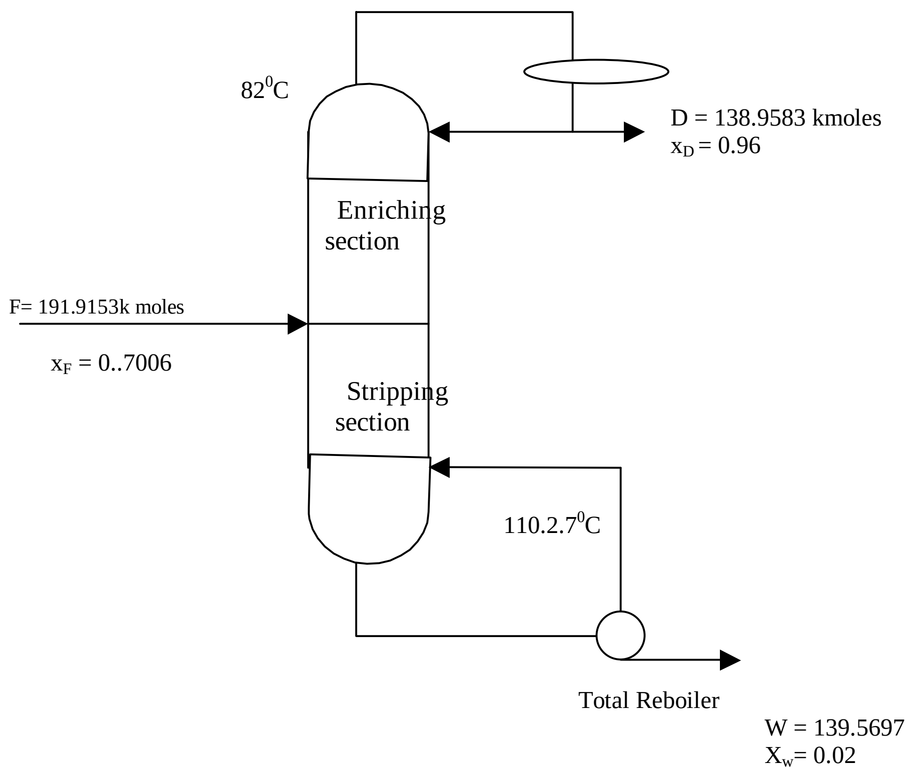
MAJOR EQUIPMENT :- DISTILLATION COLUMN

(a)Process design of distillation column:



Glossary of notations used

F = molar flow rate of feed, kmol/hr

D = molar flow rate of distillate, kmol/hr

W = molar flow rate of residue, kmol/hr.

x_F = mole fraction of benzene in feed

x_D = mole fraction of benzene in distillate

x_W = mole fraction of benzene in residue

R_m = minimum reflux ratio

R = actual reflux ratio

L = molar flow rate of liquid in the enriching section, kmol/hr

G = molar flow rate of vapour in the enriching section, kmol/hr

$\overline{L}$ = molar flow rate of liquid in stripping section, kmol/hr

$\overline{G}$ = molar flow rate of vapour in stripping section, kmol/hr

$\overline{M}$ = average molecular weight of feed, kg/kmol

q = Thermal condition of feed

Basis: - 1 hr of operation.

Feed is saturated liquid at boiling point.

F = 191.9153 kmol = 15796.04 kg

$$x_f = \frac{134.4591}{191.9153} = 0.7006$$

$$\overline{M}\text{ (feed)} = \frac{15796.04}{191.9153} = 82.3074 \text{ kg/kmol}$$

x_d = 0.96 , x_w = 0.02

$$\frac{x_D}{R_m+1} = 0.575$$

$$R_m+1 = \frac{x_D}{0.575} = \frac{0.96}{0.575} = 1.6696$$

R_m =1.6696 – 1.00 = 0.6696

$R = 1.5\ R_m = \underline{1.0044}$ kmoles

$$\frac{x_D}{R+1} = \frac{0.96}{1.0044 + 1} = 0.479$$

Number of ideal stages = 14

Number of ideal stages in the tower = 14-1 = 13

Number of ideal stages in enriching section = 4

Number of ideal stages in stripping section = 9

L = RD = 1.0044 (138.9583) = 139.5697 K-moles

G =L+D = 139.5697 + 138.9583 = 278.528 K-moles

q=1 (Feed is saturated liquid)

$\bar{L}$ = L+ qf = 278.528 + 1(191.9153) = $\underline{331.485}$ K-moles

$\bar{G}$ = G+(q –1) F = 497.544 +0 = $\underline{278.528}$ K-moles

Properties :

	Enriching section			Stripping section
	Top	Bottom	Top	Bottom
Liquid (k-moles/hr)	139.5697	139.5697	331.4850	331.4850
Liquid (kg/hr)	10980.06	11410.55	27332.99	30446.76
Vapor (k-moles/hr)	278.5280	278.5280	278.5280	278.5280
Vapor (kg/hr)	21912.02	22341.57	22458.72	25582.69
x	0.96	0.74	0.69	0.02
y	0.96	0.85	0.82	0.02
T_{liquid} (^{o} C)	80.8	85.9	87.0	109.2
T_{vapor}(^{o} C)	82.0	86.8	88.0	110.2
ρ_{vapor}(kg/m^3)	2.6697	2.7159	2.7210	2.9200
ρ_{liquid} (kg/m^3)	815	800	800	780
$(L/G)(\rho_g/\rho_L)^{0.5}$	0.0287	0.0298	0.0710	0.0728
M(l)(kg/kmol)	78.6708	81.7552	82.4562	91.8496
M(v)(kg/kmol)	78.6708	80.2130	80.6336	91.8496

Average conditions and Properties:

	Enriching section	Stripping section
Liquid (k-moles/hr) (kg/hr)	139.5697 11195.3044	331.4850 28889.8791
Vapor (k-moles/hr) (kg/hr)	278.5280 22126.7936	278.5280 24020.7004
$\bar{T}_{liq}$ (^{O}c)	83.35	98.1
$\bar{T}_{vapor}$ (^{O}c)	84.4	99.1
$\bar{\rho}_{liq}$ (kg/m^3)	807.5	790
$\bar{\rho}_{vapor}$ (kg/m^3)	2.7078	2.8205
μ_{liq}	0.3025	0.2725
μ_{vapor}	0.0088	0.0090
σ_{liq} (dyn/cm)	21	19
D_{vapor}(cm^2/s)	0.052	0.056
D_{liquid} (cm^2/s)	6.9549×10^{-5}	8.2962×10^{-5}

PLATE HYDRAULICS :

(A) **ENRICHING SECTION**:

(1) Tray spacing (t_s) = 500 mm

(2) Hole diameter (d_h) = 5.0 mm

(3) Pitch (l_p) =3d_h = 3x 5 = 15.0 mm

$\triangle^{lar}$ pitch

(4) Tray thickness (t_T) =0.6 d_{h} = 3.0 mm

(5) $\frac{A_h}{A_p} = \frac{\text{Area of hole}}{\text{Area of pitch}} = 0.10$

(6) Plate diameter (D_c) :

$(L/G)(\rho_g/\rho_L)^{0.5}$ = 0.0298 (maximum at bottom)

∴ Flooding check at bottom

(Ref :1, p: 18-7, fig :18-10)

$C_{sb,flood}$ = 0.29 ft/s

$C_{sb,flood}$ = capacity parameter (ft/s)

U_{nf} = Gas velocity through net area at flood (ft/s or m/s)

$$C_{sb,\ flood} = U_{nf} \left[\frac{20}{\sigma}\right]^{0.2} \left[\frac{\rho_g}{\rho_L - \rho_g}\right]^{0.5}$$ (Ref; 1, pg: 18-7)

σ = liquid surface tension

ρ_g = gas density

ρ_L = liquid density

$$\therefore U_{nf} = 0.29 \left[\frac{21}{20}\right]^{0.2} \left[\frac{807.5 - 2.7078}{2.7078}\right]^{0.5} = 5.0486 \text{ ft/s} = \underline{1.5388 \text{ m/s}}$$

Consider , 80% flooding

$U_n = 0.8\ U_{nf} = \underline{1.2310 \text{ m/s}}$

U_n = Gas velocity

$$\text{Volumetric flow rate of vapor} = \frac{22341.5665}{3600 \times 2.6997} = \underline{2.2988 \text{ m}^3/\text{s}}$$

$$\text{Net Area } (A_n) = \frac{\text{Volumetric flow rate of vapor}}{U_n} = \frac{2.2988}{1.2310} = \underline{1.8674 \text{m}^2}$$

Let $\frac{L_w}{D_c} = 0.75$

L_w = Weir Length

D_c = Column Diameter

$$\text{Area of column } (A_c) = \frac{\pi D_c^2}{4} = \underline{0.785\, D_c^2}$$

$$\sin(\theta_C/2) = (L_W/2)/(D_C/2) = 0.75$$

$$\theta c = \underline{97.2^0}$$

$$\text{Area of down comer } (A_d) = \left[\frac{\pi}{4} D_c^2 \frac{\theta c}{360} - \frac{Lw}{2} \frac{Dc}{2} \cos\left(\frac{\theta c}{2}\right)\right]$$

$$= \underline{0.0882\, D_c^2}$$

$A_n = A_c – A_{d.}$

$$0.785Dc^2 – 0.0882\, Dc^2 = 1.8674$$

D_c = 1.6371m.

