5.1 DESIGN OF DISTILLATION COLUMN

Process design of distillation column for the separation of Monoethanolamine and Water is given as below. Feed entering the column consist of amine mixture and water. Boiling points of the compounds entering the column at operating pressure i.e. 1atmosphere are:

Monoethanolamine	172.2°C
Diethanolamine	270°C
Triethanolamine	360°C
Water	100°C

Hence the boiling temperature difference between water and DEA,TEA is very large, so it is assumed that the DEA and TEA entering the tower directly go into the residue without vaporization. Hence the separation is done between MEA and water. Hence feed entering is taken as only water and MEA.

Terminology:

Some of the terms used in the following calculation are defined here as follows:

F = Flow rate of Feed, Kg/day.

D = Molar flow rate of Distillate, Kg/day.

W = Molar flow rate of Residue, Kg/day.

x_F = mole fraction of water in feed.

y_D = mole fraction of Water in Distillate.

x_W = mole fraction of Water in Residue.

M_F = Average Molecular weight of Feed, Kg/kmol

M_D = Average Molecular weight of Distillate, Kg/kmol

M_W = Average Molecular weight of Residue, Kg/kmol

R_m = Minimum Reflux ratio

R = Actual Reflux ratio

L = Molar flow rate of Liquid in the Enriching Section, kmol/day.

G = Molar flow rate of Vapor in the Enriching Section, kmol/day.

$\overline{L}$ = Molar flow rate of Liquid in Stripping Section, kmol/day.

$\overline{G}$ = Molar flow rate of Vapor in Stripping section, kmol/day.

q = Thermal condition of Feed

ρ_L = Density of Liquid, kg/m^3.

ρ_V = Density of Vapor, kg/m^3.

q_L = Volumetric flow rate of Liquid, m^3/s

q_V = Volumetric flow rate of Vapor, m^3/s

μ_L = Viscosity of Liquid, cP.

T_L = Temperature of Liquid, K.

T_V = Temperature of Vapor, K.

5.11 PRELIMINARY CALCULATIONS:

Basis: One-day operation.

F = 349500.0 Kg/day x_F = 0.57 (wt%) = 0.82 (mol%)

D = 197480 Kg/day x_D = 0.99 (wt%) = 0.997 (mol%)

W = 152020.0 Kg/day x_W = 0.0262 (wt%) = 0.084 (mol%)

Here the liquid entering the tower is coming from the of ammonia flash, it is assumed that vapor and liquid leaving are in equilibrium. Hence the feed entering is saturated. From T,x,y diagram:

T^{o}C	100	105	110	115	120	125	130	135	140	145	155	165	170
x,wt%	0.0	0.35	0.5	0.6	0.68	0.74	0.78	0.825	0.86	0.88	0.93	0.97	1.0
y,wt%	0.0	0.025	0.05	0.075	0.125	0.18	0.25	0.32	0.4	0.475	0.70	0.90	1.0

From the graph: intercept of enriching section operating line for minimum reflux is obtained from the graph, is given by:

$$x_D / (R_m+1) = 0.925$$

$$R_m+1= x_D/ 0.925 = 0.99/ 0.925$$

$$\boxed{R_m = 0.0656}$$

Let $R = 1.5 \times R_m$

Therefore, $R = 1.5 \times 0.0656 = 0.1$

Number of Ideal trays = 6 (excluding the reboiler).

Number of Ideal trays in Enriching Section = 3

Number of Ideal trays in Stripping Section = 3

Now, we know that,

$$R = L_o / D$$

$$\Rightarrow \quad Lo = R \times D$$

i.e., $L_o = 19748.0$ Kg/day

i.e., $L_o = 1089$ kmol/day

Since feed is Liquid, entering at bubble point i.e. saturated liquid.

Hence $\quad q = (H_V - H_F) / (H_V - H_L) = 1$

We know that slope of q-line $= q/(q-1) = \infty$

Hence q line is vertical. Liquid flow rate in the stripping section is given by

$$\bar{L} = F \times q + L$$

i.e., $\bar{L} = 14629.0$ kmoles/day

Also, we know that,

$$\bar{G} = [(q-1) \times F] + G$$

i.e., $\bar{G} = [(1-1) \times F] + G$

i.e., $\bar{G} = [0 \times F] + G$

i.e., $\bar{G} = 0 + G$

$$\bar{G} = G$$

Now, we know that,

$G = L + D$

i.e., $G = L_o + D$

i.e., G = 1089+ 10893.7 kmol/day

i.e., G = 11982.7 kmol/day.

Since the liquid entering the tower is saturated gas flow rate in both the section is same. Hence the flow rate in the stripping section is:

$\bar{G} = G =$ 11982.7 kmol/day

Parameters at the top and at the bottom of the enriching as well as stripping section.

PROPERTY	ENRICHING SECTION		STRIPPING SECTION	
	TOP	BOTTOM	TOP	BOTTOM
Liquid,L kg/day	19742.7	27174	420876.0	840601.0
Vapor,G kg/day	217055.9	246455.6	254192.4	687966.0
Liquid, L kmol/day	1089.0	1089.0	14629.0	14629.0
Vapor, G kmol/day	11982.0	11982.7	11982.7	11982.7
x (mol%)	0.997	0.8386	0.75	0.084
y (mol%)	0.997	0.98	0.925	0.084
$M_{avg.liquid}$ kg/kmol	18.13	24.9	28.76	57.46
$M_{avg.Vapor}$ kg/kmol	18.11	20.56	21.21	57.41
Density, ρ_l kg/m^3	956.97	979.8	987.8	1014.15
Density, ρ_g kg/m^3	0.58	0.64	0.637	1.565
T_{liquid}, ^{0}C	100	106	112	163
T_{vapor}, ^{0}C	102	112	127	168
σ dynes/cm	26.059	26.059	26.059	26.14
$(L/G)(\rho_g/\rho_l)^{0.5}$	0.00223	**0.00281**	0.042	**0.0479**

5.12 DESIGN OF ENRICHING SECTION

Tray Hydraulics

Sieve tray column is designed for the separation of the MEA and water.

1. **Plate Spacing, (t_s) :** Range can be selected is 0.15 to 1 m.

   Let t_s = 500 mm.

2. **Hole Diameter, (d_h):**

   Let d_h = 5 mm is within the range of 2.5 to 12 mm.

3. **Hole Pitch (l_p):**

   Range for the selection of hole pitch is 2.5 to 4 times hole diameter.

   Let $l_p = 3\times d_h$

   i.e., $l_p = 3\times5 = 15$ mm

4. **Tray thickness (t_T):**

   Let $t_T = 0.6\times d_h$

   i.e., $t_T = 0.6\times5 = 3$ mm.

5. **Ratio of hole area to perforated area (A_h/A_p):**

   Triangular pitch is selected.

