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MECHANICAL ENGINEERING

CONVENTIONAL PRACTICE SETS VOLUME - II

CONTENTS

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FLUID MECHANICS AND HYDRAULIC MACHINES

CONVENTIONAL PRACTICE SETS

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1 CHAPTER

Fluid Properties

Q.1 The velocity distribution for flow over a flat plate is given by $u = \frac{3}{4}y - y^2$ in which u is the velocity in metre per second at a distance *y* metre above the plate. Determine the shear stress at *y* = 0.15 m. Take dynamic viscosity of fluid as 8.5 poise.

Solution:

Given, $$u = \frac{3}{4}y - y^2$$

Viscosity, $$\mu = 8.5\text{poise} = \frac{8.5}{10}\text{Ns/m}^2 \qquad \left(\because 10 \text{ poise} = 1 \text{ Ns/m}^2\right)$$

∴ $$\frac{du}{dy} = \frac{3}{4} - 2y$$

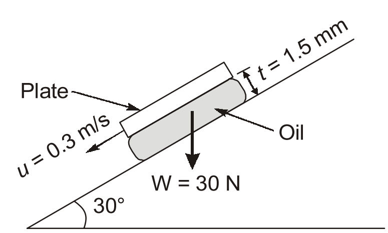
At y = 0.15, $$\frac{du}{dy} = \frac{3}{4} - 2 \times 0.15 = 0.75 - 0.30 = 0.45$$

$$\boxed{\tau = \mu\frac{du}{dy}}$$

$$= \frac{8.5}{10} \times 0.45 \text{ N/m}^2 = 0.3825 \text{ N/m}^2$$

Q.2 Calculate the dynamic viscosity of an oil, which is used for lubrication between a square plate of size 0.8 m × 0.8 m and an inclined plane with angle of inclination 30° as shown in figure. The weight of the square plate is 300 N and it slides down the inclined plane with a uniform velocity of 0.3 m/s. The thickness of oil film is 1.5 mm.

Solution:



Given: Area of plate, $A = 0.8 \times 0.8 = 0.64 \text{ m}^2$

Angle of plane, $\theta = 30°$

Weight of plate, $W = 300$ N

Velocity of plate, $u = 0.3$ m/s

Thickness of oil film, $t = dy = 1.5 \text{ mm} = 1.5 \times 10^{-3}$ m

Let the viscosity of fluid between plate and inclined plane is μ.

Component of weight W, along the plane = $W\cos 60° = 300 \cos 60° = 150$ N

Thus the shear force, *F*, on the bottom surface of the plate = 150 N

and shear stress, $$\boxed{\tau = \frac{F}{\text{Area}}} = \frac{150}{0.64}\text{N/m}^2$$

Now, $$\boxed{\tau = \mu\frac{du}{dy}}$$

Assuming linear velocity profile,

$$du = \text{change of velocity} = u - 0 = 0.3 \text{ m/sec}$$
$$dy = t = 1.5 \times 10^{-3} \text{ m}$$

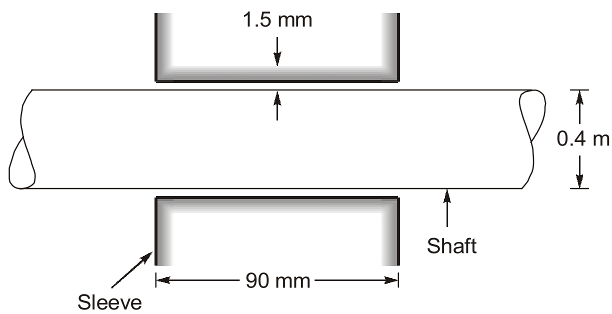
$$\therefore \quad \frac{150}{0.64} = \mu \times \frac{0.3}{1.5 \times 10^{-3}}$$

$$\mu = \frac{150 \times 1.5 \times 10^{-3}}{0.64 \times 0.3} = 1.17 \text{ Ns/m}^2 = 11.7 \text{ Poise}$$

Q.3 The dynamic viscosity of an oil, used for lubrication between a shaft and sleeve is 6 poise. The shaft is of diameter 0.4 m and rotates at 190 rpm. Calculate the power lost in teh bearing for a sleeve length of 90 mm. The thickness of the oil film is 1.5 mm.