$D_c \cong 1.7m$

$L_w = 0.75\, D_c = 1.275$m.

$L_w \cong \underline{1.3m}$

$$\therefore A_d = 0.0882(1.7)^2 = 0.2549\ m^2$$

$$A_c = \frac{\pi(1.7)^2}{4} = \underline{2.2698\ m^2}$$

$$A_n = A_c - A_d = 2.2698 - 0.2549 = 2.0149\ m^2$$

Active area (A_a) = $A_c - 2A_d = 2.2698 - 2(0.2549) = \underline{1.76\ m^2}$

$$\frac{L_w}{D_c} = \frac{1.3}{1.7} = 0.7647$$

$\therefore \theta c = 99.76^\circ$

$A_{cz} = 2\{50mm\} \times L_w = 2 \times 50 \times 10^{-3} \times 1.3 = 0.13\ m^2$

$$\frac{A_{cz}}{A_c} = \frac{0.13}{2.2698} = 0.057$$

$A_{cz} = \underline{5.7\%\ A_c}$

$\alpha = \pi - \theta_c = 180 - 99.76 = \underline{80.24^\circ}$

A_{wz} is the waste zones area.

$$A_{wz} = 2\left[\frac{\pi}{4} D_c^2 \frac{\alpha}{360} - \frac{\pi}{4}(D_c - 0.06)^2 \frac{\alpha}{360}\right]$$

$= \underline{0.0586\ m^2}$

$$\frac{A_{wz}}{A_c} = \frac{0.0586}{2.2698} = 0.026$$

$A_{wz} = \underline{2.6\%\ A_c}$

A_p = Area of perforation.

$A_p = A_c - 2A_d - A_{cz} - A_{wz}$

= 2.2698-2(.2549)-0.13-0.0586

= $\underline{1.5711\ m^2}$

(8)A_h = Area of holes.

$A_h = 0.1\ A_p = \underline{0.15711\ m^2}$

n_h = number of holes.= $n_h = \dfrac{4x\ 0.15711}{\pi(5\ x\ 10^{-3})^2} = \underline{8002}$

(9) h_w = 50mm

h_w = weir height

(10) **Weeping check :** (Sieve Tray)

(a) (Ref:1, p:18-9, eq:18-6)

$$h_d = K_1 + K_2(\rho_g/\rho_L)U_h^2$$

K_1 = 0 (for sieve tray)

U_h = Linear gas velocity through holes.

h_d = pressure drop across dry hole (mm liquid)

$$K_2 = \frac{50.8}{Cv^2}$$ (Ref :1, pg :18-9).

C_v = Discharge co-efficient. (Ref :1, fig: 18-14, pg :18-9)

For $\frac{A_h}{A_a} = 0.0893$

$\frac{t_T}{d_h} = 0.6$

$C_v = 0.74.$

$$\therefore K_2 = \frac{50.8}{0.74^2} = 92.77$$

$$(U_h)_{top} = \frac{21912.0206}{2.6997 \times 0.15711 \times 3600} = 14.35 \text{ m/s}$$ (minimum)

$$(U_h)_{bottom} = \frac{22341.5665}{3600 \times 2.7159 \times 0.15711} = 14.54 \text{ (m/s)}$$ (maximum)

$(h_d)_{top}$ = 63.28 mm of clear liquid .

$(h_d)_{bottom}$ = 66.58 mm of clear liquid.

(b) $h_\sigma = 409\left(\frac{\sigma}{\rho_L d_h}\right)$ (Ref: 1, pg:18-7, eq:18-2 (a)

h_σ = head loss due to the bubble formation

$$h_\sigma = 409 \left(\frac{21}{815x5} \right) = 2.1077 \text{ mm of clear liquid}$$

(c) $h_{ow} = F_w \, 664 \left(\frac{q}{L_w} \right)^{2/3}$ (Ref: 1, pg: 18-10, eq:18-12 (a)).

h_{ow} = height of crest over weir

F_w = weir constriction correction factor.

$$q = \frac{L_t}{\rho_L}$$

q = liquid flow per serration (m^3/s)

$$q = \frac{10980.06}{815 \text{ x } 3600} = 3..7424 \text{ x}10^{-3} \text{ m}^3/\text{s}$$

$$\frac{q^1}{(L_w)^{2.5}} = 1.5789$$ (Ref:1, pg:18-11, fig:18-16)

$$\frac{L_w}{D_c} = 0.7647$$

F_w = 1.02

$$\therefore h_{ow} = 1.02\,(664)\left\{\frac{3.7424 \times 10^{-3}}{1.3}\right\}^{2/3} = \underline{13.7059}\ \underline{mm} \text{ of clear liquid}$$

$h_d + h_\sigma = 63.28 + 2.11 = 65.39$ mm

$h_w + h_{ow} = 50 + 13.71 = 63.71$ mm

For $\frac{A_h}{A_a} = 0.0893$ & $h_{w} + h_{ow} = 63.71$ mm,

(Ref :1, pg:18-7, fig:18-11)

$h_{d} + h_\sigma = 16$ mm < 65.39 mm

Since design value is greater than the required, weeping will not occur.

(11) **Flooding check:**

Since the maximum flow rate is at the bottom, flooding is checked at the bottom.

$$h_{ds} = h_w + h_{ow} + \frac{h_{hg}}{2} \qquad \text{(For sieve trays)}$$

h_{hg} = liquid gradient across plate (mm liquid) (neglected)

$(h_{ow})_{bottom}$ = $\underline{14.24\ \text{mm}}$

h_{ds} = Calculated height of clear liquid over the dispersers.

h_{ds} = 50+14.24 = $\underline{64.24 \text{ mm}}$

U_a = linear gas velocity through active area.

$$U_a = \frac{22341.5665}{3600 \times 2.7159 \times 1.76} = 1.2983 \text{ ft/s}$$

$\rho_g = 2.7159 \text{ kg/m}^3$

$F_{ga} = U_a\,(\rho_g)^{½}$ =1.2983 $(2.7159)^{½}$ = 2.1396 $(\text{m/s})(\text{kg/m}^3)^{1/2}$ = 1.7540 $(\text{ft/s})(\text{lb/ft}^3)^{1/2}$

(Ref:1, pg:18-10, fig:18-15)

Aeration factor (ß) =0.58

Relative froth density (ϕ_t) =0.20

h_l^l = pressure drop through aerated liquid

h_f = actual height of froth.

$h_l^l = \beta\, h_{ds}$ = 0.58 (64.24) = $\underline{37.26 \text{ mm}}$

$$h_f = \frac{h_l^l}{\phi_t} = \frac{37.26}{0.20} = \underline{186.30 \text{ mm}}$$

$$h_{da} = 165.2 \left(\frac{q_b}{A_{da}}\right)^2$$ (Ref:1, Pg: 18-10, eq:18-14)

h_{da} = head loss under the down –comer

A_{da} = minimum area of flow under the down comes apron.

$h_{ap} = h_{ds} - c = 64.24 – 25.4 = 38.84$ mm

$A_{da} = L_w \times h_{ap} = 1.3 \times 38.84 \times 10^{-3} = \underline{0.0505\ m^2}$

$$q_b = \frac{L_b}{\rho_L} = \frac{11410.5487}{800 \times 3600} = \underline{3.962 \times 10^{-3}\ m^3/s}$$

$$h_{da} = 165.2 \left(\frac{3.962 \times 10^{-3}}{0.0505} \right)^2 = \underline{1.02\ mm}$$

h_t = total head loss across the plate

$h_t = h_d + h_l^1 = 66.58 + 37.26 = \underline{103.84mm}$

$h_{dc} = h_t + h_w + h_{ow} + h_{hg} + h_{da}$ (Ref :1, eg:18-3, pg:18-7)

$= 103.84 + 50 + 14.24 + 0 + 1.02$

$= \underline{169.1\ mm}$

Taking (ϕ_{dc}) average = 0.50 ; ϕ_{dc} = relative froth density & h_{dc}^1 = actual back-up

$$h^1_{dc} = \frac{169.1}{0.5} = 338.2 \text{ mm} < 500 \text{ mm}$$

Hence flooding will not occur.