   Ratio of hole area to perforated area $(A_h/A_p) = ½\ (\pi/4\times d_h^2)/\ [(\sqrt{3}/4)\times l_p^2]$

   i.e., $(A_h/A_p) = 0.90\times (d_h/l_p)^2$

   i.e., $(A_h/A_p) = 0.90\times (5/15)^2$

   i.e., $(A_h/A_p) = 0.1$

6. **Plate Diameter (D_c):**

   The plate diameter is calculated based on the flooding considerations

   $L/G\ \{\rho_g/\rho_l\}^{0.5} = 0.00281$ ---------- (maximum value)

   (From fig. 18.10 p-18-7 Perry hand book 6th edition)

   $L/G\ \{\rho_g/\rho_l\}^{0.5} = 0.00281$ and for a tray spacing of 500 mm.

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

   From eq^{n}. 18.2, page 18.6, 6th edition Perry hand book

   $$U_{nf} = C_{sb,\ flood} \times (\sigma / 20)^{0.2} [(\rho_l - \rho_g) / \rho_g]^{0.5}$$

where,

U_{nf} = gas velocity through the net area at flood, m/s (ft/s)

$C_{sb, flood}$ = capacity parameter, m/s (ft/s, as in fig.18.10)

σ = liquid surface tension, mN/m (dyne/cm.)

ρ_l = liquid density, kg/m^3 (lb/ft^3)

ρ_g = gas density, kg/m^3 (lb/ft^3)

Now, we have,

σ = 26.059 mN/m = 26.059 dyne/cm.

ρ_l = 979.8 kg/m^3.

ρ_g = 0.64 kg/m^3.

Hence

$U_{nf} = 0.28\times (26.059/20)^{0.2}\times [(979.8-0.64)/ 0.64]^{0.5}$

i.e., U_{nf} = 11.95 ft/s = 3.58 m/s.

Let

Actual velocity, $U_n = 0.8\times U_{nf}$

U_n = 2.864 m/s

Volumetric flow rate of Vapor at the bottom of the Enriching Section

= q_o = 246455.6 / (3600×24×0.6) = 4.45 m^3/s.

Net area available for gas flow (A_n)

Net area = (Column cross sectional area) - (Downcomer area.)

$A_n = A_c - A_d$

Thus,

Net Active area, $A_n = q_o/ U_n$ = 4.45/ 2.864 = 1.55 m^2.

Let L_w / D_c = 0.75 is in the range of 0.6 to 0.85

Where, L_w = weir length, m

D_c = Column diameter, m

Now,

$\Theta_c = 2\times\sin^{-1}(L_w / D_c) = 2\times\sin^{-1}(0.75) = 97.18^0$

Column cross sectional area

$A_c = (\pi/4) \times D_c^2 = 0.7854 \times D_c^2$, m^2

$A_d = [(\pi/4) \times Dc^2 \times (\theta c/360^0)]$ - $[(Lw/2) \times (Dc/2) \times \cos(\theta c/2)]$

i.e., $A_d = [0.7854\times Dc^2 \times (97.18^0/360^0)]-[(1/4) \times (L_w / D_c) \times D_c^2 \times \cos(97.18^0)]$

i.e., $A_d = (0.2120\times D_c^2) - (0.1241\times D_c^2)$

i.e., $A_d = 0.088\times D_c^2$, m^2

Since An = Ac -Ad

$1.55 = (0.7854- 0.088)\times Dc^2$

Therefore $D_c^2 = 2.22\ m^2$

$D_c = 1.49$ m

$\Rightarrow L_w = 0.75\times D_c = 1.1175$ m.

Taking , $L_w = 1.12$ m.

then

$A_c = 0.7854\times1.49^2 = 1.743\ m^2$

$A_d = 0.0879\times D_c^2 = 0.088\times1.49^2 = 0.1953\ m^2$

7. Perforated plate area (A_p):

$A_a = Ac - (2\times A_d)$

i.e., $A_a = 1.743- (2\times0.1953)$

$A_a = 1.56\ m^2$

We have,

$L_w / D_c = 0.75$

$\Theta_c = 97.18\ ^0$

$\alpha = 180\ ^0 - \Theta_c$

i.e., $\alpha = 82.82\ ^0$

Area of distribution and calming zone (A_{cz})

$A_{cz} = 2\times L_w\times$ (thickness of distribution)

$A_{cz} = 2\times1.12\times (60\times10^{-3}) = 0.1344\ m^2$ -------- (which is 7.71% of A_c)

Area of waste peripheral zone (A_{wz})

Taking thickness as 12 cm.

$$A_{wz} = \{(\pi/4) \times D_c^2 \times (\alpha/360^0)\} - \{(\pi/4) \times (D_c - 0.12)^2 \times (\alpha/360^0)\}$$

$$\text{i.e., } A_{wz} = \{(\pi/4) \times 1.49^2 \times (82.82^0/360^0)\}$$

$$- \{(\pi/4) \times (1.49-0.12)^2 \times (82.82^0/360^0)\}$$

i.e., $A_{wz} = 0.0618\ m^2$ is 3.5 % of A_c. Which is acceptable.

Perforated area

$$A_p = A_c - (2 \times A_d) - A_{cz} - A_{wz}$$

$$\text{i.e., } A_p = 1.743 - (2 \times 0.1953) - 0.1344 - 0.0618$$

Thus, $A_p = 1.3708\ m^2$

8. Total Hole Area (A_h):

$$A_h / A_p = 0.1$$

$$A_h = 0.1 \times A_p$$

Total hole area

$$A_h = 0.13708\ m^2$$

Now we know that,

$$A_h = n_h \times (\pi/4) \times d_h^2$$

Where n_h = number of holes.

$$n_h = (4 \times A_h) / (\pi \times d_h^2)$$

$$\text{i.e., } n_h = (4 \times 0.13708) / (\pi \times 0.005^2)$$

$$n_h = 6980.5$$

Therefore, Number of holes = 6981

9. Weir Height (h_w):

For normal pressure h_w lies between 40 and 50 mm.

Let $h_w = 50$ mm.

10. Weeping Check

The static pressure below the tray should be capable of enough to hold the liquid above the tray so that no liquid fall through the hole.

Head loss through dry hole

$h_d = k_1 + [k_2 \times (\rho_g/\rho_l) \times U_h^2]$ --------- (eq$^{n.}$ 18.6, page 18.9, 6th edition Perry)

where h_d = head loss across the dry hole

U_h =gas velocity through hole area

k_1, k_2 are constants

For sieve plates $k_1 = 0$ and

$k_2 = 50.8 / (C_v)^2$

where C_v = discharge coefficient, taken from fig. edition 18.14, page 18.9 6th Perry).

