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MECHANICAL ENGINEERING

CONVENTIONAL Practice Sets

CONTENTS

HEAT TRANSFER

1 CHAPTER Introduction and Basic Concepts

Practice Questions : Level-I

Q.1 The ratio of radius of the earth's orbit to that of sun is 216 : 1. The solar insolation on the earth is 1.4 kW/m^2.
Find the surface temperature of the sun if it assumed to be an ideal radiator (black body).

Solution:

Given data: $\frac{R}{r} = 216$; where r is radius of the sun and T is the surface temperature of the sun. Therefore,

Total radiation from the sun, $Q_r = 1.4 \times 4\pi R^2$; where R is the radius of the earth's orbit.

Total radiation emitted by the sun, $Q_r = \sigma 4\pi r^2 T^4$

Therefore, $\sigma 4\pi r^2 T^4 = 1.4 \times 4\pi R^2$

$$\therefore \quad T^4 = \frac{1.4 \times 10^3}{5.67 \times 10^{-8}} \times (216)^2 = 0.1152 \times 10^{16}\ \text{K}^4$$

$$T = 5826\ \text{K}$$

Q.2 A pipe 2 cm in diameter at 40°C is placed in (i) an air flow at 50°C, with h = 20 W/m^{2}K and in (ii) water at 30°C with h = 70 W/m^{2}K. Find the heat transfer rate per unit length of the pipe.

Solution:

Given data: $D = 2$ cm, $T_w = 40°C$

The definition of the mean heat transfer coefficient gives

$$Q = hA(T_w - T_\infty)$$

Here, $T_w = 40°C$, and since 1 m length of pipe ie being considered

$$A = \pi DL = \pi \times 0.02\ \text{m}^2$$

$$\therefore \quad Q = h\pi \times 0.02 \times (40 - T_\infty)$$

For case (i),

$$h = 20\ \text{W/m}^2\text{K}, \quad T_\infty = 50°C$$

$$Q = 20 \times \pi \times 0.02 \times (40 - 50) = -12.57\ \text{W}$$

The negative sign indicates that the heat transfer is from the air to the cylinder.

For case (ii),

$$h = 70\ \text{W/m}^2\text{K}, \quad T_\infty = 30°C$$

$$Q = 70 \times \pi \times 0.02 \times (40 - 30) = 43.98\ \text{W}$$

This result is positive which indicates the heat transfer to be occurring from the cylinder to the water.

Q.3 The outer surface temperature of a refrigerator is 16°C where h = 10 W/m^{2}K and the room temperature is 20°C. The sides are 3 cm thick and k = 0.1 W/mK. Find the net heat flow and inside temperature of the refrigerator.

Solution:

Given data: $T_{s,0}$ = 16°; T_∞ = 20°C, L = 0.03 cm, h = 10 W/m^{2}K, k = 0.1 W/mK

Convective heat flux to the surface

$$\boxed{q = \frac{Q}{A} = h(T_{s,0} - T_\infty)} = 10(16 - 20) = -40 \text{ W/m}^2$$

Since this must be equal to the heat conducted through the sides,

$$q = -k\frac{dT}{dx} = -k\frac{T_{s,0} - T_{s,i}}{L}$$

$$\therefore \quad T_{s,i} = -\frac{qL}{k} + T_{s,0} = -\frac{40 \times 0.03}{0.1} + 16 = 4°\text{C}$$

Q.4 A steam pipe (O.D. = 10 cm, T_s = 500 K, ε = 0.8) passing through a large root at 300 K. The pipe loss heat by natural convection (h = 15 W/m^{2}K) and radiation.
Find: (i) the surface emissive power of the pipe, (ii) the total radiation falling upon the pipe, and (iii) the total rate of heat loss from the pipe.

Solution:

Given data: D_0 = 10 cm; T_S = 500 K, T_R = 300 K, ε = 0.8

(i) Surface emissive power of the pipe,

$$E = \varepsilon\sigma T_S^4 = 0.8 \times 5.67 \times 10^{-8} \times (500)^4 = 2835 \text{ W/m}^2$$

(ii) Total radiation falling upon the pipe surface = Total radiation leaving the surface,

$$G = \sigma T_R^4 = 5.67 \times 10^{-8} \times (300)^4 = 459.27 \text{ W/m}^2$$

(iii) Heat loss from pipe by radiation,

$$Q_r = \varepsilon A\sigma(T_S^4 - T_R^4) = 0.8 \times \pi \times 0.1 \times 5.67 \times 10^{-8} \times (500^4 - 300^4) = 775.21 \text{ W/m}^2$$

Heat loss by natural convection,

$$Q_c = h_c A(\Delta T) = 15 \times \pi \times 0.1 \times (500 - 300) = 942.5 \text{ W/m}$$

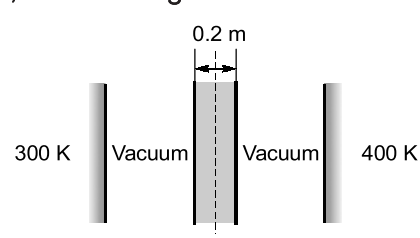
Thus, total rate of heat loss,

$$Q = Q_c + Q_r = 942.5 + 775.21 = 1717.71 \text{ W/m}$$

Q.5 A 0.2 m thick infinite black plate having a thermal conductivity of 3.96 W/m-K is exposed to two infinite black surfaces at 300 K and 400 K as shown in the figure. At steady state the surface temperature of the plate facing the cold side is 350 K. The value of Stefan-Boltzmann constant σ is

$$5.67 \times 10^{-8} \text{ W/m}^2 \text{ K}^4$$

Assuming 1-D heat conduction, find the magnitude of heat flux through the plate (in W/m^2).