Solution:

Given:



Viscosity, $\mu = 6$ Poise

$$= \frac{6}{10} \frac{\text{Ns}}{\text{m}^2} = 0.6 \text{Ns/m}^2$$

Diameter of shaft, $D = 0.4$ m

Speed of shaft, $N = 190$ rpm

Sleeve length, $L = 90 \text{ mm} = 90 \times 10^{-3}$ m

Thickness of oil film, $t = 1.5 \text{ mm} = 1.5 \times 10^{-3}$ m

Tangential velocity of shaft, $\boxed{u = \frac{\pi DN}{60}}$

$$u = \frac{\pi \times 0.4 \times 190}{60} = 3.98 \text{ m/s}$$

Using the relation and assuming linear velocity profile,

$$\boxed{\tau = \mu \frac{du}{dy}}$$

where, du = Change of velocity $= u - 0 = u = 3.98$ m/s

dy = Change of distance $= t = 1.5 \times 10^{-3}$ m

$$\tau = 10 \times \frac{3.98}{15 \times 10^{-3}} = 1592 \text{ N/m}^2$$

This is shear stress on shaft,

$\therefore$ Shear force on the shaft, $\boxed{F = \text{Shear stress} \times \text{Area}}$

$$= 1592 \times \pi D \times L = 1592 \times \pi \times 0.4 \times 90 \times 10^{-3} = 180.05 \text{ N}$$

Torque on the shaft, $$T = \text{Force} \times \frac{D}{2}$$

$$= 180.5 \times \frac{0.4}{2} = 36.01 \text{ Nm}$$

$\therefore$ $$\text{Power lost} = \frac{2\pi NT}{60}$$

$$= \frac{2\pi \times 190 \times 36.01}{60} = 716.48 \text{ W}$$

Q.4 **A vertical gap 23.5 mm wide of infinite extent contains oil of specific gravity 0.9 and viscosity 2.5 N-s/m^2. A metal plate 1.5 m × 1.5 m × 1.5 mm weighing 50 N is to be lifted through the gap at a constant speed of 0.1 m/sec. Estimate the force required to lift the plate.**

Solution:

Given:

Width of gap = 23.5 mm

Viscosity, μ = 2.5 Ns/m^2

Specific gravity oil = 0.9

$\therefore$ Weight density of oil = 0.9 × 1000 = 900 kgf/m^3

= 900 × 9.81 N/m^3 ($\because$ 1 kgf = 9.81 N)

Assuming that the plate lies in the middle of the gap

Volume of plate = 1.5 m × 1.5 m × 1.5 mm

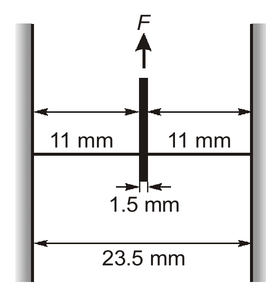
= 1.5 × 1.5 × 0.0015 m^3

= 0.003375 m^3

Thickness of plate = 1.5 mm

Velocity of plate = 0.1 m/sec

Weight of plate = 50 N



When the plate is in the middle of the gap, the distance of plate from

$$\text{Vertical surface of the gap} = \left(\frac{\text{Width of gap} - \text{Thickness of plate}}{2}\right)$$

$$= \left(\frac{23.5 - 1.5}{2}\right) = 11 \text{ mm} = 0.011 \text{ m}$$

Now, shear force on left side of the metallic plate

$$F_1 = \text{Shear stress} \times \text{Area}$$

$$= \mu\left(\frac{du}{dy}\right)_1 \times (1.5 \times 1.5) = 2.5 \times \left(\frac{0.1}{0.011}\right) \times 1.5 \times 1.5 = 51.136 \text{ N}$$

Similarly, the shear force on the right side of the metallic plate,

$$F_2 = \text{Shear stress} \times \text{Area}$$

$$= 2.5 \times \left(\frac{0.1}{0.011}\right) \times (1.5 \times 1.5) = 51.136 \text{ N}$$

$\therefore$ **Total shear force,** $F = F_1 + F_2 = 51.136 + 51.136 = 102.273$ N

In this case the weight of plate (which is acting downward) and upward thrust is also to be taken into account.

∴ The upward thrust = Weight of fluid displaced = $\rho v g$

= (unit weight of fluid) × Volume of fluid displaced

= 9.81 × 900 × 0.003375 = 29.80 N

The net force acting in the downward direction due to the weight of the plate and upward thrust

= Weight of plate – Upward thrust = 50 – 29.80 = 20.20 N

∴ Total force required to lift the plate up

= Total shear force + 20.20 = 102.273 + 20.20 = 122.473 N

Q.5 Find the surface tension in a soap bubble of 40 mm diameter when the inside pressure is 2.5 N/m^2 above atmospheric pressure.

Solution:

Given: Diameter of bubble, d = 40 mm = 40 × 10^{-3} m

Pressure in excess of outside, p = 2.5 N/m^2

For a soap bubble, $\boxed{\Delta p = \frac{8\sigma}{d}}$

or $$2.5 = \frac{8 \times \sigma}{40 \times 10^{-3}}$$

$$\sigma = \frac{2.5 \times 40 \times 10^{-3}}{8} = 0.0125 \text{ N/m}$$

Q.6 Calculate the capillary effect in mm in a glass tube 3 mm in diameter when immersed in (a) water (b) mercury. Both the liquids are at 20°C and the values of the surface tensions for water and mercury at 20°C in contact with air are respectively 0.0736 N/m and 0.51 N/m. Contact angle for water = 0° and for mercury = 130°.