(III) **Column efficiency :** (Average Conditions)

(a) $N_g = \dfrac{0.776+0.00457h_w - 0.238\, U_a\, \rho_g^{0.5} + 105\, w}{(N_{sc,g})^{0.5}}$ (Ref :1, pg:18-15, eq:18-36)

N_g = gas phase transfer unit

$N_{sc,g} = \dfrac{\mu_g}{\rho_g D_g} = \dfrac{0.0088 \times 10^{-3}}{2.7078 \times 5.2 \times 10^{-6}} = 0.6250$

$N_{sc,g}$ = gas phase schmidt number

$U_a = \dfrac{22126.7936}{3600 \times 2.7078 \times 1.76} = 1.2897$ m/s

$D_f = \dfrac{L_w + D_c}{2} = \dfrac{1.3+1.7}{2} = 1.5$m

D_f = width of flow path on plate

W = liquid flow rate (m^3/sm)

$W = \dfrac{q}{D_f}$

$q = \dfrac{1195.3044}{807.5 \times 3600} = 3.8512 \times 10^{-3}$ m^3/s

$W = \dfrac{3.8512 \times 10^{-3}}{1.5} = 2.5674 \times 10^{-3}$ m^3/m-s

$N_g = \dfrac{0.776+0.00457(50) - 0.238\,(1.2897)\,(2.7078)^{0.5} + 105\,(2.5674 \times 10^{-3})}{(0.625)^{0.5}}$

$N_g = 0.9727$

(b) $N_L = K_{L\,a}\ \theta_L$ (Ref:1, pg: 18-15, eq:18-36 (a))

N_L = liquid phase transfer units

$K_{L\,a}$ = liquid phase transfer coefficient (m/s)

Q_L =Residence time of liquid in froth or spray zone.

$(D_L)_{average} = 6.9549 \times 10^{-9}\ m^2/s$

$K_{L\,a} =(D_L)^{1/2}\ (0.40\ U_a\ \rho_g{}^{1/2} +0.17)$ (Ref:1, pg:18-16, eg:18-40(a))

$K_{L\,a} = (3.875 \times 10^8 \times 6.9549 \times 10^{-9})^{1/2}\ (0.40 \times 1.2897\ (2.7078)^{1/2} +0.17)$

$= 1.6727$ m/s

$$\theta_L = \frac{h_L A_a}{1000 q_b}$$ (Ref:1, pg:18-16, eq:18-39)

h_l = liquid hold-up on plate

$$\theta_L = \frac{37.26 \times 1.76}{1000(3.8512 \times 10^{-3})} = \underline{17.03\ \ s}$$

$N_L = 1.6727 \times 17.03 = \underline{28.48}$

$m_{top} = 0.425$ $\Big\}$ $\frac{G_m}{L_m} = \frac{278.5280}{139.5697} = 1.9956$

$m_{bottom} = 0.625$

$$\lambda_t = m_{top} \left(\frac{G_m}{L_m} \right) = 0.848$$

$$\lambda_b = m_{bottom} \left(\frac{G_m}{L_m} \right) = 1.2473$$

$$\bar{\lambda}_{avg} = 1.0476$$

λ = stripping factor

$$N_{og} = \frac{1}{\frac{1}{N_g} + \frac{\lambda}{N_L}}$$

(Ref: 1, pg:18-15, eq:18-34)

$$= \frac{1}{\frac{1}{0.9727} + \frac{1.0476}{28.48}} = 0.9391$$

$$E_{OG} = 1 - e^{-(N_{og})}$$

(Ref:1, pg: 18-15, eq:18-33)

$$E_{OG} = 1 - e^{-(0.9391)} = \underline{0.609}$$

(B) **Murphee plate efficiency :** E_{mv}

$$N_{pe} = \frac{Z_l^2}{D_E \theta_L}$$

Z_l= length of liquid travel, m

$= D_c \cos(\theta_C/2) = 1.7 \cos(99.76/2) = 1.0955$ m

D_E = eddy diffusivity

$= 6.675 \times 10^{-3}(U_a)^{1.44} + 0.922 \times 10^{-4} h_l - 0.00562$ (Ref:1, pg: 18-17, eq:18-45)

$= 6.675 \times 10^{-3}(1.2897)^{1.44} + 0.922 \times 10^{-4} \times 37.26 - 0.00562$

$= 7.4438 \times 10^{-3}\ m^2/s$

$$N_{pe} = \frac{1.0955^2}{7.4438 \times 10^{-3} \times 17.03} = 9.4671$$

$\lambda E_{OG} = 1.0476 \times 0.609 = 0.638$

From (Ref:1, p18-18, fig 18-29a), $\frac{E_{mv}}{E_{OG}} = 1.3$

$\therefore\ E_{mv} = 1.3 \times 0.609 = 0.7917$

(C) **Overall column efficiency :** $E_{oc} = \frac{N_{theoretical}}{N_{actual}}$

$$E_{oc} = \frac{\log\{1+Ea(\lambda - 1)\}}{\log(\lambda)}$$ (Ref:1, pg:18-17, eq:18-46)

E_a = Murphee plate efficiency corrected to liquid entrainment

$$\frac{E_a}{E_{mv}} = \frac{1}{1 + E_{mv}\left(\frac{\psi}{1-\psi}\right)}$$ (Ref:1, pg:18-13, eq:18-37)

ψ = fractional entrainment

For $\frac{L}{G}\left(\frac{\rho_g}{\rho_L}\right)^{0.5} = \frac{11195.30}{22126.8}\left(\frac{2.7078}{807.5}\right)^{0.5}$ = 0.0293 &

For 80% flood,

From (Ref:1, fig:18-22, pg:18-44)

$\psi = 0.11$

$$E_a = 0.7917\left\{\frac{1}{1+0.7917 \times \frac{0.11}{1-0.11}}\right\} = 0.7211$$

$$Eoc = \log\left\{\frac{1+0.7211(1.0476-1)}{\log(1.0476)}\right\} = 0.7257$$

N_A = Actual trays;

N_T= theoretical trays.

$$N_A = \frac{N_T}{Eoc} = \frac{4}{0.7257} = 5.512 \simeq 6 \text{ trays}$$

Height of enriching section = 6 x 0.500 = 3.0 m

(B) **STRIPPING SECTION** :

(1) Tray spacing (t_s) = 500 mm

(2) Hole diameter (d_n) = 5mm

(3) Pitch (l_p) =15mm

$\triangle$ lar pitch

(4) Tray thickness (t_r) =3mm

(5) $\frac{A_h}{A_p} = 0.10$

(6) Plate Diameter (D_c) :

$(L/G)(\rho_g/\rho_L)^{0.5}$ = 0.0728 (maximum of bottom)

$C_{sb\ flood}$ =0.27 ft/s

U_{nf} = 1.3288 m/s

Consider , 80% flooding .

U_n =1.0631 m/s

Volumetric flow rate of vapor =2.4337 m^3/s

Net area (A_n) =2.2892 m^2

Column diameter (D_c) =1.82 m

L_w =1.4m

A_d=0.2922 m^2

A_c=2.6016m^2

A_n=2.3094 m^2

A_a=2.0172m^2

$\frac{L_w}{D_c}$ = 0.7692

θ_c = 100.57^0

A_{cz} = 0.14 m^2 (5.4% of A_c)

A_{wz} = 0.0622 m^2 (2.3% of A_c)

α = 79.43^0

A_p = 1.815 m^2

A_h = 0.1815 m^2

n_h = 9244

(9) h_w =50mm

(10) **Weeping check (top):**

(a) $(h_d)_{top}$ = 50.35 mm of clear liquid

$(h_d)_{bottom}$ = 62.44 mm of clear liquid

(b) h_σ = 1.94 mm of clear liquid

(c) h_{ow} = 24.50 mm of clear liquid

$h_w + h_{ow}$ = 74.50mm

$h_d + h_\sigma$ = 52.29mm

From graph, $h_d + h_\sigma$ = 16 mm < 52.29 mm

$\therefore$ There is no weeping.

11) **Flooding check (Bottom)**:

h_{ow} = 26.77 mm

h_{ds} = 76.77mm ; β =0.58 ; ϕ_t = 0.20

h_l^1 = 44.53 mm

h_f = 222.65mm

h_{ap} = 51.37mm

A_{da} = 0.0719 m^2

h_{da} = 3.76 mm

h_t = 106.97 mm

h_{dc} = 185.39 mm

h_{dc}^1 = 370.78 mm < 500 mm

$\therefore$ There is no flooding

(III) **Column Efficiency**:

(a) N_g =1.5873

(b) θ_L = 8.8427s.