Solution:

Given data: $T_c = 300$ K; $T_h = 400$ K; $T_s = 350$ K

Under steady state condition, all rate of heat transfer i.e. from surface at 400 K to black plate (via radiation), inside black plate (via conduction) and from black plate to surface at 300 K (via radiation) are equal.

So, heat flux through wall = Radiation flux from wall to surface at 300 K

$$= \frac{\sigma(T_s^4 - T_c^4)}{\frac{1}{\varepsilon_1} + \frac{1}{\varepsilon_2} - 1} \qquad \therefore \varepsilon_1 = \varepsilon_2 = 1$$

$$= \frac{5.67 \times 10^{-8}(350^4 - 300^4)}{\frac{1}{1} + \frac{1}{1} - 1} = 391.584 \text{ W/m}^2$$

Q.6 A coolant fluid at 30°C flows over a heated flat plate maintained at a constant temperature of 100°C. The boundary layer temperature distribution at a given location on the plate may be approximated as $T = 30 + 70 \exp(-y)$ where y (in m) is the distance normal to the plate and T is in °C. If thermal conductivity of the fluid is 1.0 W/mK, the local convective heat transfer coefficient (in W/m²K) at that location will be

Solution:

At $y = 0$; $q_{cond} = q_{conv}$

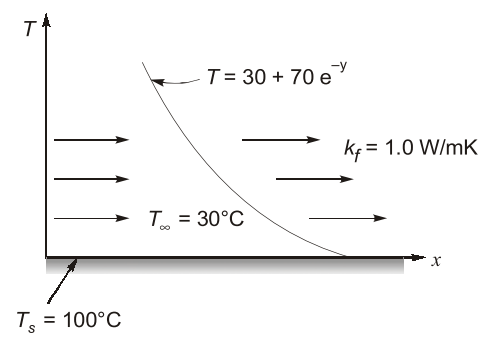
$$-k_f \left.\frac{\partial T}{\partial y}\right|_{y=0} = h\Delta T = h(T_s - T_\infty)$$

$$-(1)\left.\frac{\partial}{\partial y}\left[30 + 70\, e^{-y}\right]\right|_{y=0} = h(100 - 30)$$

$$-\left[0 + 70(-1)\, e^{-y}\right]\Big|_{y=0} = h(70)$$

$$70\, e^{-0} = h(70)$$

or $h = 1$ W/m²K



Alternative :

Given data:

$T_\infty = 30$°C, $T_s = 100$°C, $k_f = 1$ W/mK,

$$T = 30 + 70 \exp(-y)$$

Differentiating w.r.t y, we get

$$\frac{dT}{dy} = -70\, e^{-y}$$

At $y = 0$

$$\left(\frac{dT}{dy}\right)_{y=0} = -70$$

We know that local convective heat transfer coefficient:

$$\boxed{h_x = \frac{-k_f\left(\frac{dT}{dy}\right)_{y=0}}{T_s - T_\infty}} = \frac{-1 \times (-70)}{100 - 30} = 1 \text{ W/m}^2\text{K}$$

Q.7 A solid sphere of diameter 10 cm is heated to 1000°C and suspended in a room whose walls are at 30°C. Compute the following:

(i) Rate of heat transfer due to radiation only neglecting other losses.

(ii) Time taken by the sphere to cool to 500°C assuming emissivity for the sphere = 0.1 and density 8.68 gm/cc. Specific heat 0.098 J/kgK.

Solution:

Given data: Emissivity, $\in = 0.1$; Density, $\rho = 0.868$ gm/cc = 868 kg/m^3

Specific heat, $c_p = 0.098$ J/kgK; Diameter = 10 cm, $T = 1000 + 273 = 1273$ K

Room temperature, $T_0 = 30 + 273 = 30$°C

Radiation heat transfer,

(i) $$Q = \varepsilon\sigma A(T^4 - T_0^4) = 0.1 \times 5.67 \times 10^{-8} \times 4\pi \times (0.05)^2 \times (1273^4 - 303^4) = 466.2 \text{ W}$$