Solution:

The capillary rise (or depression) is given as

$$\boxed{h = \frac{2\sigma\cos\theta}{\rho g r}}$$

(a) For water θ = 0, $\cos\theta$ = 1

σ = 0.0736 N/m

ρg = 9810 N/m^3

d = 3 mm

$$r = \frac{3}{2} = 1.5 \text{ mm} = 1.5 \times 10^{-3} \text{ m}$$

By substitution, we get $$h = \frac{2 \times 0.0736 \times 1}{9810 \times 1.5 \times 10^{-3}}$$

= 1.00 × 10^{-2} m = 10 mm

(b) For mercury θ = 130°, $\cos\theta$ = – 0.6428

σ = 0.51 N/m

ρg = (13.6 × 9810) N/m^3

$$r = \frac{3}{2} = 1.5 \text{ mm} = 1.5 \times 10^{-3} \text{ m}$$

By substitution, we get $$h = \frac{2 \times 0.51 \times (-0.6425)}{13.6 \times 9810 \times 1.5 \times 10^{-3}} = -3.276 \times 10^{-3} \text{ m}$$

= –3.276 mm

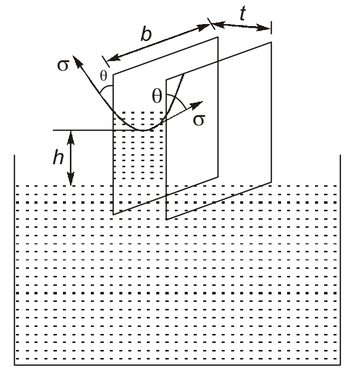
The negative (–) sign in the case of mercury indicates that there is capillary depression.

Q.7 Determine capillarity rise between two thin vertical plates spaced '*t*' distance apart. Calculate the distance between the plates when the capillarity rise is not to exceed 60 mm. Assume surface tension of water at 20°C as 0.075 N/m.

Solution:

For two vertical plates, '*t*' distance apart

Let width of plate be '*b*' and contact angle be 'θ'



$$\text{Force due to surface tension} = \text{Force due to gravity}$$

$$2\sigma\cos\theta\, b = \rho g\,(b \times t)h$$

Height of capillarity rise,

$$\boxed{h = \frac{2\sigma\cos\theta}{\rho g t}}$$

For $\sigma = 0.075$ N/m and $h = 60$ mm

Assuming $\theta = 0°$ i.e., $\cos\theta = 1$

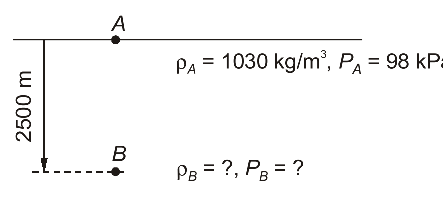
$$0.06 = \frac{2 \times 0.075 \times 1000}{9.81 \times 1000 \times t}$$

$$t = 0.255 \text{ mm}$$

Q.8 The density of sea water at free surface where pressure is 98 kPa is 1030 kg/m^3. Taking bulk modulus of sea water to be 2.34×10^9 N/m^2 (assume constant), determine the density and pressure at a depth of 2500 m. Neglect the effect of temperature

Solution:

Calculation of density:



$$K = 2.34 \times 10^9 \text{ N/m}^2$$

$$K = \rho\frac{dP}{d\rho}$$

Since $dP = \gamma dh$

$$\Rightarrow \quad K = \frac{\rho\gamma dh}{d\rho} = \rho^2 g\frac{dh}{d\rho}$$

$$\int_{\rho_A}^{\rho_B}\frac{d\rho}{\rho^2} = \int_0^H \frac{g}{K}dh$$

$$\Rightarrow \quad \left.\frac{1}{\rho(-1)}\right|_{\rho_A}^{\rho_B} = \frac{g}{K}\times H$$

$$\Rightarrow \quad \frac{1}{\rho_A} - \frac{gH}{K} = \frac{1}{\rho_B}$$

$$\therefore \quad \rho_B = \frac{1}{\left(\frac{1}{\rho_A} - \frac{gH}{K}\right)}$$

$$\rho_B = \frac{1}{\frac{1}{1030} - \frac{9.81 \times 2500}{2.34 \times 10^9}} = 1041.24 \text{ kg/m}^3$$