$(A_h/A_a) = 0.8075$ and ratio of tray thickness to hole diameter

$t_T/d_h = 0.60$

For above values of (A_h/A_a) and t_T/d_h, from fig. edition 18.14, page 18.9 6th Perry. We get

$C_v = 0.74$

And hence $k_2 = 50.8 / 0.74^2 = 92.76$

Volumetric flow rate of Vapor at the top of the Enriching Section

$q_t = 217055.9/ (3600\times24\times0.58) = 4.33\ m^3/s$ -------- (minimum at top)

Volumetric flow rate of Vapor at the bottom of the Enriching Section

$q_o = 5762.3938 / (3600\times24\times0.64) = 4.45\ m^3/s$. ---- (maximum at bottom)

Velocity through the hole area (U_h):

Velocity through the hole area at the top = $U_{h,\ top} = q_t / A_h = 4.33/0.13708$

$=31.59$ m/s

Velocity through the hole area at the bottom= $U_{h,\ bottom} = q_o / A_h$

$= 4.45/0.13708$

$= 32.46$ m/s

Now,

$h_{d,\,top} = k_2\, [\rho_g/\rho_l]\, (U_{h,top})^2$

$= 92.76\times(0.58/956.97)\times 31.59^2$

Therefore $h_{d,\,top}$ = 56.1 mm clear liquid. -------- (minimum at top)

$h_{d,\,bottom} = k_2\, [\rho_g/\rho_l]\, (U_{h,\,bottom})^2$

$= 92.76\times(0.64/979.8)\times 32.46^2$

$\Rightarrow$ $h_{d,\,bottom}$ = 63.84 mm clear liquid ----- (maximum at bottom)

Head Loss Due to Bubble Formation

$h_\sigma = 409\, [\sigma / (\rho_L \times d_h)]$ …………($eq^{n.}$ 18.2a, page 18.7, 6th edition Perry)

where σ =surface tension, mN/m (dyne/cm)

d_h =Hole diameter, mm

ρ_l = density of liquid in the bottm section, kg/m^3

=979.8 kg/m^3

$h_\sigma = 409\, [\, 26.059 / (\, 979.8 \times 5)]$

h_σ = 2.17 mm clear liquid

Height of Liquid Crest over Weir:

$h_{ow} = 664\times F_w\, [(q/L_w)^{2/3}]$

q = liquid flow rate at top, m^3/s

$= 2.387\times10^{-4}$ m^3/s

Thus, q' = 3.785 gal/min.

L_w = weir length = 1.12 m = 3.674 ft

$q'/L_w^{2.5} = 3.785/(3.674)^{2.5} = 0.146$

For $q'/L_w^{2.5} = 0.146$ and $L_w/D_c = 0.75$

We have from fig.18.16, page 18.11, 6th edition Perry

F_w= correction factor =1.0

Thus, $h_{ow} = 1.0 \times 664 \times [(2.387 \times 10^{-4})/1.12]^{2/3}$

$h_{ow} = 2.4$ mm

$(h_d + h_\sigma) = 63.84 + 2.17 = 66.01$ mm (Design value)

$(h_w + h_{ow}) = 50 + 2.4 = 52.4$ mm

The minimum value of $(h_d + h_\sigma)$ required is calculated from a graph given in Perry, plotted against A_h/A_a.

From fig. 18.11, page 18.7, 6th edition Perry hand book

for $A_h/A_a = 0.0875$ and $(h_w + h_{ow}) = 50 + 2.4 = 52.4$ mm

We get

$(h_d + h_\sigma)_{min} = 17$ mm (Theoretical value)

Design value of sum of head loss through dry hole and loss due to bubble formation more than the theoretically required value to avoid weeping. Hence is there is no problem with weeping.

Downflow Flooding: (eq^n 18.3, page 18.7, 6th edition Perry)

$h_{dc} = h_w + h_{ow} + (h_{hg}/2) + h_t + h_{da}$ ------- (eq^n 18.3, page 18.7, 6th edition Perry)

where,

h_w = weir height, mm = 50 mm

h_{ds} = static slot seal (weir height minus height of top of slot above plate floor, height equivalent clear liquid, mm)

h_{ow} = height of crest over weir, equivalent clear liquid, mm

h_{hg} =hydraulic gradient across the plate, height of equivalent clear liquid, mm

h_{da}= head loss over downcomer apron, mm liquid

h_t= total pressure across plate, mm liquid

In the above equation h_{ow} is calculated at bottom of the section and since the tower is operating at atmospheric pressure, h_{hg} is very small for sieve plate and hence neglected.

Calculation of h_{ow} at bottom conditions of the section:

q = liquid rate at the bottom of the section, m^3/s

$= 27174/(360\times24\times979.9) = 3.209\times10^{-4}\ m^3/s$

Thus, q' = 5.086 gal/min

L_w = weir length = 1.12 m = 3.674 ft.

$q'/L_w^{2.5} = 0.196$

For $q'/L_w^{2.5} = 0.196$ and $L_w/D_c = 0.75$

From fig.18.16, page 18.11, 6th edition Perry

F_w= correction factor =1.0

$h_{ow} = 1.0\times664\times [(3.209\times10^{-4})/1.12]^{2/3}$

h_{ow} = 2.88 mm clear liquid. ----- (maximum at the bottom of section).

Therefore,

$h_{ds} = h_w + h_{ow} + (h_{hg}/2)$

= 52.88 mm.

Now, $F_{ga} = U_a \times \rho_g^{0.5}$

Where F_{ga} = gas-phase kinetic energy factor,

U_a = superficial gas velocity, m/s (ft/s),

ρ_g = gas density, kg/m^3 (lb/ft^3)

Here U_a is calculated at the bottom of the section.

Thus, $U_a = (G_b/\rho_g)/ A_a = (246455.6/3600\times24\times0.64) / (1.567) = 2.84$ m/s

$\rho_g = 0.64\ kg/m^3$

$= 0.0082\ lb/ft^3$

Therefore, $F_{ga} = 2.84\times (0.0082)^{0.5}$

$F_{ga} = 0.813$

From fig. 18.15, page 18.10 6th edition Perry for $F_{ga} = 0.813$

Aeration factor = β = 0.58

Relative Froth Density = ϕ_t = 0.2

Now $h_l' = \beta \times h_{ds}$ ---- (eq$^{n.}$ 18.8, page 18.10, 6th edition Perry)

Where, h_l' = pressure drop through the aerated mass over and around the disperser, mm liquid,

$\Rightarrow h_l' = 30.67$ mm.

$h_t = h_d + h_l`$

$h_t = 96.68$ mm

Head loss over downcomer apron:

$h_{da} = 165.2 \{q/ A_{da}\}^2$ ----- (eq$^{n.}$ 18.19, page 18.10, 6th edition Perry)

where, h_{da} = head loss under the downcomer apron, as millimeters of liquid,

q = liquid flow rate calculated at the bottom of section, m^3/s

and A_{da} = minimum area of flow under the downcomer apron, m^2

Now,

$q = 3.209 \times 10^{-4}\ m^3/s$

Assuming clearance as C= 25mm

$h_{ap} = h_{ds} - C = 52.88-25 = 27.88$ mm

$A_{da} = L_w \times h_{ap} = 1.12 \times 27.88 \times 10^{-4}$

$= 0.0312 m^2$

Therefore $h_{ad} = 165.2 \times (3.209 \times 10^{-4}/0.0312)^2$

$h_{ad} = 0.0175$mm

Therefore

$h_{dc} = 50+2.88+0.0175+96.68$

$=149.57$ mm

Average froth density is assumed as 0.5.

$h_{dc}' = h_{dc}/\phi_{dc}$

$= 149.57/0.5$

$h_{dc}' = 299.14$ mm< 500 mm (tray spacing)

Hence tray spacing given is sufficient, and the design of enriching section is acceptable.