N_L = 15.1866

N_{og}=1.4233

E_{oG}=0.7591

(B) **Murphee plate efficiency :**

$Z_l = 1.1629$

$D_E = 6.8829 \times 10^{-3}\ m^2/s$

$N_{pe} = 22.2194$

$\lambda E_{OG} = 0.8371$

$\underline{E_{mv}} = 1.5$

E_{OG}

$E_{mv} = \underline{1.1387}$

(C) **Overall column efficiency :**

$E_a = 1.0871$

$E_{oc} = 1.0826$

$N_A = 9/1 = 9$ trays

Height of stripping section = 9 x 0.500 = 4.5 m

Total height of the column = Enriching section + stripping section

= 3.0 + 4.5 = 7.5 m

Summary of the Distillation Column:

Enriching section

Tray spacing = 500 mm

Column diameter = 1.7 m

Weir length = 1.3m

Weir height = 50 mm

Hole diameter = 5 mm

Hole pitch = 15 mm, triangular

Tray thickness = 3 mm

Number of holes = 8002

Flooding % = 80%

Stripping section

Tray spacing = 500 mm

Column diameter = 1.82 m

Weir length = 1.4 m

Weir height = 50 mm

Hole diameter = 5 mm

Hole pitch = 15 mm, triangular

Tray thickness = 3 mm

Number of holes = 9244

Flooding % = 80%

<u>(b)Mechanical Design of Distillation Column</u>:

a) Shell:

Diameter = 1.82 m

Operating pressure = 1atm

= 1.0329 kg/cm^2

Design pressure = 1.1 x operating pressure

= 1.1 x 1.0329

=1.1362 kg/cm^2

Operating temperature = 110 ^0C

Design Temperature = 1.1 x 110

= 121 ^0C

Shell material - Carbon steel

Shell -Double welded bolt joints stress relieved

Skirt = 1.5 m

Tray spacing = 500 mm

Top Disengaging Space = 0.3 m

Bottom separator space = 2.25 m

Allowable stress for shell material = 950 Kg/cm^2

Insulation material - Asbestos

Insulation thickness = 75 mm

Density of Insulation = 575 Kg/m^3

(b) Head: Torrspherical dished head.

Material -Carbon Steel

Allowable tensile stress = 950 kg/cm^2

(c) Skirt support

Height = 1.5 m

Material - Carbon steel

(d) Nozzles:

Number of Nozzles = 4

(e) Trays – Sieve type

Number of trays	15
Spacing	500 mm
Hole diameter	5 mm
Thickness	3 mm
Weir height	50 mm
Material for trays & downcomers weirs	Stainless steel.

(1) Calculations of shell thickness :

Considering the vessel as an internal pressure vessel.

$$t_s = \frac{PD_i}{2f_T - P} + C \quad \text{(Ref: 4, p:13, eq:3.1)}$$

t_s = Thickness of shell (mm)

P = Design pressure (kg/cm^2) =1.1362 kg/cm^2

D_i = Diameter of the shell (mm) = 1820 mm

f = Allowable /permissible tensile stress (kg/cm^2)= 950kg/cm^2

C = Corrosion allowance (mm) =2mm

J = Joint Efficiency.

Considering double welded bolt joints with backing strip

J = 85%

= 0.85

$$t_s = \frac{1.1362 \times 1820}{2(950 \times 0.85)-1.1362} + 2$$

= 3.28 mm

Taking the thickness of the shell as t_s = 6mm

(2) Head -shallow dished & torispherical head.

$t_h = \frac{PR_cW}{2fJ}$ (Ref: 3, Pg: 238)

R_c - Crown radius = outer diameter of the shell = 1820+ 2(6) = 1832 mm

R_K = knuckle radius = 0.06 R_c

W= Stress intensification factor

$W = 1/4[3 + (R_c/R_K)^{1/2}]$

= 1.77

$t_h = \frac{1.1362x1832x1.77}{2x950x0.85}$

= 2.28mm

Thickness of head is t_h = 6mm

Weight of head:

Diameter = OD + $\frac{OD}{24}$ + 2Sf + $\frac{2}{3}$ icr (Ref: 6, pg:88, eq: 5-12)

OD = outside diameter of shell = 1832 mm = 72 (inches)

icr = inside cover radius = 0.75 inches
Sf = straight flange length = 1.5 inches } (Ref: 6, table 5.7, pg:88)

Diameter = 72+ $\frac{72}{24}$ + 2 (1.5) + $\frac{2}{3}$(0.75)

Diameter (d) = 78.5 inches = 1.9939 m

Weight of head $= \frac{\pi}{4} (1,9939)^2 (6 \times 10^{-3}) \times 7700$

$= 144.26$ Kg

weight of head $\simeq$ 2670 Kg (Ref:3, pg: 325)

(3) Calculation of stresses:

(i) Axial tensile stress due to pressure (Ref : 3, pg :293)

$$f_{ap} = \frac{P_{di}}{4(t_s-c)} = \frac{1.1362 \times 1820}{4\,(6-2)} = 129.24\ Kg/cm^2$$

This is same throughout the column height

(ii) Circumferential stress :

$2\ f_{ap} = 2 \times 129.24 = 258.48\ Kg/cm^2$

(iii) compressive stress due to dead loads:

(a) Compressive stress due to weight of shell up to a distance x metre.

$$f_{ds} = \frac{\text{weight of shell}}{\text{Cross-section area of shell}}$$

$$f_{ds} = \frac{(\pi/4)\ (D^2o - Di^2) S_s\ x}{(\pi/4)\ (Do^2 - Di^2)}$$

Di&Do - Internal & external diameters of shell

S_s - density of shell.

Also,

$$f_{ds} = \frac{\text{weight of shell per unit height x X}}{\pi D_m (t_s - c)}$$

Dm = Mean diameter of the shell (cm)

t_s = thickness of the shell (cm)

C = Corrosion allowance (cm)

$f_{ds} = S_s$ (x)

S_S = 7700 kg/cm^3

= 0.0077 kg/cm^3

f_{ds} = 0.77x kg/cm^2

(b) Compressive stress due to weight of insulation at height (x) m

$$f_{d(ins)} = \frac{\pi \text{ Dins tins Sins (x)}}{\pi D_m (t_s - c)}$$ (Ref: 3, pg: 293)

Dins = Diameter of insulation

tins = Thickness of insulation

Sins = Density of insulation

D_m = Mean diameter of shell

$$= \frac{[\ Dc + (\ Dc + 2\ t_s)]}{2}$$

Assume : asbestos in the insulation material.

S_{ins} = 575 kg/m^3 = 0.000575 kg/cm^3

tins = 75mm = 7.5cm

Dins = Dc+2 t_s +2tins

Dins = 1820 + 2(6) + 2(75)

= 1982 mm

= 198.2 cm

$$D_m = \frac{1820 + 1832}{2}$$

= 1826 mm

$$= \frac{182.6 \text{ cm}}{2}$$

$$f_d(ins) = \frac{\pi\ (198.2)\ 7.5 \times 0.000575}{\pi\ (182.6)\ (0.6 - 0.2)}$$

= 1.17 x kg/cm^2

(b) Compressive stress due to liquid & tray in the column up to height (x) m.

Liquid & tray weight fox height (x)

$$F_{liq} = \left[\frac{(x-0.3)}{(0.5)} + 1\right] \frac{\pi Di^2}{4} \times S_{liquid}$$

$$F_{liq} = \left[\frac{(x - \text{top disengaging space})}{\text{Tray spacing}} + 1\right] \frac{\pi Di^2}{4} \times S_{liquid}$$ (Ref: 3, pg :294)

$$= \left[\frac{x - 0.3}{0.5} + 1 \right] \frac{\pi (1.82)^2}{4} \times 800$$

$$= \left[\frac{x - 0.3 + 0.5}{0.5} \right] \frac{\pi (1.82)^2}{4} \times 800$$

$$= (x + 0.2)\ 4162.49 \text{ Kg.}$$

$$f_d(liq) = \frac{F_{liq}}{\pi D_m (t_s - c)}$$ (Ref :3, pg:294)

$$= \frac{(x+0.2)\ 4162.49}{\pi (192.6)(0.6-0.2)}$$

$$= (18.14x + 3.63) \text{ kg/cm}^2$$

(d) Tensile stress due to wind loads in self supporting vessel

$$f_{wx} = \frac{M_w}{z}$$ (Ref :3; pg; 295)

M_w = bending moment due to wind load

$$= \frac{\text{wind load x distance}}{2}$$

$$= \frac{0.7 P_w D_m X^2}{2}$$ (Ref: 3; pg: 295)

z=modulus for the area of shell $= \frac{\pi}{4} D^2 m (t_s - c)$ (Ref : 3, pg: 295)

$$f_{wx} = \frac{0.7 P_w D_m x^2}{2 \frac{\pi}{4} D_m^2 (t_s - c)} = \frac{1.4 Pw\ x^2}{\pi D_m (t_s - c)}$$

P_w = wind pressure

P_w = 25 lb/ft^2 (Ref: 6, pg:159, table :9.1)

= 121.9 kg/m^2

$$Mw = \frac{(0.7 \times 121.9 \times 1.826)}{2} x^2 = 77.91\ x^2$$

$$Z = \frac{\pi}{4} \underline{(1.826)^2}\ \underline{(0.006 - 0.002)} = 0.0105$$

$$f_{wx} = \frac{77.91}{0.0105} x^2 = 7437.75\ x^2 \ \text{kg/m}^2 = 0.7438\ x^2\ \text{kg/cm}^2$$

Stresses due to seismic load are neglected.