Calculation of pressure:

$$K = \frac{dP}{\left(\frac{d\rho}{\rho}\right)}$$

$$\int_{P_A}^{P_B} dP = K.\int_{\rho_A}^{\rho_B} \frac{d\rho}{\rho}$$

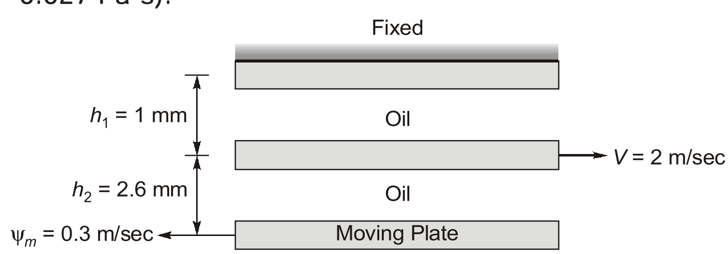
$$P_B - P_A = K[\ln \rho]_{\rho_A}^{\rho_B}$$

$$P_B = P_A + K \ln\left(\frac{P_B}{P_A}\right)$$

$$P_B = 98 + 2.34 \times 10^6 \ln\left(\frac{1041.24}{1030}\right)$$

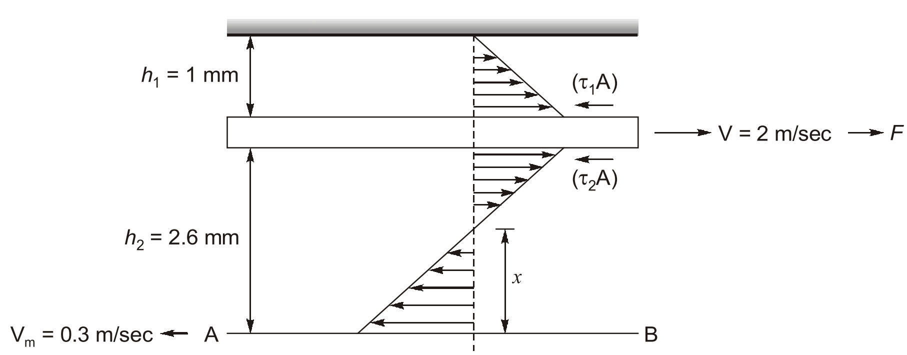
$$= 25495.20 \text{ kPa} = 25.5 \text{ MPa}$$

Q.9 A thin 40 cm × 40 cm flat plate is pulled at 2 m/sec horizontally through a 3.6 mm thick oil layer sandwitched between two plates, one stationary and other moving at a constant speed of 0.3 m/sec as shown in figure. Determine the force that is required to be applied on the plate to maintain this motion. Take (μ_{oil} = 0.027 Pa-s).



Solution:

Given:



Let at a distance x from plate AB, where the velocity of oil will be zero.
From the property of similarly of triangle

$$\frac{x}{2.6 - x} = \frac{0.3}{2}$$

$$2x = 2.6 \times 0.3 - 0.3x$$

$$2.3x = 2.6 \times 0.3$$

$$x = \frac{2.6 \times 0.3}{2.3} = 0.34 \text{ mm}$$

Now, force, F required to maintain this motion

$$\boxed{F = (\tau_1 A + \tau_2 A)}$$

$$= \mu\left[\frac{V}{h_1} + \frac{V - (-V_m)}{h_2}\right]A = 0.027\left[\frac{2}{1 \times 10^{-3}} + \frac{2 + 0.3}{2.6 \times 10^{-3}}\right] \times 0.4 \times 0.4$$

$$= 12.46 \text{ N}$$

HEAT TRANSFER

CONVENTIONAL PRACTICE SETS

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

$$\therefore \quad T^4 = \frac{1.4\times10^3}{5.67\times10^{-8}}\times(216)^2 = 0.1152\times10^{16}\text{ K}^4$$

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

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),

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

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

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

For case (ii),

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

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

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/m²K 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: $T_{s,0} = 16°$; $T_\infty = 20°C$, $L = 0.03$ cm, $h = 10$ W/m²K, $k = 0.1$ 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,

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

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

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/m²K) 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, $\varepsilon = 0.8$

(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,

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

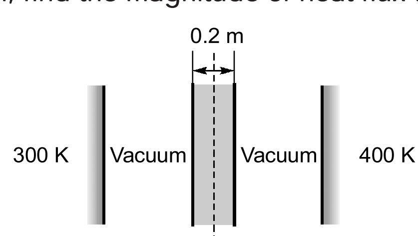
Thus, total rate of heat loss,

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

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 × 10⁻⁸ W/m² K⁴

Assuming 1-D heat conduction, find the magnitude of heat flux through the plate (in W/m²).