5.13 DESIGN OF STRIPPING SECTION

Plate hydraulics:

1. tray spacing t_s = 500 mm
2. hole diameter d_h = 5 mm
3. Hole pitch l_p = 15 mm
4. Tray thickness t_T = 3 mm
5. Holes arrangement triangular pitch

Column diameter:

$L/G \{\rho_g/\rho_l\}^{0.5} = 0.0479$ maximum at the bottom.

(From fig. 18.10 p-18-7 Perry hand book 6th edition)

$L/G \{\rho_g/\rho_l\}^{0.5} = 0.0479$ and for a tray spacing of 500 mm.

Flooding parameter, $C_{sb,\ flood} = 0.28$ ft/s

From eqn. 18.2, page 18.6, 6th edition Perry hand book

$$U_{nf} = C_{sb,\ flood} \times (\sigma / 20)^{0.2} [(\rho_l - \rho_g) / \rho_g]^{0.5}$$

where,

U_{nf} = gas velocity through the net area at flood, m/s (ft/s)

$C_{sb,\ flood}$ = capacity parameter, m/s (ft/s, as in fig.18.10)

σ = liquid surface tension, mN/m (dyne/cm.)

ρ_l = liquid density, kg/m^3 (lb/ft^3)

ρ_g = gas density, kg/m^3 (lb/ft^3)

Now, we have,

σ = 26.059 mN/m = 26.059 dyne/cm.

ρ_l = 1014.15 kg/m^3.

ρ_g = 1.565 kg/m^3.

Hence

$$U_{nf} = 0.28 \times (26.059/20)^{0.2} \times [(1014.15-1.565)/ 1.565]^{0.5}$$

i.e., U_{nf} = 7.509 ft/s.

Let

Actual velocity, $U_n = 0.8 \times U_{nf}$

$U_n = 1.83$ m/s

Volumetric flow rate of Vapor at the bottom of the Enriching Section

$= q_o = 687966 / (3600\times24\times1.565) = 5.087\ m^3/s.$

Net area available for gas flow (A_n)

Net area = (Column cross sectional area) - (Downcomer area.)

$A_n = A_c - A_d$

Thus,

Net Active area, $A_n = q_o / U_n = 5.087 / 1.83 = 2.779\ m^2$.

Let $L_w / D_c = 0.75$ is in the range of 0.6 to 0.85

Where, L_w = weir length, m

D_c = Column diameter, m

Now,

$\Theta_c = 2\times\sin^{-1}(L_w / D_c) = 2\times\sin^{-1}(0.75) = 97.18^0$

Column cross sectional area

$A_c = (\pi/4) \times D_c^2 = 0.7854\times D_c^2$, m^2

$A_d = [(\pi/4) \times Dc^2 \times (\theta c/360^0)] - [(Lw/2) \times (Dc/2) \times \cos(\theta c/2)]$

i.e., $A_d = [0.7854\times Dc^2 \times (97.18^0/360^0)]-[(1/4) \times (L_w/D_c)\times D_c^2\times \cos(97.18^0)]$

i.e., $A_d = (0.2120\times D_c^2) - (0.1241\times D_c^2)$

i.e., $A_d = 0.088\times D_c^2$, m^2

Since An = Ac -Ad

$2.779 = (0.7854 - 0.088)\times Dc^2$

Therefore$D_c^2 = 3.987\ m^2$

$D_c = 1.99$ m

Since $L_w / D_c = 0.75$,

$L_w = 1.49$ m.

Then

$A_c = 0.7854\times1.99^2 = 3.11\ m^2$

$A_d = 0.0879 \times D_c^2 = 0.088 \times 1.99^2 = 0.331\ m^2$

$A_a = A_c - 2 \times A_d = 2.448\ m^2$

7. Perforated plate area (A_p):

We have,

$L_w / D_c = 0.75$

$\Theta_c = 97.18^0$

$\alpha = 180^0 - \Theta_c$

i.e., $\alpha = 180^0 - 97.18^0$

$\alpha = 82.82^0$

Area of distribution and calming zone (A_{cz})

$A_{cz} = 2 \times L_w \times$ (thickness of distribution)

Thickness is taken as 80 mm

$A_{cz} = 2 \times 1.49 \times (80 \times 10^{-3}) = 0.2388 m^2$ -------- (which is 7.6% of A_c)

Area of waste peripheral zone (A_{wz})

Taking thickness as 15 cm.

$A_{wz} = \{(\pi/4) \times D_c^2 \times (\alpha/360^0)\} - \{(\pi/4) \times (D_c - 0.15)^2 \times (\alpha/360^0)$

i.e., $A_{wz} = 0.1038\ m^2$ is 3.34 % of A_c. Which is acceptable.

Perforated area

We have,

$A_p = A_c - (2 \times A_d) - A_{cz} - A_{wz}$

$A_p = 2.1054\ m^2$

8. Total Hole Area (A_h):

$A_h / A_p = 0.1$

$A_h = 0.1 \times A_p$

Total hole area

$A_h = 0.21054\ m^2$

Now we know that,

$A_h = n_h \times (\pi/4) \times d_h^2$

Where n_h = number of holes.

$\Rightarrow \quad n_h = 10726.11$

Therefore, Number of holes = 10726

9. Weir Height (h_w):

For normal pressure h_w lies between 40 and 50 mm.

Let h_w = 50 mm.

10. Weeping Check

The static pressure below the tray should be capable of enough to hold the liquid above the tray so that no liquid fall through the hole.

Head loss through dry hole

$h_d = k_1 + [k_2 \times (\rho_g/\rho_l) \times U_h^2]$ --------- ($eq^{n.}$ 18.6, page 18.9, 6^{th} edition Perry)

where h_d = head loss across the dry hole

U_h =gas velocity through hole area

k_1, k_2 are constants

For sieve plates $k_1 = 0$ and

$k_2 = 50.8 / (C_v)^2$

where C_v = discharge coefficient, taken from fig. edition 18.14, page 18.9 6^{th} Perry).

$(A_h/A_a) = 0.2105/ 2.448 = 0.085$ and ratio of tray thickness to hole diameter

$t_T/d_h = 3/5 = 0.60$

For above values of (A_h/A_a) and t_T/d_h, from fig. edition 18.14, page 18.9 6^{th} Perry.

We get

$C_v = 0.74$

And hence $\quad k_2 = 50.8 / 0.74^2 = 92.76$

Volumetric flow rate of Vapor at the top of the stripping Section

$q_t = 254192.4/ (3600\times24\times0.637) = 4.618\ m^3/s$ -------- (minimum at top)

volumetric floe rate of vapor at the bottom of stripping section

q_b=687966.0/(24×3600×1.565) = 5.087

Velocity through the hole area (U_h):

Velocity through the hole area at the top = $U_{h, top} = q_t / A_h$ = 4.618/0.2105

=21.94 m/s

Velocity through the hole area at the bottom= $U_{h, bottom} = q_o / A_h$

= 5.087/0.2105

= 24.17 m/s

Now,

$$h_{d, top} = k_2 [\rho_g/\rho_l] (U_{h,top})^2$$

$$= 95.32\times(0.637/987.9) \times 21.94^2$$

Therefore $h_{d, top}$ = 29.58 mm clear liquid. -------- (minimum at top)

Also

` $h_{d, bottom} = k_2 [\rho_g/\rho_l] (U_{h, bottom})^2$

$$= 92.76\times(1.565/1014.15) \times 24.17^2$$

$\Rightarrow$ $h_{d, bottom}$ = 85.93 mm clear liquid ----- (maximum at bottom)

Head Loss Due to Bubble Formation

$h_\sigma = 409 [\sigma / (\rho_{L\times} d_h)]$ …………($eq^{n.}$ 18.2a, page 18.7, 6^{th} edition Perry)

where σ =surface tension, mN/m (dyne/cm)

d_h =Hole diameter, mm

ρ_l = density of liquid in the bottom section, kg/m^3

=1014.15 kg/m^3

h_σ = 409 [26.14 / (1014.15 x 5)]

h_σ = 2.11 mm

Height of Liquid Crest over Weir:

$$h_{ow} = 664\times F_w [(q/L_w)^{2/3}]$$

q = liquid flow rate at top, m^3/s

= 420876/ (360×24×987.9)

$q = 4.93\times10^{-3}\ m^3/s$

Thus, $q' = 78.16$ gal/min.