Calculations of resultant longitudinal stress (upwind side)

Tensile:

$f_{t,max} = f_{wx} + f_{ap} - f_{ds}$ (Ref: 3, pg:293)

f_{wx} = stress due to wind load.

f_{ap} = Axial tensile stress due to pressure

f_{ds} = Stress due to dead loads.

$f_{t,max} = 0.7438\ x^2 + 129.24 - 0.77x$

$f_{t,max} = fJ$

f = allowable stress = 950 kg/cm^2

J= Joint factor = 0.85

$\therefore$ $f_{t,max}$ = 950 (0.85) = 807.5 kg/cm^2

$0.7438\ x^2 + 129\ 24\ x - 0.77x = 807.5$

$0.7438\ x^2 - 0.77x – 678.26 = 0$

a =0.7438, b = -0.77, c = - 678.26

$x = [-b \pm (b^2-4ac)^{1/2}] /2$

x = 30.72 m

(4)Calculation of resultant longitudinal stress (downwind side) compressive :

fc,max = fwx - fap + fds

$fc,max = 0.7438\ x^2 – 129.24 + 0.77x$

$fc,max = 0.125E(t/D_0)$

E= Elastic modulus = $2x10^5\ MN/m^2 = 2x10^6\ kg/cm^2$

t = Shell thickness = 6mm.

D_o = 1832 mm

$$fc,max = 0.125 \times 2x10^6 \left(\frac{6}{1832}\right) = 818.78\ kg/cm^2$$

$818.78 = 0.7438\ x^2 – 129.24 + 0.77\ x$

$0.7438\ x^2 + 0.77x – 948.02 = 0$

a= 0.7438, b = 0.77, c= - 948.02

$x = [-b \pm (b^2-4ac)^{1/2}] /2$

x= 35.19 m

∴ The calculated height is greater than the actual tower height. So we conclude that the design is safe and thus design calculations are acceptable.

∴ A thickness of 6mm is sufficient throughout the length of the shell.

(5)Design of skirt support :

Total height of column including skirt height (H) = 7.5 +1.5 +0.3 +0.4

= 9.7 m

Minimum weight of vessel (W_{min}) = $\pi(D_i+t_s)t_s$ (H-skirt height)s

+2 (2670) (Ref: 5 ; pg:167)

D_i = diameter of shell = 1.82 m

t_s = 0.006m

S_s = Density of material

$W_{min} = \pi$ (1.82 + 0.006) 0.006 (9.7-1.5) 7700+2(2670)

=7513.25 kg.

Maximum weight of column (W_{max}) = $W_w + W_i + W_e + W_a$ (Ref: 5, pg: 167)

W_s = weight of shell during test = 1987.71 kgs.

W_i = weight of insulation = $\underline{\pi}$ $(d^2_{ins} - d^2o)$ H S_{ins}

$$= \frac{\pi}{4}\{1.982^2 - 1.832^2\}\, 9.7\, (575)$$

$= 2506.12$ kgs

W_e = weight of water during test $= \frac{\pi}{4} Di^2 (H-1.5)\ Swater$

$$= \frac{\pi}{4} (1.82)^2 (9.7-1.5)\ 1000$$

$= 21332.73$ kgs

Wa = weight of attachments = 7100 kgs

W_{max} = 1987.7+2506.12+21332.73+7100 = 32926.56 kgs

Period of vibration at minimum dead weight

$$T_{min} = 6.35 \times 10^{-5} \left(\frac{H}{D}\right)^{3/2} \left(\frac{W_{min}}{t_s}\right)^{½}$$

$$= 6.35 \times 10^{-5} \left\{\frac{9.7}{1.82}\right\}^{3/2} \left\{\frac{7513.23}{0.006}\right\}^{½}$$

$= 0.874$ s

∴ K_2 = a coefficient to determine wind load =2 (Ref: 5, pg:147)

Period of vibration at maximum dead weight,

$$T_{max} = 6.35 \times 10^{-5} \left(\frac{H}{D}\right)^{3/2} \left(\frac{W_{max}}{t_s}\right)^{1/2}$$

$$= 6.35 \times 10^{-5} \left(\frac{9.7}{1.82}\right)^{3/2} \left\{\frac{32926.56}{0.006}\right\}^{1/2}$$

$$= 1.83 \text{ s}$$

Therefore $K_2 = 2$

Total load due to wind acting on the bottom & upper part of vessel

$P_W = k_1\ k_2\ P_w\ HD$ (Ref: 5, pg: 168)

K_1 = coefficient depending upon safe factor

= 0.70 (for cylindrical surface)

P_W = wind load

P_W = wind pressure = 1000 N/M^2 = 100 kg/m^2

For minimum weight condition $D = D_i$ = 1.82 m

For maximum weight condition $D = D_{ms}$ = 1.982 m

$\therefore (P_W)_{min}$ = 0.7x2x100x1.82x9.7

= 2417.56 kg

$(P_W)_{max}$ = 0.7x2x100x1.982x9.7

= 2691.56 kg

Minimum & maximum wind moments

$(M_W)_{min} = (P_W)_{min} \times \frac{H}{2} = 2417.56 \times \frac{9.7}{2} = 11987.1$ kg-m

$(M_W)_{max} = (P_W)_{max} \times \frac{H}{2} = 2691.56 \times \frac{9.7}{2} = 13054.05$ kg.m

As the thickness of the skirt is expected to be small, assume

$D_i \simeq Do = 1.7m$

$$\sigma_{zwm}(min) = \frac{4\ M_{W(min)}}{\pi D^2 t}$$

$$= \frac{4 \times 11987.1}{\pi (1.82)^2 t}$$

$= 4607.7/t\ Kg/m^2$

$$fzwm(max) = \frac{4 \times 13054.05}{\pi (1.82)^2 t}$$

$$= \frac{5017.8}{t}\ Kg/m^2$$

Minimum and maximum dead load atresses:

$$fzw\ (min) = \frac{W_{min}}{\pi Dt} = \frac{7513.23}{\pi (1.82) t} = \frac{1314.03}{t}\ Kg/m^2$$

$$fzw\ (max) = \frac{W_{max}}{\pi Dt} = \frac{32926.56}{\pi (1.82) t} = \frac{5758.71}{t}\ Kg/m^2$$

Maximum tensile stress without any eccentric load is computed as follows.

(tensile) fz = σ_{zwm}(min) - fzw (min)

fz = fJ

$95\times10^{5}\times0.85 = \dfrac{4607.7 - 1314.03}{t}$ Kg/m^2

Therefore $t = 4.1\times10^{-4}$ m

= 0.41 mm

Maximum compressive load:

Compressive: fz = fzwm(max) + fzw (max)

fz = 0.125 E(t/Do)

$= 0.125\times2\times10^{5}\times10^{6}\times(t/1.832)$

$\dfrac{5017.8+5758.71}{t} = 1.3646 \times10^{10}$

Therefore $t = 8.8865\times10^{-4}$ m

= 0.8887 mm

As per IS 2825-1969,minimum corroded skirt thickness is 7 mm. Providing 1 mm corrosion allowance, a standard 8 mm thick plate can be used for skirt.

(6)Design of skirt bearing plate:

Maximum compressive stress between plate and foundation:

$fc = \dfrac{Wmax}{A} + \dfrac{Ww(max)}{Z}$

$A = \pi(1.82 - l)\, l$

l - 0uter radius of bearing plate - outer radius of skirt support

$Z = \pi R_m^{2} l$

$R_m = \frac{Do - l}{2}$

$A = \pi(1.82 - l)l$

$R_m = \frac{(1.82 - l)}{2}$

$Z = \pi \frac{(1.82 - l)^2}{4} l$

$$fc = \frac{32926.56}{\pi(1.82 - l)l} + \frac{13054.05}{\pi \frac{(1.82 - l)^2}{4} l}$$

Allowable compressive strength of concrete foundation values from 5.5 - 9.5 MN/m^2

Assume :5.5 -9.5 MN/m^2

$$5.5 \times 10^5 = \frac{32926.56}{\pi(1.82 - l)l} + \frac{13054.05}{\pi \frac{(1.82 - l)^2}{4} l}$$

$$l = \frac{0.0191}{(1.82 - l)} + \frac{0.0302}{(1.82 - l)^2}$$

By hit and trial method. l = 0.02 m

Therefore 20 mm is the width of the bearing plate

Thickness of bearing plate ,$t_{bp} = l(3fc/t)^{1/2}$

fc- maximum compressive load at l = 0.02 m = 0.23×10^6 Kg/m^2

$t_{bp} = 20[(3\times0.23 \times 10^6)/(95 \times 10^5)]^{1/2}$

= 5.4 mm

$\simeq$ 6 mm

Minimum stress between the bearing the plate and the concrete foundation:

$$fmin = \frac{Wmin}{A} - \frac{Mw(min)}{Z}$$

$$= \frac{7513.23}{[\pi(1.82-0.02)0.02]} - \frac{11987.1}{[\pi(1.82-0.02)^2 0.02]}$$

$= 7548.63\ Kg/m^2$

$$J = \frac{WminD}{(Mw)max}$$

$$= \frac{(7513.23 \times 1.82)}{13054.05}$$

$= 1.05$

Therefore this is less then 1.5,the vessel will not be steady by its own weight

Therefore anchor bolts has to be used.