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

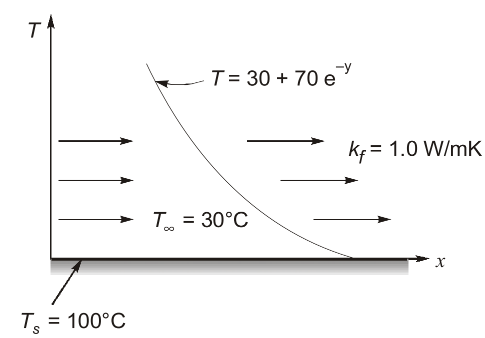
$$-k_f \left.\frac{\partial T}{\partial y}\right|_{y=0} = h\Delta T = h(T_s - T_\infty)$$

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

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

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

or
$$h = 1 \text{ W/m}^2\text{K}$$



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:

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

Practice Questions : Level-II

Q.7 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.

∴ 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.

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

∴ 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.8 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: $\lambda_{max} = 0.5\ \mu m$; $\theta = 60°$; $A = 2 \times 2 = 4\ m^2$

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

From Wien's displacement law,

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

∴ Surface temperature of the sun,

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

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

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

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

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

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

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

∴ Energy received by the solar collector = **1.39 × 2 = 2.78 kW**

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POWER PLANT ENGINEERING

CONVENTIONAL PRACTICE SETS

1 CHAPTER Steam Generators

Practice Questions : Level-I

Q.1 A boiler producing 2000 kg/hr of steam with enthalpy content of 2426 kJ/kg from feed water at temperature 40°C (liquid enthalpy = 168 kJ/kg). What is the equivalent evaporation in kg/hr? (enthalpy of vaporization of water at 100°C = 2258 kJ/kg)

Solution:

Given data: Rate of steam producing, m_s = 2000 kg/hr; Specific enthalpy of feed water, h_f = 168 kJ/kg; Specific enthalpy steam, h = 2426 kJ/kg; Enthalpy of vaporization of water, h_{fg} = 2258 kJ/kg

we know that,

Equivalent evaporation,
$$m_e = \frac{\text{Total heat required to evaporated feed water}}{\text{Latent heat of steam at 100°C}}$$

$$= \frac{m_s(h - h_f)}{h_{fg}} = \frac{2000(2426 - 168)}{2258} = \textbf{2000 kg/hr}$$

Q.2 Economizer of a power boiler operating at 150 bar pressure receives 500 kg/s of water from boiler feed pump with specific enthalpy of 340 kJ/kg. Superheated steam leaves the boiler at 550°C with specific enthalpy of 3448.6 kJ/kg. Efficiency of the boiler is 90% and calorific value of the coal used is 10000 kJ/kg. Find the following :

(i) Heat added in economizer, evaporator and superheater in kJ/s
(ii) Percentage of heat added in economizer, evaporator and superheater out of total heat
(iii) Rate of coal consumption in kg/s

Also draw T-s plot showing the position of different components and heat added.

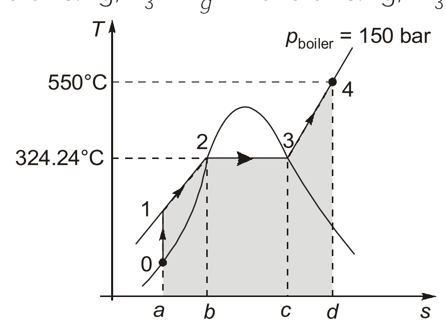
For 150 bar pressure, use the following table :

p_s (bar)	T_s (°C)	h_f (kJ/ kg)	h_{fg} (kJ/ kg)	h_g (kJ/ kg)
150	324.24	1610.5	1000	2610.5

Solution:

Given data: p_{boiler} = 150 bar; m = 500 kg/s; h_1 = 340 kJ/kg; h_4 = 3448.6 kJ/kg
η_{boiler} = 90%; CV = 10000 kJ/kg,

From steam table; $h_2 = h_f$ = 1610.5 kJ/kg, $h_3 = h_g$ = 2610.5 kJ/kg, $h_3 - h_2$ = 1000 kJ/kg



(i)

$$Q_{12} = Q_{economizer} = \dot{m}(h_2 - h_1) = 500\ (1610.5 - 340) = 635250 \text{ kJ/s}$$

$$Q_{23} = Q_{evaporator} = \dot{m}(h_3 - h_2) = 500\ (1000) \text{ kJ/s} = 500000 \text{ kJ/s}$$

$$Q_{34} = Q_{superheater} = \dot{m}(h_4 - h_3) = 500\ (3448.6 - 2610.5) \text{ kJ/s} = 419050 \text{ kJ/s}$$

$$\text{Total heat added} = Q_{12} + Q_{23} + Q_{34} = 1554300 \text{ kJ/s}$$

(ii)