L_w = weir length = 1.49 m = 4.88 ft

$q'/L_w^{2.5} = 78.16/(4.88)^{2.5} = 1.47$

For $q'/L_w^{2.5} = 1.47$ and $L_w/D_c = 0.75$

We have from fig.18.16, page 18.11, 6th edition Perry

F_w= correction factor =1.01

Thus, $h_{ow} = 1.01\times664\times[(4.93\times10^{-4})/1.492]^{2/3}$

$h_{ow} = 14.87$ mm

$(h_d + h_\sigma) = 29.58 + 2.11 = 31.69$ mm (Design value)

$(h_w + h_{ow}) = 50 + 14.87 = 64.87$mm

The minimum value of $(h_d + h_\sigma)$ required is calculated from a graph given in Perry, plotted against A_h/A_a.

From fig. 18.11, page 18.7, 6th edition Perry hand book

for $A_h/A_a = 0.085$ and $(h_w + h_{ow}) = 50 + 14.87 = 64.87$ mm

we get

$(h_d + h_\sigma)_{min} = 18$ mm (Theoretical value) < 31.69 i.e. design value

Design value of sum of head loss through dry hole and loss due to bubble formation more than the theoretically required value to avoid weeping. Hence is there is no problem with weeping.

Downflow Flooding: (eq^n 18.3, page 18.7, 6th edition Perry)

$h_{dc} = h_w + h_{ow} + (h_{hg}/2) + h_t + h_{da}$ ------- (eq^n 18.3, page 18.7, 6th editionPerry)

Where,

h_w = weir height, mm = 50 mm

h_{ds} = static slot seal (weir height minus height of top of slot above plate floor, height equivalent clear liquid, mm)

h_{ow} = height of crest over weir, equivalent clear liquid, mm

h_{hg} = hydraulic gradient across the plate, height of equivalent clear liquid, mm.

h_{da}= head loss over downcomer apron, mm liquid

h_t= total pressure across plate, mm liquid

In the above equation h_{ow} is calculated at bottom of the section and since the tower is operating at atmospheric pressure, h_{hg} is very small for sieve plate and hence neglected.

Calculation of h_{ow} at bottom conditions of the section:

q = liquid rate at the bottom of the section, m^3/s

= $840601.0/(360\times24\times1014.15) = 9.59\times10^{-3}\ m^3/s$

Thus, q' = 158.85 gal/min

L_w = weir length = 1.49 m = 4.88 ft.

$q'/L_w^{2.5} = 158.85/\ (4.88)^{2.5} = 8.648$

now for $q'/L_w^{2.5} = 8.647$ and L_w/D_c =0.75

we have from fig.18.16, page 18.11, 6th edition Perry

F_w= correction factor =1.07

Thus, $h_{ow} = 1.07\times664\times [(9.59\times10^{-3})/1.49]^{2/3}$

$\Rightarrow$ h_{ow} = 24.58 mm clear liquid. ----- (maximum at the bottom of section).

Therefore, $h_{ds} = h_w + h_{ow} + (h_{hg}/2)$ =50 +24.58

= 74.58 mm. since h_{hg} is neglected.

Now, $F_{ga} = U_a \times \rho_g^{0.5}$

Where F_{ga} = gas-phase kinetic energy factor,

U_a = superficial gas velocity, m/s (ft/s),

ρ_g = gas density, kg/m^3 (lb/ft^3)

Here U_a is calculated at the bottom of the section.

Thus, $U_a = (G_b/\rho_g)/\ A_a = (687966/(3600\times24\times1.565))\ /\ (2.448) = 2.078$ m/s

$\rho_g = 1.565\ kg/m^3 = 0.0201\ lb/ft^3$

Therefore, $F_{ga} = 2.078\times (0.0201)^{0.5}$

$F_{ga} = 0.966$

From fig. 18.15, page 18.10 6th edition Perry for $F_{ga} = 0.966$

Aeration factor = β = 0.66

Now $h_l' = \beta \times h_{ds}$ ---- (eq$^{n.}$ 18.8, page 18.10, 6^{th} edition Perry)

Where, h_l' = pressure drop through the aerated mass over and around the disperser, mm liquid,

$\Rightarrow h_l' = 0.66 \times 74.58 = 49.2$ mm.

$h_t = h_d + h_l`$

$= 85.93+49.2$

$h_t = 135.13$ mm

Head loss over downcomer apron:

$h_{da} = 165.2 \{q/ A_{da}\}^2$ ----- (eq$^{n.}$ 18.19, page 18.10, 6^{th} edition Perry)

where, h_{da} = head loss under the downcomer apron, as millimeters of liquid,

q = liquid flow rate calculated at the bottom of section, m^3/s

and A_{da} = minimum area of flow under the downcomer apron, m^2

Now,

$q = 9.59 \times 10^{-3} m^3/s$

Assuming clearance as C= 25mm

$h_{ap} = h_{ds} - C = 74.58-25 = 49.58$ mm

$A_{da} = L_w \text{ x } h_{ap} = 1.49 \times 49.58 \times 10^{-3}$

$= 0.0738\ m^2$

Therefore $h_{ad} = 165.2 \times (9.59 \times 10^{-3}/0.0738)^2$

$h_{ad} = 2.78$ mm

Therefore

$h_{dc} = 50+24.58+2.78+135.13$

$=212.49$ mm

Average froth density is assumed as 0.5.

$h_{dc}' = h_{dc}/\phi_{dc}$

$= 212.49/0.5$

$h_{dc}' = 424.98$ mm< 500 mm (tray spacing)

Hence tray spacing given is sufficient, and the design of stripping section is acceptable.

PROPERTY EVALUATION:

Diffusivity:

1.Diffusivity of the vapor is calculated by using following equation:

$$D_{AB} = 10^{-3}\times T^{1.75}\times [(M_A+M_B)/(M_A\times M_B)]^{1/2}\}/\{P\times[(\sum v_A)^{1/3}+(\sum v_B)^{1/3}]^2$$

------ (eq$^{n.}$ 3.133, page 3-281, 6th edition Perry)

2.Diffusivity of liquid is calculated by using the equation given below:

$$D_{12} = 8.621\times 10^{-14}/(\mu_2^{1.14}\times V_1^{0.589})$$ --------(eq^{n}. 2.159,7th edition perry)

Viscosity:

Viscosity data for MEA vapor is predicted by using the equation 3.85 p-3-278 Perry hand book 6th edition. And the mixture property is calculated by using equation 3-87 and 3-90from Perry hand book.