$P_{bolt}(n) = fmin\ A$

$= 7548.63 \times 3.14 \times (1.82 - 0.02)0.02$

$= 853.73\ Kg$

If hot rolled carbon steel is selected for bolts, $f = 57.3\ MN/m^2$

$= 5.8409 \times 10^6\ kg/m^2$

$(a_r n)f = n\ P_{bolt}$

$$(a_r n) = \frac{853.73}{5.8409 \times 10^6} = 1.4616 \times 10^{-4}\ m^2 = 146.16\ m^2$$

where a_r = root area of a bolt & n = no. of bolts

For M12 x 1.5 bolts, $a_r = 63\ mm^2$

n = 146.16/63 = 2.32 = 3 bolts

But, as the wind may blow from any side, 8 equally distributed bolts are to be used.

MINOR EQUIPMENT:-CONDENSER

(a)Process design of condenser

(I) **Preliminary Calculations**:

(a) Heat Balance:

Vapor flow rate $(\bar{G})$ = 21912.0206 kg/hr
= 6.0867 kg/s

Vapor Feed Inlet Temperature =82^0c.

Let Condensation occur under Isothermal conditions i.e F_T=1

Condensate outlet temperature = $82\ ^0C$

$\therefore$ Average Temperature = $82\ ^0C$

Latent heat of vaporisation (λ)=3.1e7 (0.96)+3.5e7 (0.04)

= 396.0802 KJ/kg

q_h = mass flow rate of hot fluid x latent heat of hot fluid

q_h = heat transfer by the hot fluid .

q_h =6.0867 x 396.0802 = 2410.8256 KW
Assuming 10% overload, q_h^1= 1.1 x 2410.8256 = 2651.9082 kW

q_C= mass flow rate of cold fluid x specific heat x $\triangle$t

q_c = heat transfer by the cold fluid.

Assume : $q_h = q_c$.

Inlet temperature of water = 30 ^{0}C.

Let the water be untreated water.

$\therefore$ Outlet temperature of water (maximum) = <u>40 ^{0}C</u>

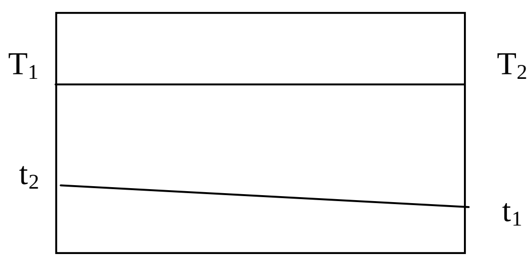
$\therefore \triangle t = 40\text{-}30 = \underline{10^0C}$

$\bar{C}p$ = 4.187 KJ/kg K.

$$m_c = \frac{2651.9082 \times 10^3}{4.187 \times 10^3 \times 10} = \underline{63.3367} \text{ kg/s.}$$

(b) <u>LMTD Calculations:</u>

assume : counter current



$$\text{LMTD} = \frac{(T_1 - t_2) - (T_2 - t_1)}{\ln \dfrac{(T_1 - t_2)}{(T_2 - t_1)}}$$

$T_1 = 82\ ^0C$; $T_2 = 82\ ^0C$; $t_1 = 30\ ^0C$; $t_2 = 40\ ^0C$

$\therefore$ LMTD = <u>46.82 ^{0}C</u>

(C) <u>Routing of fluids :</u>

Vapors - Shell side

Liquid - Tube side

(D) Heat Transfer Area:

(i) $q_h = q_C = UA\,(\triangle T)_{LMTD,corrected}$.

U= Overall heat transfer coefficient ($W/m^2\,K$)

Assume : $U = 500\ W/m^2K$

$$\therefore A_{assumed} = \frac{2651.2082 \times 10^3}{500 \times 46.82} = 113.2810\ m^2$$

(ii) Select pipe size: (Ref 1: p: 11-10 ; t: 11-2)

Outer diameter of pipe (OD) = ¾" = 0.0191 m

Inner diameter of pipe (ID) =0.620" = 0.0157m

Let length of tube =16' = 4.88m

Heat transfer area of each tube ($a_{heat-transfer}$) = $0.2921\ m^2$

$$\therefore \text{Number of tubes } (N_{tubes}) = \frac{A_{assumed}}{a_{heat-transfer}} = \frac{113.2810}{0.2921}$$

$$= 387.8756 = 388 \text{ tubes}$$

(iii) Choose Shell diameter: (Ref-1, p: 11-15, t : 11-3 (F))

Choose TEMA : P or S. ¾" OD tubes in 15/16" $\triangle^{lar}$ pitch.
1 - 2 Horizontal Condenser

$\therefore N_{tubes}$ (Corrected) = 430

Shell Diameter (D_i) =0.591 m.

$\therefore A_{corrected} = 430 \times 0.2921 = \underline{125.603}\ m^2$

$$\therefore U_{corrected} = \frac{2651.9082 \times 10^3}{125.603 \times 46.82} = \underline{450.9486}\ W/m^2K$$

(II) **Fluid velocity check** :

(a) Vapor side – need not check
(b) Tube side

$$\text{Flow area } (a_{tube}) \text{ Per pass} = \frac{a_{pipe} \times N_{tubes}}{N_{tube\ passes}}$$

$$a_{pipe} = \text{C.S of pipe} = \frac{\pi (ID^2)}{4}$$

$$\therefore a_{tube} = \frac{\pi}{4}(0.0157)^2 \times \frac{430}{2} = \underline{0.0419}\ m^2/\text{pass}$$

$$\text{Velocity of fluid in pipe } (V_{pipe})\ v_p = \frac{m_{pipe}}{\rho_{pipe} \times a_{tube}}$$

m_{pipe} = mass –flow rate of fluid in pipe.
ρ_{pipe} = Density of fluid in pipe (water)

$$\therefore v_p = \frac{63.3367}{1000 \times 0.0419} = \underline{1.5116\ m/s}$$

$\therefore$ fluid velocity check is satisfied

(III) **Film Transfer Coefficient** :

Properties are evaluated at ^{t}film :

$$^{t}\text{film} = \left[\frac{t_v + \frac{1}{2}\left\{t_v + \frac{(t_1+t_2)}{2}\right\}}{2}\right] = \left[\frac{82 + \frac{1}{2}\left\{82 + \frac{(30+40)}{2}\right\}}{2}\right] = \underline{70.25\ ^0C}$$

ρ_l = 820 kg/m^3, Cp = 1.8802 kJ/kgK, k = 0.1296 W/mK, μ_l = 0.36 x 10^{-3} Pa-s

a) Shell side:

$$\text{Reyonld's Number (Re)} = \frac{4\,\Gamma}{\mu} = \frac{4}{\mu}\ \frac{W}{(N_{tubes})^{2/3} \times L}$$

$$= \frac{4}{0.00036} \times \frac{6.0867}{(430)^{2/3} \times 4.88} = \underline{243.2618}$$

For Horizontal condenser :

$$Nu = 1.51 \left\{\frac{(0D)^3 (\rho)^2 g}{\mu^2}\right\}^{1/3} (Re)^{-1/3}$$

$$h = 1.51 \left\{\frac{0.1296^3 (820)^2 \times 9.81}{(0.36 \times 10^{-3})^2}\right\}^{1/3} (243.26183)^{-1/3}$$

$$Nu = \frac{h_o\,(OD)}{K}$$

h_o = outside heat transfer coefficient (W/m^{2}K)

k = Thermal conductivity of liquid.

