[Take $\alpha_p = 0.9$]



Collector coupled to a separate storage tank by a pump

1. Calculate the flow rate needed to produce a temperature rise of 4°C.
2. Suppose the pump continues to pump at night, when $G = 0$. What will be the temperature fall in each passage through the collector?
(Assume that $T_1 = 40°C$, $T_a = 20°C$ still and $T_p = 38°C$).
3. Explain the heat transfer sequence for the collector.

[20 marks]

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(a) A wind turbine generator having a overall efficiency of 45% generates 1500 Watt power at upstream wind speed of 24 kmph at the atmospheric pressure and temperature of 30°C. Calculate the percentage change in output if the wind turbine generator is operated at an altitude of 1800 m, temperature 10°C, upstream wind speed 30 kmph, and air pressure 88% of atmospheric pressure with same overall efficiency. Explain solidity and show its variation with tip speed ratio.

[20 marks]

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(b) A furnace is insulated with a firebrick lining of 200 mm thickness. The temperature of hot gases in the furnace is 1800 K and the temperature of the surroundings of the furnace is 300 K. The thermal conductivity of the firebricks is given by $k = k_0(1 + \beta T)$ where k_o is equal to 0.85 W/m-K and β is equal to 7×10^{-4} per K. The heat transfer coefficient on the hot and cold sides of wall is 40 W/m^{2}K and 10 W/m^{2}K respectively. Determine the temperature at inner and outer surfaces of the wall. Also find out the heat lost per unit area of the wall.

[20 marks]

(c) **(i)** Write the different types of tidal power plants on the basis of their operation. Also explain double basin with paired-basin operation type tidal plant with a neat sketch.

(ii) Explain the I-V characteristics of a solar cell and define fill factor. What is the significance of fill factor?

[10 + 10 marks]

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Space for Rough Work

Space for Rough Work

Space for Rough Work