Component	Heat added (kJ/s)	Percentage %
Economizer	635250	40.87
Evaporator	500000	32.17
Superheater	419050	26.96

(iii) Rate of coal consumption,

$$\eta_{boiler} = \frac{Q_{total}}{\dot{m}_{coal} \times (CV)}$$

$$0.9 = \frac{1554300}{\dot{m}_{coal} \times 10000}$$

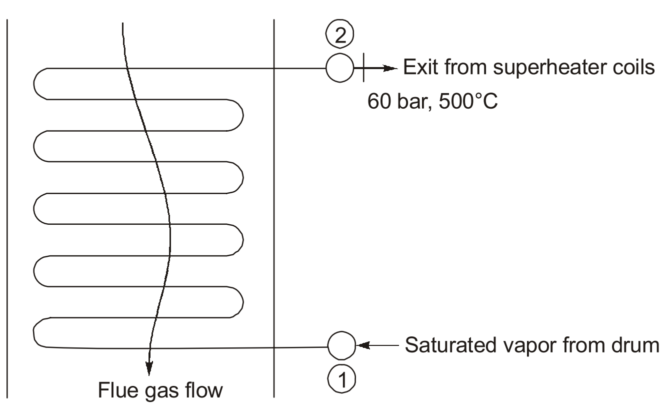
$$\dot{m}_{coal} = 172.7 \text{ kg/s}$$

Q.3 A superheater is to be designed using metallic coils (heat flux 150 kW/m^2) of inside diameter 50 mm and wall thickness 5 mm. The steam leaving the superheater coils is at 60 bars, 500°C and flows at a velocity of 10 m/s. If the steam mass flow rate is 90 kg/s, find the number and length of coils. For steam at 60 bars, take the following values – dry saturated steam h = 2784.3 kJ/kg, at 500°C superheated steam temperature h_{sup} = 3422.2 kJ/kg and specific volume v_{sup} = 0.05665 m^3/kg. The steam enters the superheater as dry and saturated.

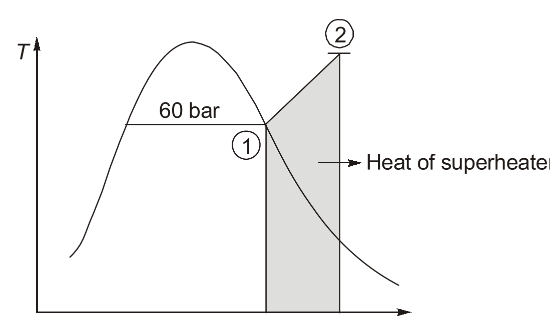
Solution:

Given data: Heat flux, $\dot{q}$ = 150 kW/m^2; d_i = 50 mm = 0.05 m,

Velocity, V = 10 m/s; $\dot{m}_s$ = 90 kg/s



Schematic of Superheater coils



Process on *T-s* coordinate

As given, $h_1 = h_g$ = 2784.3 kJ/kg, h_2 = 3422.2 kJ/kg and specific volume, v_2 = 0.05665 m^3/kg

Heat absorption rate in superheater coils,

$$\dot{Q} = \dot{m}_s(h_2 - h_1) = 90(3422.2 - 2784.3) = 57411 \text{ kW}$$

$$\text{Surface area required} = \frac{57411}{150} = 382.74 \text{ m}^2 \qquad [\text{As, } \dot{Q} = \dot{q} \times A]$$

From continuity equation, $\dot{m}_s = \rho_1 A_1 V_1 = \rho_2 A_2 V_2 = \left(n\frac{\pi}{4}d_i^2\right)\frac{V_2}{v_2} = 90$ kg/s

[where 'n' is the number of superheater coils]

$$n = \frac{4 \times 90 \times 0.05665}{\pi \times (0.05)^2 \times 10} = 259.664 \simeq 260$$

Number of superheater coils, $n = 260$

As, Surface area, $A_0 = 382.74 = n\pi d_0 l$

d_0 = outer diameter = 50 + 2 × 5 = 60 mm [As thickness is 5 mm]

$$\text{Length of one coil} = \frac{382.74}{260 \times \pi \times 0.06} = 7.8 \text{ m}$$

Practice Questions : Level-II

Q.4 A coal-based 660 MW capacity thermal power plant is having overall efficiency of 42%. It uses 600 kg/s of steam for running the turbine. Coal used in the power plant is having calorific value of 10000 kJ/kg. Fuel to air ratio is 1 : 10 for combustion in the boiler. Find the following :

(i) Specific steam consumption in kg/kWh
(ii) Mass flow rate of coal required in Tph (Tonnes per hour)
(iii) Mass flow rate of air required for combustion in kg/s
(iv) Heat required to be supplied to generate one unit of power (in kJ/kWh)
(v) Coal required to be supplied to generate one unit of power (in kg/kWh)