h_o = $\underline{1161.7728\ \text{W/m}^2\text{K}}$

b) Tube side: water

$$G_t = \frac{m_{pipe}}{a_{tube}}$$

G_t= Superficial mass velocity

$$G_t = \frac{63.3367}{0.0419} = 1511.616 \text{ kg/m}^2\text{s}$$

$$Re = \frac{1000 \times 1.5116 \times 0.0191}{0.85 \times 10^{-3}} = \underline{33{,}877.6235}$$

$$Pr = \frac{\mu C_p}{K} = \frac{0.85 \times 10^{-3} \times 4.187 \times 10^{3}}{0.5936} = \underline{5.995}$$

$$\frac{hi\,(d_i)}{K} = 0.023\,(Re)^{0.8}\,(Pr)^{0.3}$$

h_i = inside –heat transfer coefficient

$$h_i = \frac{0.023\,(33{,}877.6235)^{0.8}\,(5.995)^{0.3}}{0.0157} \times 0.5936$$

$h_i = 5159.4748$ W/m^{2}K

Fouling factor
(Dirt –coefficient) = 0.003 [Ref :1 , p :10-44, t:10-10]

$$\frac{1}{U_0} = \frac{1}{h_o} + \frac{(OD)}{(ID)}\frac{1}{h_i} + \text{Fouling factor} + \text{wall resistance}$$

U_o = overall heat –transfer coefficient

$$\frac{1}{U_0} = \frac{1}{1161.7728} + \frac{0.0191}{0.0157} \times \frac{1}{5159.4748} + 0.003 + 4.0265 \times 10^{-5}$$

$\underline{U_0 = 601.05 \text{ W/m}^2\text{K}}$

$U_0 > U_{assumed}$

(IV) **Pressure Drop Calculations** :

a) Tube Side :

Re = 33877.6235

$f = 0.079\,(Re)^{-1/4} = 0.079\,(33877.6235)^{-1/4} = 0.0058$

f = friction factor

Pressure Drop along the pipe length $(\triangle P)_L = (\triangle H)_L \times \rho \times g$

$$= \frac{4fLVp^2}{2g(ID)} \times \rho \times g$$

$$= \frac{4 \times 0.0058 \times 4.88 \times 1.5116^2 \times 1000 \times 9.81}{2 \times 9.81 \times 0.0157}$$

$$= \underline{4.1062\ KPa}$$

Pressure Drop in the end zones $(\triangle P)_e = \frac{2.5\,\rho\,Vp^2}{2} = \frac{2.5 \times 1000 \times 1.5116^2}{2} = 2.856\ KPa$

Total pressure drop in pipe $(\triangle P)_{total} = [4.1062 + 2.856]2 = \underline{13.92\ KPa} < 70\ KPa$

b) Shell side: Kern's method

Number of baffles =0

$\therefore$ Baffle spacing (B) = 4.88 m

$C^1 = 2.3813 \times 10^{-2} - 0.0191 = \underline{0.00476\ m}$

P_T = pitch = 23.81×10^{-2} m

$$a_{shell} = \frac{\text{shell diameter} \times C^1 \times B}{P_T} = \frac{0.591 \times 0.00476 \times 4.877}{23.8 \times 10^{-3}}$$

$= \underline{0.5768\ m^2}$

$$De = \frac{4\left\{\frac{P_T}{2} \times 0.86\,P_T - \frac{1}{2}\,\frac{\pi}{4}\,(OD)^2\right\}}{\frac{(\pi\, do)}{2}} = \frac{4\left\{\frac{(23.8 \times 10^{-3})^2}{2} \times 0.86 - \frac{\pi}{8}(0.0191)^2\right\}}{\frac{\pi\,(0.0191)}{2}}$$

$= \underline{13.51mm.}$

$$Gs = \text{Superficial velocity in shell} = \frac{m_{shell}}{a_{shell}} = \frac{6.0867}{0.5768} = 10.5522\ kg/m^2s$$

$$(N_{Re})_s = \frac{G_s\, D_c}{\mu} = \frac{610.5522 \times 13.51 \times 10^{-3}}{0.0088 \times 10^{-3}} = 16200.08$$

$f = 1.87\,(16200.08)^{-0.2} = \underline{0.2691}$

∴ Shell side pressure drop

$$(\triangle P)_s = \left[\frac{4\, f\,(N_b + 1) D_s\, Gs^2\ \ g\,]}{2\, g\, De\, \rho_{vapor}}\right] \times 0.5$$

$N_b = 0$

$$\therefore \quad \triangle Ps = \left[\frac{4(0.2691)\,(1)\,(0.591)\,(10.5522)^2\ 9.81}{2 \times 9.81\,(13.51 \times 10^{-3}) \times 2.6997}\right] \times 0.5$$

$= 46.015\ Pa \quad < \quad 14\ Kpa$

(b)Mechanical Design of condenser

(a) Shell Side:

Material carbon steel (Corrosion allowance = 3mm)
Number of shells passes =1

Working pressure = 1 atm = 0.101 N/mm^2
Design pressure = 1.1 x 0.101 = 0.11 N/mm^2
Temperature of the inlet = 82 ^{0}C
Temperature of the outlet = 82 ^{0}C

Permissible Strength for
Carbon steel = 95 N/mm^2 [Ref : 4, p: 115]

b) Tube side :

Number of tubes = 430
Outside diameter = 0.0191m
Inside diameter = 0.0157m
Length = 4.88 m
Pitch, $\triangle^{lar}$ = 15/16 inches = 23.8 x 10^{-3} m
Feed =Water.
Working Pressure =1 atm = 0.101 N/ mm^2
Design Pressure =0.11 N/mm^2
Inlet temperature =30 ^{0}C.
Outlet temperature = 40 ^{0}C

Shell :

$$t_s = \frac{PD_i}{2fJ-P}$$ [Ref:4, pg:13, eq : 3-1]

t_s = Shell thickness
P = design pressure =0.11 N/ mm^2
Di = Inner diameter of shell = 0.591 m =591 mm
f = Allowable stress value = 95 N/mm^2
J= Joint factor = 0.85

$$t_s = \frac{0.11 \times 591}{2 \times 95\ (0.85) - 0.11} = 0.4028 \text{ mm}$$

Minimum thickness = 6.3 mm (Including corrosion allowance)
$\therefore t_s$ = 10 mm

Head : (Torrispherical head)

$t_h = \frac{PR_C W}{2fJ}$ [Ref –3 ; pg: 238]

t_h = thickness of head

$W = ¼\{3+ \sqrt{R_c / R_k}\}$

R_c = Crown radius = outer diameter of shell =1219mm
R_k = knuckle radius = 0.06 R_C

$\therefore W = ¼\{3+ \sqrt{R_c / 0.06 R_c}\}$ = 1.77

$\therefore t_h = \frac{0.11 \times 591 \times 1.77}{2 \times 95 \times 0.85}$ = 0.7125 mm

Minimum shell thickness should be = 10 mm (Ref .7)

$\therefore t_h$ = 10mm

Since for the shell, there are no baffles, tie-rods & spacers are not required.

Flanges :

Loose type except lap-joint flange.
Design pressure (p) =0.11 N/mm^2
Flange material : IS:2004 –1962 class 2
Bolting steel : 5% Cr Mo steel.
Gasket material = Asbestos composition
Shell side diameter =591mm
Shell side thickness =10mm

Outside diameter of shell =591 + 10x 2 = 611mm

Determination of gasket width :

$\frac{d_o}{d_i} = \left[\frac{y - pm}{y - p(m+1)}\right]^{½}$ (Ref :6 Pg:227)

y= Yield stress

m= gasket factor

Gasket material chosen is asbestos with a suitable binder for the operating conditions.
Thickness = 10mm
m= 2.75
y=2.60 x 9.81 = 25.5 N/mm^2

$$\frac{d_o}{d_i} = \left[\frac{25.5 - 0.11\,(2.75)}{25.5 - 0.11\,(2.75+1)} \right]^{1/2} = 1.004$$

d_i = inside diameter of gasket = outside diameter of shell
= 611 + 5mm
=616 mm

d_o = outside diameter of the gasket
= 1.004 (616)
= 619 mm

Minimum gasket width = $\frac{619 - 616}{2}$ = 1.5 mm

But minimum gasket width = 6mm
∴ G= 616 + 2 (0.006) = 0.628 m

G = diameter at the location of gasket load reaction

Estimation of bolt loads :

Load due to design pressure (H) = $\frac{\pi}{4} G^2 P$ [Ref: 4, pg :44]

$H = \frac{\pi}{4} (0.628)^2 \quad (0.11 \times 10^6) = 34072.33$ N

Load to keep the joint tight under operating conditions.

$H_p = \pi\, g\, (2b)\, m\, p$ [Ref: 4, pg :45]

b= Gasket width = 6mm = 0.006m

$H_p = \pi\,(0.628)\,(2 \times 0.006)\, 2.75 \times 0.11 \times 10^6 = 7161.7$ N

Total operating load (W_o) = $H+H_p$
= 41234.03 N

Load to seat gasket under bolt –up condition $=W_g$.