(ii) Performing energy balance,

Rate of change of Internal energy = Heat loss rate due to radiation

$$-mc\frac{dT}{dt} = \sigma \in A(T^4 - 303^4)$$

$$-\frac{mc}{\sigma \in A}\int_{1273}^{773}\frac{dT}{(T^4 - 303^4)} = \int_0^t dt$$

$$\Rightarrow -\frac{868 \times 4/3\pi(0.05)^3 \times 0.098 \times 10^3}{5.67 \times 10^{-8} \times 0.1 \times 4\pi \times (0.05)^2} \times \int_{1273}^{773}\frac{dT}{(T^4 - 303^4)} = t$$

$$-2.5 \times 10^{12} \times (-5.67 \times 10^{-10}) = t$$

$$\Rightarrow \quad t = \mathbf{141.84 \text{ seconds}}$$

Practice Questions : Level-II

Q.8 The sun may be regarded as a black body with a surface temperature of 5600 K at a mean distance of 15×10^{10} m from the earth. The diameter of the sun is 1.4×10^9 m and that of the earth is 12.8×10^6 m. Make calculations for

(a) the total energy radiated by the sun,

(b) the energy received per m^2 just outside the earth's atmosphere,

(c) the total energy the earth would receive if no energy were blocked by the earth's atmosphere,

(d) the energy received by a 1.25 × 1.25 m solar collector whose perpendicular is inclined at 35° to the sun. The energy loss through the atmosphere is 35% and the diffuse radiation is 15% of direct radiation.

Solution:

Given data: $T = 5600$ K

(a) For the sun: $\in = 1$ (Black body) and Surface area $= 4\pi r^2 = 4\pi(0.7 \times 10^9)^2$

∴ Energy radiated by the sun,

$$\boxed{Q = \varepsilon\sigma_b A T^4} = 1 \times (5.67 \times 10^{-8}) \times 4\pi\,(0.7 \times 10^9) \times (5600)^4 = 3.43 \times 10^{26} \text{ W}$$

(b) The sun may be regarded as a point source at a distance of 15×10^{10} from the earth. The mean area over which the radiation is distributed becomes $4\pi(15 \times 10^{10})^2$

∴ Radiation received at this distance

$$= \frac{3.43 \times 10^{26}}{4\pi(15 \times 10^{10})^2} = 1.213 \times 10^3 \text{ W/m}^2$$

(c) The earth is nearly spherical and as such the energy received by it will be proportional to the perpendicular projected area, i.e., that of a circle.

$\therefore$ Energy received by the earth = $1.213 \times 10^3 \times \pi(6.4 \times 10^6)^2 = 1.56 \times 10^{17}$ W

(d) Direct energy reaching the earth,

$$= \left(1 - \frac{35}{100}\right) \times 1.213 \times 10^3 = 788.45 \times 10^3 \text{ W/m}^2$$

$$\text{Diffused radiation, } = \frac{15}{100} \times 0.788 \times 10^3 = 118.2675 \text{ W/m}^3$$

Total radiation reaching the plate,

$$788.45 + 118.2675 = 906.7175$$

Since the plate surface is not oriented perpendicular to the incoming radiations, the relevant area is equivalent to the projected perpendicular surface area.

$$\text{Projected plate area} = A\cos\theta = 1.25 \times 1.25 \times \cos 35 = 1.28 \text{ m}^2$$

$\therefore$ Energy received by the plate = $906.7174 \times 1.28 = 1160.6$ W

A reduction in energy received due to inclination explains the variation in solar intensity with season and much reduced solar intensity at the poles of earth.

Q.9 **Assuming the sun as a black body, it emits maximum radiation at 0.5 μm wavelength. Calculate**

(i) the surface temperature of the sun,

(ii) its emissive power,

(iii) the energy received by the surface of the earth and

(iv) the energy received by a 2 m × 2 m solar collector whose normal is inclined at 60° to the sum. Take the diameter of the sun as 1.4×10^9 m, diameter of the earth as 13×10^6 m and the distance of the earth from the sun as 15×10^{10} m.

Solution:

Given data: $\lambda_{max} = 0.5\ \mu\text{m}$; $\theta = 60°$; $A = 2 \times 2 = 4 \text{ m}^2$

$$\lambda_{max} = 0.5\ \mu\text{m}$$

From Wien's displacement law,

$$\lambda_{max} T = 2898 \times 10^{-6} \text{ mK}$$

$\therefore$ Surface temperature of the sun,

$$T = \frac{2898 \times 10^6}{0.5 \times 10^{-6}} = 5796 \text{ K} \quad \text{... (i)}$$

Emissive power of the sun, a black body, is obtained from Stefan - Boltzmann law:

$$E_b = \sigma T^4 = 5.67 \times 10^{-8} (5796)^4 = 63987.7 \text{ kW/m}^2 \quad \text{... (ii)}$$

$$\text{Radiation reaching the earth would be} = \text{Emissive power of the sun} \times \left(\frac{\text{Radius of the sun}}{\text{Distance from the earth}}\right)^2$$

$$= 63987.7 \times \left(\frac{0.7 \times 10^9}{15 \times 10^{10}}\right)^2 = \mathbf{1.39 \text{ kW/m}^2} \quad \text{... (iii)}$$

Surface area fo the solar collector in the direction normal to solar radiation

$$= A\cos\theta = 4 \cos 60° = 2 \text{ m}^2$$

$\therefore$ Energy received by the solar collector = **1.39 × 2 = 2.78 kW**

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