Density of the liquid mixture:

$\rho_{mix}= M_{avg}/\sum(x_i/\rho_I)$

Where ρ_i is the molar density of ith component and x_i is the mole fraction of that component. M_{avg} is the average molecular weight of the liquid.

Surface tension:

For aqueous solutions the mixture property, surface tension is calculated by using the following equation:

$$\sigma_{mix}^{1/4} = \Psi_w\times \sigma_w^{1/4} + \Psi_o\times \sigma_o^{1/4}$$

$$\Psi_o = 1-\Psi_w$$

Ψ is calculated by using formulae:

$$\log (\Psi_w/(1-\Psi_w) = \log [(x_w\times V_w)^q\times(x_w\times V_w+x_o\times V_o)/x_oV_o]+ 0.441\times q\times(\sigma_oV_o^{2/3}/q - \sigma_wV_w^{2/3})/T$$

Where q is number of carbon atoms present in the organic liquid. Two for MEA.

V is in cm^3/mol

Individual liquid surface tension is calculated by:

$\sigma_i = P\times(\rho_l-\rho_g)$ ------- equation (3-151) Perry hand book

Where P is Parachor of component

Average Conditions and Properties:

property	Enriching Section	Stripping Section
Liquid Flow Rate (L)		
kmol/day	1089	14629
kg/day	23458.35	630738.5
Vapor Flow Rate (G)		
kmol/day.	11982.7	11982.7
kg/day.	231755.75	471079.2
Temperature (T)		
$T_{avg.,liquid}$ (^{0} C)	103	137.5
$T_{avg., vapor}$ (^{0} C)	107	147.5
Viscosity (μ)		
$\mu_{avg., liquid}$ (cP)	0.2885	0.528
$\mu_{avg., vapor}$ (cP)	0.0137	0.0624
Density (ρ)		
$\rho_{avg., liquid}$ (kg/m^3)	968.38	1000.98
$P_{avg., vapor}$ (kg/m^3)	0.61	1.101
Surface Tension (σ)		
σ_{mix} (dyne/cm)	26.059	26.09
Diffusivities (D)		
Liquid Diffusivity, D_L cm^2/s	1.35×10^{-5}	2.21×10^{-5}
Vapor Diffusivity, D_V cm^2/s	1.365	1.6
Schmidt number ,$S_c=\mu/(\rho\times D)$		
Gas $N_{Sc, g}$	0.165	0.354

5.14 EFFICENCY CALCULATION: (AIChE Method)

A) Enriching Section:

Point Efficiency, (E_{og}):

$E_{og} = 1-e^{-Nog} = 1-\exp(-N_{og})$ ----- (eq$^{n.}$ 18.33, page 18.15, 6th edition Perry)

Where N_{og} = Overall transfer units

$N_{og} = 1/ [(1/N_g) + (\lambda/N_l)]$ ---- (eq$^{n.}$ 18.34, page 18.15, 6th edition Perry)

Where N_l = Liquid phase transfer units,

N_g = Gas phase transfer units,

$\lambda = (m \times G_m)/ L_m$ = Stripping factor,

m = slope of Equilibrium Curve,

G_m = Gas flow rate, mol/s

L_m = Liquid flow rate, mol/s

$$N_g = (0.776 + (0.00457 \times h_w) - (0.238 \times U_a \times \rho_g^{0.5}) + (104.6 \times W))/ (N_{Sc,\,g})^{0.5}$$

----- (eq$^{n.}$ 18., page 18., 6th edition Perry)--- *

Where h_w = weir height = 50.00 mm

U_a = Gas velocity through active area, m/s

= (Avg. vapor flow rate in kg/day)/ (3600×Avg. vapor density ×active area)

= 231755.75/ (3600×0.61×24×1.567)

U_a = 2.806 m/s

$D_f = (L_w + D_c)/2 = (1.12 + 1.49)/2 = 1.305$ m

Average Liquid rate = 23458.35 kg/day

Average Liquid Density =968.38 kg/m^3

q = 23458.35/ (3600×24×968.38) =2.804 x 10^{-4} m^3/s

W = Liquid flow rate, m^3/ (s.m) of width of flow path on the plate,

$= q/D_f = 2.804 \times 10^{-4}/1.305 = 2.148 \times 10^{-4}$ m^3/ (s.m)

$N_{Sc,\,g}$ = Schmidt number $= \mu_g/ (\rho_g \times D_g) = 0.165$

<u>Number of gas phase transfer units</u>

$$N_g = (0.776 + (0.00457 \times 50) - (0.238 \times 2.806 \times 0.61^{0.5}) + (104.6 \times 2.148 \times 10^{-4}))/ (0.165)^{0.5}$$

N_g = <u>1.24</u>

Also,

Number of liquid phase transfer units

$N_l = k_l \times a \times \theta_l$ ----- (eq^n 18.36a, page 18.15, 6th edition Perry)

Where k_l = Liquid phase transfer coefficient kmol/ (sm^2 kmol/m^3) or m/s

a = effective interfacial area for mass transfer m^2/m^3 froth or spray on the plate,

θ_l = residence time of liquid in the froth or spray, s

$\theta_l = (h_l \times A_a)/ (1000 \times q)$ ---- (eq$^{n.}$ 18.38, page 18.16, 6th edition Perry) now, q = liquid flow rate, m^3/s

$h_l = h_l' = 30.67$ mm

$A_a = 1.567\ m^2$

$k_l \times a = (3.875\times10^8\times D_L)^{0.5}\times ((0.40\times U_a\times\rho_g{}^{0.5}) + 0.17)$

--- (eq$^{n.}$ 18.40a, page 18.16, 6th edition Perry)

D_L= liquid phase diffusion coefficient, m^2/s

$k_l \times a = (3.875\times10^8\times1.35\times10^{-9})^{0.5}\times ((0.40\times2.806\times0.61^{0.5}) + 0.17)$

$=0.7569$ per second

$\theta_l = (30.67\times1.567)/ (1000\times2.8037\times10^{-4})$

$=171.4$

Therefore $N_l = 0.7569\times171.4 =129.7$ m

Slope of equilibrium Curve

$m_{top} = 0.0512$

$m_{bottom} = 0.192$

$G_m/L_m = 4.357$

$\lambda t = m_t \times G_m/L_m = 0.223$

$\lambda b = m_b\times G_m/L_m = 0.836 \quad \Rightarrow \quad \lambda = 0.529$

$N_{og} = 1/ [(1/N_g) + (\lambda/N_l)]$

$= 1/ [(1/1.24) + (0.529/129.7)]$

$N_{og} = 1.234$

$E_{og} = 1-e^{-Nog} = 1-\exp(-N_{og})$

$= 1-e^{-1.234} = 1-0.2912$

$E_{og} = 0.71$

Murphee stage efficiency:

U_a=2.806 m/s

h_l =30.67 mm

$D_E=6.675\times10^{-3}\times U_a{}^{1.44}+0.922\times10^{-4}\times h_l-0.00562$ --- (equation 18-45,p-18-17)

$= 6.675\times10^{-3}\times 2.806^{1.44}+0.922\times10^{-4}\times30.67-0.00562$

$= 0.0266$

$N_{pe} = Z_l^2 / (D_E \theta_l)$

$Z_l = D_c \times \cos(\theta/2)$

$= 1.49 \times \cos(97.18/2)$

$Z_l = 0.983$ m

$N_{pe} = 0.983^2/(0.0266 \times 171) = 0.216$

$\lambda = 0.529$

$\lambda \cdot E_{og} = 0.375$

from fig. 18.299

$E_{mv}/E_{og} = 1.08$

$\boxed{E_{mv} = 0.766}$

Overall efficiency calculation:

$$\text{Overall Efficiency} = E_{OC} = \frac{\log [1 + E_\alpha (\lambda - 1)]}{\log \lambda} = N_T/N_a$$

$$\text{where } E_\alpha / E_{mv} = \frac{1}{1 + E_{MV} [\psi / (1 - \psi)]}$$

----- (eq$^{n.}$ 18.27, page 18.13, 6th edition Perry)

E_{mv} = Murphee Vapor efficiency,

E_α = Murphee Vapor efficiency, corrected for recycle effect of liquid entrainment.

$(L/G) \times \{\rho_g/\rho_l\}^{0.5} = (23458.35/231755.75) \times \{0.61/968.38\}^{0.5} = 0.00254$

Thus, for $(L/G) \times \{\rho_g/\rho_l\}^{0.5} = 0.00254$ and at 80 % of the flooding value,

We have from fig.18.22, page 18.14, 6th edition Perry

ψ = fractional entrainment, moles/mole gross downflow = 0.12

$$\Rightarrow E_\alpha = \frac{E_{mv}}{1 + E_{mv} [\psi / (1 - \psi)]}$$

$= 0.766/ (1+0.766[0.12/ (1-0.12)])$

$\Rightarrow$ $\underline{E_{\alpha} = 0.693}$

Overall Efficiency = E_{OC} = log [1 + E_{α} (λ - 1)]

E_{OC} = log [1+ 0.693(0.529-1)]/ log 0.529

$\boxed{\text{Overall Efficiency} = E_{OC} = 0.62}$

Actual trays = N_{act} = N_T/E_{OC} = (ideal trays)/ (overall efficiency)

Where N_T = Theoretical plates,

N_{act} = actual trays

N_{act} = 3/0.62 = 4.83≈ 5

Thus, Actual trays in the Enriching Section = 5

Total Height of Enriching section = 5×t_s = 5×500 = 2500 mm = 2.5 m

B) Stripping Section:

Point Efficiency, (E_{og}):

$E_{og} = 1\text{-}e^{-Nog} = 1\text{-}\exp(-N_{og})$

$N_{og} = 1/ [(1/N_g) + (\lambda/N_l)]$

$N_g = (0.776 + (0.00457\times h_w) - (0.238\times U_a\times \rho_g^{0.5}) + (104.6\times W))/ (N_{Sc,\,g})^{0.5}$

Where h_w = 50mm

U_a = Gas velocity through active area, m/s

= (Avg. vapor flow rate in kg/day)/ (3600×Avg. vapor density ×active area)

= 471079.2/ (3600×1.101×24×2.448)

U_a = 2.023 m/s

$D_f = (L_w + D_c)/2 = (1.49 + 1.99)/2 = 1.74$ m

Average Liquid rate = 630738.5 kg/day

Average Liquid Density =1000.97 kg/m^3

q =7.29 x 10^{-3} m^3/s

W = Liquid flow rate, m^3/ (s.m) of width of flow path on the plate,

= $q/D_f = 7.29\times10^{-4}/1.74$

$= 4.19\times10^{-3}\ m^3/(s.m)$

$N_{Sc,\ g}$ = Schmidt number $= \mu_g/(\rho_g\times D_g) = 0.354$

Number of gas phase transfer units

$N_g = (0.776 + (0.00457\times50) - (0.238\times2.023\times1.101^{0.5}) + (104.6\times4.19\times10^{-4}))/(0.354)^{0.5}$

$N_g = 1.53$

Also,

Number of liquid phase transfer units

$N_l = k_l\times a\times\theta_l$ ----- (eq^n 18.36a, page 18.15, 6th edition Perry)

$\theta_l = (h_l\times A_a)/(1000\times q)$ ---- (eq$^{n.}$ 18.38, page 18.16, 6th edition Perry)

Now, q = liquid flow rate, m^3/s

$h_l = h_l' = 45.92$ mm

$A_a = 2.448\ m^2$

$k_l\times a = (3.875\times10^8\times D_L)^{0.5}\times((0.40\times U_a\times\rho_g^{0.5}) + 0.17)$

--- (eq$^{n.}$ 18.40a, page 18.16, 6th edition Perry)

D_L= liquid phase diffusion coefficient, m^2/s

$k_l\times a = (3.875\times10^8\times2.21\times10^{-9})^{0.5}\times((0.40\times2.023\times1.101^{0.5}) + 0.17)$

=0.943 per second

$\theta_l = (45.92\times2.448)/(1000\times7.2\times10^{-3})$

=15.6

Therefore $N_l = 0.943\times15.6 = 14.54$ m

Slope of equilibrium Curve

$m_{top} = 1.42$

$m_{bottom} = 3.33$

$G_m/L_m = 0.6$

$\lambda t = m_t\times G_m/L_m = 0.852$

$\lambda b = m_b\times G_m/L_m = 2.0 \Rightarrow \lambda = 1.43$

$N_{og} = 1/[(1/N_g) + (\lambda/N_l)]$

$= 1/ [(1/1.53) + (1.43/14.54)]$

$N_{og} = 1.272$

$E_{og} = 1-e^{-Nog} = 1-\exp(-N_{og})$

$= 1-e^{-1.272}$

$E_{og} = 0.719$

Murphee stage efficiency(M_v):

U_a=2.023 m/s

h_l =45.92 mm

$D_E=6.675\times10^{-3}\times U_a^{1.44}+0.922\times10^{-4}\times h_l-0.00562$ --- (equation 18-45,p-18-17)

$= 6.675\times10^{-3}\times 2.023^{1.44}+0.922\times10^{-4}\times45.92-0.00562$

$= 0.017$

$N_{pe}=Z_l^2/ (D_E\theta_l)$

$Z_l=D_c\times\cos(\theta/2)$

$= 1.99\times\cos(97.18/2)$

Z_l=1.31 m

$N_{pe}=1.31^2/(0.017\times15.6)=6.47$

$\lambda = 1.43$

$\lambda\cdot E_{og}=1.02$

from fig. 18.299

$E_{mv}/E_{og} =1.42$

$E_{mv}= 1.02$

Overall efficiency calculation:

$$\text{Overall Efficiency} = E_{OC} = \frac{\log [1 + E_\alpha (\lambda - 1)]}{\log \lambda} = N_T/N_a$$

$$\text{Where } E_\alpha/E_{mv}= \frac{1}{1 + E_{MV} [\psi/ (1- \psi)]}$$

----- (eq$^{n.}$ 18.27, page 18.13, 6th edition Perry)

E_{mv} = Murphee Vapor efficiency,

E_α=Murphee Vapor efficiency, corrected for recycle effect of liquid entrainment.