$W_g = \pi g b y$ [Ref: 4, pg :45]

$= \pi \times 0.628 \times 0.006 \times 25.5 \times 10^6$

$W_g = 301856.79$ N

$W_g > W_0$

$\therefore W_g$ is the controlling load
$\therefore$ Controlling load = 301856.79 N

Calculation of minimum bolting area :

Minimum bolting area $(A_m) = A_g = \frac{W_g}{S_g}$ [Ref: 4, pg :45]

S_g = Tensile strength of bolt material (MN/m^2)
Consider , 5% Cr-Mo steel, as design material for bolt

At 82^0C.

$S_g = 138 \times 10^6$ N/m^2 [Ref: 6, pg :108]

$A_m = \frac{301856.79}{138 \times 10^6} = 2.1874 \times 10^{-3}$ m^2

Calculation for optimum bolt size :

$g_1 = \frac{g_o}{0.707} = 1.415 \ g_o$

g_l = thickness of the hub at the back of the flange
g_o = thickness of the hub at the small end = 10+ 2.5 =12.5mm

Selecting bolt size M18x2

R = Radial distance from bolt circle to the connection of hub & back of flange

$R = 0.027$

C = Bolt hole diameter = ID +2 (1.415 g_o + R) [Ref: 6, pg :122]

$C = 0.591 + 2(1.415(0.0125) + 0.027) = 0.6804$ m

Actual flange outside diameter (A) = C+ bolt diameter + minimum left out

= 0.6804 +0.018+ 0.02

= 0.7184 m

Check for gasket width :

A_b = minimum bolt area = 44 x 1.54 x 10^{-4} m^2

$$\frac{A_b S_g}{\pi GN} = \frac{(44 \times 1.54 \times 10^{-4})138}{\pi \times 0.628 \times 0.012} = 39.5 \quad N/mm^2$$ [Ref: 6, pg :123]

$2y = 2 \times 25.5 = 51 \quad N/mm^2$

$$\frac{A_b S_g}{\pi GN} < 2y$$

i.e., bolting condition is satisfied.

Flange Moment calculations : (loose type flange)

(a) For operating conditions : [Ref: 4, pg :113]

$W_Q = W_1 + W_2 + W_3$

$W_1 = \frac{\pi}{4} B^2 P$ = Hydrostatic end force on area inside flange.

$W_2 = H - W_1$

W_3= gasket load = $W_Q - H = H_p$

B= outside shell diameter = 0.611 m

$$W_1 = \frac{\pi}{4} (0.611)^2 \times 0.11 \times 10^6 = 32252.62 \text{ N}$$

$W_2 = H - W_1 = 34072.33 - 32252.62 = 1819.71$ N

$W_3 = 7161.7$ N

$W_o = 32252.62 + 1819.71 + 7161.7$

$= \underline{41234.03}$ N

M_o = Total flange moment = $W_1 a_1 + W_2 a_2 + W_3 a_3$ [Ref: 4, pg :53]

$a_1 = \frac{C - B}{2}$; $a_2 = \frac{a_1 + a_3}{2}$; $a_3 = \frac{C - G}{2}$ [Ref: 4, pg :55]

C=0.6804; B=0.611; G=0.628

$a_1 = \frac{0.6804 - 0.611}{2} = 0.0347$

$a_3 = \frac{C - G}{2} = \frac{0.6804 - 0.628}{2} = 0.0262$

$a_2 = \frac{a_1 + a_3}{2} = \frac{0.0347 + 0.0262}{2} = 0.0305$

$M_o = 32252.62 \times 0.0347 + 1819.71\,(0.0305) + 7161.7\,(0.0262)$

$= \underline{1362.3}$ J

(b) <u>For bolting up condition :</u>

M_g = Total bolting Moment $= W a_3$ [Ref: 4, pg :56, eq: 4.6]

$W = \frac{(A_m + A_b)}{2} S_g$. [Ref: 4, pg :56, eq: 4.6]

$A_m = 2.1874 \times 10^{-3}\ m^2$

$A_b = 44 \times 1.5\ 4 \times 10^{-4} = 67.76 \times 10^{-4}\ m^2$

$S_g = 138 \times 10^6$

$W = \left(\frac{2.1874 \times 10^{-3} + 67.76 \times 10^{-4}}{2}\right) \times 138 \times 10^6 = \underline{618474.6}$

$M_g = 0.6185 \times 10^6 \times 0.0262 = \underline{16204.03\ J}$

$\underline{M_g > M_o}$

$\therefore M_g$ is the moment under operating conditions

$M = M_g = 16204.03$ J

Calculation of the flange thickness:

$$t^2 = \frac{MC_FY}{BS_{FO}}$$ [Ref: 6, eq:7.6.12]

C_F= Bolt pitch correction factor = $\sqrt{B_s / (2d + t)}$ [Ref: 4, pg:43]

B_s = Bolt spacing = $\frac{\pi C}{n} = \frac{\pi(0.6804)}{44} = 0.0486$ m

n= number of bolts.

Let $C_F = 1$

S_{FO} = Nominal design stresses for the flange material at design temperature.

$S_{FO} = 100 \times 10^6$ N (Ref : 6, pg : 24)

$M = 0.016 \times 10^6$ J

B = 0.611

$K = \frac{A}{B} = \frac{\text{Flange diameter}}{\text{Inner Shell diameter}} = \frac{0.7184}{0.611} = 1.1758$

Y = 24 (Ref : 6, pg : 115, fig:7.6).

$$t = \sqrt{\frac{0.016 \times 10^6 \times 1 \times 24}{0.611 \times 100 \times 10^6}} = \underline{0.0798 \text{ m}}$$

d = 18 x 2 = 36mm

$$C_F = \sqrt{\frac{0.0486}{2(36 \times 10^{-3}) + 0.0798}} = \underline{0.5659}$$

$C_F^{1/2} = 0.7522$

t = 0.0798 x 0.7522 = $\underline{0.06 \text{ m}}$

Let t = 60mm = $\underline{0.06\text{m}}$

Tube sheet thickness : (Cylindrical Shell) .

$T_{1s} = G_c \sqrt{KP / f}$ (Ref :3, pg : 249, e.g. : 9.9)

G_c = mean gasket diameter for cover.
P = design pressure.
K = factor = 0.25 (when cover is bolted with full faced gasket)
F = permissible stress at design temperature.

$t_{1s} = 0.628 \sqrt{(0.25 \times 0.11 \times 10^6) / (95 \times 10^6)}$ = $\underline{0.0107}$ m

Channel and channel Cover

$t_h = G_c \sqrt{(KP/f)}$ (K = 0.3 for ring type gasket)

$= 0.628 \sqrt{(0.3 \times 0.11/ 95)}$

= 0.0117 m =11.7mm

Consider corrosion allowance = 4 mm.

t_h=0.004 + 0.0117 = 0.0157 m.

Saddle support

Material: Low carbon steel

Total length of shell: 4.88 m

Diameter of shell: 0.611 m

Knuckle radius = 0.06 x 0.611 = 0.0367 m = r_o

Total depth of head (H)= $\sqrt{(D_o r_o/2)}$

$= \sqrt{(0.611 \times 0.0367/2)}$

= 0.106 m

Weight of the shell and its contents = 3464.73 kg = W

R=D/2=305.5 mm

Distance of saddle center line from shell end = A =0.5R=0.15 m.

Longitudinal Bending Moment

M_1 = QA[1-(1-A/L+(R^2-H^2)/(2AL))/(1+4H/(3L))]

Q = W/2(L+4H/3)

= 3464.73 (4.88 + 4 x 0.106/3)/2

= 8698.78 kg m

M_1=8698.78 x 0.1528 [1-(1-0.1528/4.88+(0.3055^2-0.106^2)/(2x4.88 x 0.1528))/(1+4x0.106/(3x4.88))]

= 6.75 kg-m

Bending moment at center of the span

M_2 = QL/4[(1+2(R^2-H^2)/L)/(1+4H/(3L))-4A/L]

M_2 =9462.84 kg-m

Stresses in shell at the saddle

(a) At the topmost fibre of the cross section

$f_1 = M_1/(k_1\pi R^2 t)$ $k_1=k_2=1$

=6.75/(3.14 x 0.3055^2 x 0.008)

= 2877.67 kg/m^2 = 0.2877 kg/cm^2

The stresses are well within the permissible values.

Stress in the shell at mid point

$f_2 = M_2/(k_2\pi R^2 t)$

= 4034216.563 kg/m^2

Axial stress in the shell due to internal pressure

f_p= PD/4t

= 0.11 x 10^6 x 0.591 /(4 x 0.008)

$= 2031562.5 \text{ kg/m}^2$

$f_2 + f_p = 6065779.13 \text{ kg/m}^2 = 606.6 \text{ kg/cm}^2$

The sum of f_2 and f_p is well within the permissible values.