Solution:

Given data: Overall efficiency, η_0 = 42%; Capacity of thermal power plant, P = 660 MW,
Mass flow rate of steam, $\dot{m}_s$ = 600 kg/s, Calorific value of coal, $(CV)_f$ = 10000 kJ/kg,
Air fuel ratio, $\dot{m}_a : \dot{m}_f = 10 : 1$

We know that,

$$\dot{m}_s \times W_{net}(\text{kJ/kg}) = 660 \times 10^3 \text{ kW}$$

$$W_{net} = \frac{660 \times 10^3}{600} = 1100 \text{ kJ/kg (of steam)}$$

(i) $$\text{Specific steam consumption} = \frac{3600}{W_{net}} = \frac{3600}{1100} = 3.273 \text{ kg/kWh}$$

(ii) $$\text{Total heat supplied} = \frac{660}{\eta_0} \text{ MW}$$

$$\dot{m}_f \times (CV)_f = \frac{660 \times 10^3}{0.42} \text{ kW}$$

$$\dot{m}_f = \frac{660 \times 10^3}{0.42 \times 10000} = 157.142 \text{ kg/s}$$

Mass flow rate of coal required, $\dot{m}_f$ = 565714.30 kg/hour = 565.714 tonne per hour

(iii) Mass flow rate of air required = (AFR) × $\dot{m}_f$ = 10 × 157.143 = 1571.43 kg/s

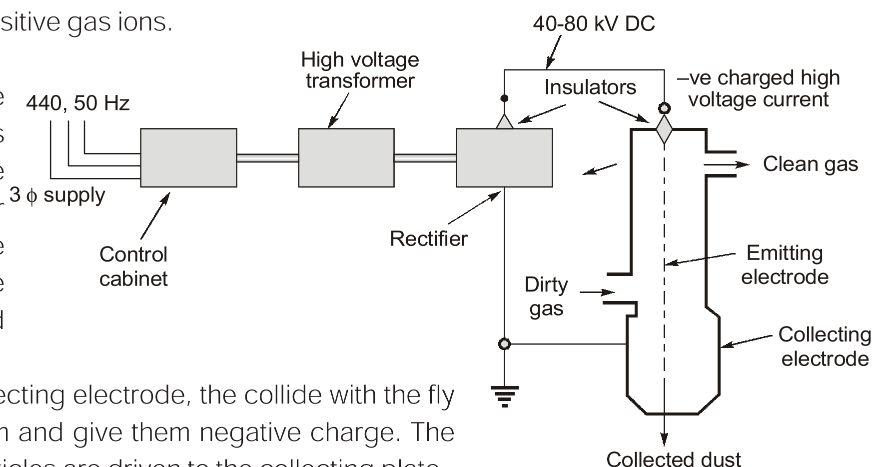
(iv) $$\text{Heat required for unit power generation} = \frac{1 \times 3600}{0.42} \text{ kJ/kWh} = 8571.4286 \text{ kJ/kWh}$$

(v) $$\text{Coal required for unit power generation} = \frac{565.714 \times 10^3}{(660) \times 10^3} = 0.857 \text{ kg/kWh}$$

Q.5 Explain the working of electrostatic precipitator and discuss variation of its collection efficiency with operating parameters like collector area, migration velocity and mass flow rate.

Solution:

Electrostatic Precipitator: The principal components of an electrostatic precipitator (ESP) are two sets of electrodes insulated from each other. The first set is composed of rows of electrically grounded vertical parallel plates, called the collection electrodes, between which the dust-laden gas flows. The second set of electrodes consists of wires, called the discharge or emitting electrodes that are centrally located between each pair of parallel plates. The wires carry a unidirectional negatively charged high-voltage current from an external DC source. The applied high voltage generates a unidirectional, non-uniform electrical field. When that voltage is high enough, a blue luminous glow called a corona, is produced around them. Electrical forces in the corona accelerate the free electrons present in the gas so that they ionize the gas molecules, thus forming more electrons and positive gas ions.



The positive ions travel to the negatively charged wire electrodes. The electrons follows the electrical field toward the grounded electrodes but their velocity decreases toward the plates. Gas molecules capture the low velocity electrons and become negative ions.

As these ions move to the collecting electrode, the collide with the fly ash particles in the gas stream and give them negative charge. The negatively charged fly ash particles are driven to the collecting plate.

Collected particulate matter must be removed from the collecting plates on a regular schedule to ensure efficient collector operation. Removal is usually accomplished by a mechanical hammer scrapping system.

An electrostatic precipitator like a cyclone separator, has an overall collection efficiency, η_o is defined by

$$\eta_o = \frac{\text{mass of all particles retained by collector}}{\text{mass of all particles entering collector}} = 1 - \exp\left(-\frac{AV_{mo}}{Q}\right)$$

where, A = Area of collector plate (m^2); V_{mo} = effective migration velocity of particles (m/sec)

Q = Flue gas volume flow rate for each plate (m^3/sec)

(i) With increase in collector area, collection efficiency increases.

(ii) With increase in migration velocity, collection efficiency increases.

(iii) With decrease in mass flow rate, collection efficiency increases.

Q.6 A steam power plant employing a natural circulation boiler generates 600 MW of power. The boiler generates steam at a pressure of 100 bar and 527°C. The condenser pressure is 0.02 bar. The turbine, mechanical and generator efficiencies are: 90%, 95% and 95% respectively. The boiler uses coal having calorific value of 25 MJ/kg and yields 90% efficiency. Feedwater enters the boiler at 150°C. The risers of the furnace produce natural circulation. The quality of steam at the top of riser is 10% and minimum exit velocity of mixture leaving risers and entering the drum is 1.5 m/s. The dimensions of the riser tubes are 60 mm outer diameter and 5 mm thickness, while the dimensions of downcomer are 190 mm and 10 mm thick.

Find.

(a) the rate of steam generation
(b) the rate of fuel flow (in kg/s)
(c) circulation ratio
(d) number of riser tubes
(e) number of downcomers
(f) Evaporation factor

Given data: h_1 = 3500 kJ/kg; h_2 = 2000 kJ/kg; h_3 = 140 kJ/kg; h_4 = 700 kJ/kg

ρ downcomer, inlet = 600 kg/m^3; ρ riser, top = 400 kg/m^3

Solution:

(a) Assuming isentropic expansion in the turbine and neglecting losses:

$$\dot{m}_s (h_1 - h_2)\eta_t \eta_{mech} \eta_{gen} = 600 \times 10^3$$

$$\Rightarrow \quad \dot{m}_s = \frac{600 \times 10^3}{(3500 - 2000) \times 0.90 \times 0.95 \times 0.95} = 492.46 \text{ kg/s}$$

(b) Rate of fuel flow

$$\dot{m}_f \times (CV) \times \eta_{boiler} = \dot{m}_s (h_1 - h_2)$$

$$\Rightarrow \quad \dot{m}_f = \frac{\dot{m}_f (h_1 - h_4)}{CV \times \eta_{boiler}} = \frac{492.46 \times (3500 - 700)}{25 \times 10^3 \times 0.90} = 61.28 \text{ kg/s}$$

(c) $$\text{Circulation Ratio} = \frac{1}{\text{Steam quality at the top of riser}} = \frac{1}{x_{top}} = \frac{1}{0.1} = 10$$

(d) Number of riser tubes;

Rate of steam formation in one riser $= \dot{m}_{rs} = A_i \rho_{top} \times C_i \times x_{top}$

$$d_{ro} = 60 \text{ mm}$$

$$d_{ri} = 50 \text{ mm}$$

$$A_i = \frac{\pi}{4}\left(dr_i^2\right) = \frac{\pi}{4} \times (0.05)^2 = 1.96 \times 10^{-3} \text{ m}^2$$

$$\rho_{top} = 400 \text{ kg/m}^3$$

$$C_i = 1.5 \text{ m/s}$$

$$x_{top} = 0.10$$

$$\dot{m}_{rs} = 1.96 \times 10^{-3} \times 400 \times 1.5 \times 0.10 = 0.1176 \text{ kg/s}$$

$$\text{Number of riser tube} = \frac{\dot{m}_s}{\dot{m}_{rs}} = \frac{492.46}{0.1176} = 4187.58 \simeq 4188 \text{ tubes}$$

(e) Number of downcomers

Mass flow rate of feedwater through one downcomer is:

$$\dot{m}_{dw} = A_i \rho_f C_i$$

$$A_i = \frac{\pi}{4}\left(d_{d_i}^2\right)$$

$$d_{d_i} = (190 - 20) \text{ mm}$$

$$d_{d_i} = 170 \text{ mm} = 0.17 \text{ m}$$

$$A_i = 0.0226 \text{ m}^2$$

$$\rho_f = 600 \text{ kg/m}^3$$

$$C_i = 1.5 \text{ m/s}$$

$$\dot{m}_{dw} = 20.43 \text{ kg/s}$$

$$\text{No. of downcomers} = \frac{\dot{m}_s}{\dot{m}_{dw}} = \frac{492.46}{20.43} = 24.10 \simeq 25$$

(f) $$\text{Evaporation factor} = \frac{\dot{m}_s}{\dot{m}_f} = \frac{492.46}{61.28} = 8.04$$

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