$(L/G)\times \{\rho_g/\rho_l\}^{0.5} = (630738.5/471079.2)\times\{1.101/1014.15\}^{0.5} = 0.044$

Thus, for $(L/G)\times\{\rho_g/\rho_l\}^{0.5} = 0.044$ and at 80 % of the flooding value,

We have from fig.18.22, page 18.14, 6th edition Perry

ψ = fractional entrainment, moles/mole gross downflow = 0.08

$$\Rightarrow E_\alpha = \frac{E_{mv}}{1 + E_{mv}\,[\psi/(1-\psi)]}$$

$$= 1.02/ (1+1.02[0.08/ (1-0.08)])$$

$\Rightarrow$ $\underline{E_\alpha = 0.936}$

Overall Efficiency = $E_{OC} = \log [1 + E_\alpha (\lambda - 1)]$

$E_{OC} = \log [1+ 0.936(1.43-1)]/ \log 1.43$

Overall Efficiency = E_{OC} = 0.945

Actual trays = $N_{act} = N_T/E_{OC}$ = (ideal trays)/ (overall efficiency)

Where N_T = Theoretical plates,

N_{act} = actual trays

$N_{act} = 3/0.945 = 3.17 \approx 4$

Thus, Actual trays in the Enriching Section = 4

Total Height of Enriching section = $4\times t_s = 4\times500$ = 2000 mm = 2.0 m

Total number of trays in the column = 9

Five in the enriching section and four in the stripping section.

Total height of the tower = 4.5 m

5.2 PROCESS DESIGN OF CONDENSER

Vertical condenser is used to condense the water vapor coming at the top of the dehydration tower. Condenser is operated at the same pressure as that of dehydration tower that is one atmosphere.

Amount of the vapor to be condensed is 11982.7 kmol/day i.e. 217055.9 kg/ day. Feed entering is at its dew point. Weight fraction of water in the feed is 99% and MEA is 1%. At one atmosphere

λ(latent heat of vaporisation)for MEA =848.1KJ/Kg.

for water =2265.2 KJ/Kg.

5.21 ENERGY BALANCE

1. SHELL SIDE: (VAPOR)

Condensed liquid leaving the condenser is at its saturation temperature. Hence the heat load:

$Q_H = q_{\text{latent heat}}$

$= m \times \lambda$

$= 217055.9/(24 \times 3600) \times 2251.03$

$Q_H = 5650.08$ kW.

2. TUBE SIDE: (WATER)

$Q_C = (m_w \times C_p \times \Delta T)$

Latent heat of the vapor entering is removed completely i.e. completelly condensed.

Hence $Q_C = Q_H$

$\Rightarrow m_w = Q_H / (C_p \times \Delta T) = (676.4126 \times 10^3) / (4.187 \times 10^3 \times (40-30)) = 134.9$ kg/s

Where m_w is the cooling water flow rate.

5.22 LMTD calculation:

Considering **Counter- Current Operation.**

HOT SIDE (VAPOR)	COLD SIDE (WATER)	TEMPERATURE DIFFERENCE, ΔT
102	30 ^{0}C	72 ^{0}C
102	40 ^{0}C	62 ^{0}C

ΔT_{lm} = ((102-30)-(102-40))/ln ((102-30)/ (102-40)) = 66.87 ^{0}C

Consider one-one pass exchanger:

Routing:
Tube side: cooling water
Shell side: vapor.

Let choose ¾" OD, 20 BWG tube from table 11-2 p-11-8,
Outer diameter =19.05 mm
Inner diameter = 17.27 mm
Let length of tube = 12 ft.= 3.66 m
External heat transfer area / ft length = 0.1963 ft^2/ft length
= 0.0598 m^2/m length
50 mm allowance is given for the tube sheet. Hence tube length available for the heat transfer is = 3.61 m
Heat transfer area of one tube = 0.0598 × 3.61
= 0.213 m^2
Total number of tubes required = 37.199/0.213
=174.65 tubes.
For TEMA P or S 1" triangular pitch from table 11-3 p-11-14
Nearest tube count = 208 tubes for that Shell diameter = 438 mm
Therefore corrected area = 208×0.213
=44.9 m^2

Corrected U_d = 5650.8×10^3/(66.87×44.9)
= 1881.8 W/(m^2 K)
Fluid velocity:
Tube side:
N_p= 1
Flow area = $(\pi\times D_i^2/4)\times N_t/N_p$
= 0.0488 m^2
therefore tube side fluid velocity = m_W/(994.03×0.0488)

= 134.9/(994.03×0.0488)
V_t = 2.78 m/s

5.23 FILM TRANSFER COEFFICIENTS:

SHELL SIDE:

Fluid is condensing vapor
Wall temperature $T_W=1/2\times[T^{sat}+(30+40)/2]$
= 1/2[102+35]
T_W = 68.5^{o}C

Film temperature $T_F = (T_W + T^{sat})/2$

$= 85.25\,^{o}C$

Properties of vapor are taken at 86°C and it is assumed that amount of MEA present is negligible.

ρ_l=967.97Kg/m^3 C_p=4.39KJ/Kg K

k=0.679 W/mK μ=0.33cP

Reynolds number:

$N_{Re} = 4\Gamma/\mu = 4/\mu \times W/(Nt^{2/3}\, L)$

$= 4\times 2.512/(0.33\times 10^{-3}\times 3.61\times 208^{2/3})$

$N_{Re} = 240.26$

We have

$h_o = 1.51\times (k^3\times\rho^2\times g/\mu^2)^{1/3}\times N_{Re}^{-1/3}$

$= 1.51 \times (0.679^3\times 967.97^2\times 9.81/(0.33\times 10^{-3})^2)^{1/3}\times 240.26^{-1/3}$

=7234.48 W/mK

TUBE SIDE:

Fluid is cooling water:

Fluid velocity in the tube $V_t = 2.78$ m/s

At average temperature 35 °C properties of cooling water:

ρ_l=994.032Kg/m^3 C_p=4.187KJ/Kg K

k=0.578 W/mK μ=0.8cP

$N_{Re} = \rho vD/\mu = 59655.09$

$N_{pr} = \mu C_p/k = 5.79$

From Dittus Boitus equation:

$N_u = 0.023\times N_{Re}^{0.8}\times N_{pr}^{0.3} = h_i D_i/k$

Therefore

$\underline{h_i = 8623.53\ W/m^2K}$

5.24 OVERALL HEAT TRANSFER COEFFICIENT:

Overall efficiency can be calculated by formulae:

$$1/U_o=1/h_o+1/h_i\times D_o/D_i + x_w\times A_o/(k_w\times A_w)\text{+ dirt factor}$$

Where

x_w is the thickness of the tube.

k_w is the thermal conductivity of the material =50 W/m K

Dirt factor from table11-3 $=8.805\times 10^{-5}$

$1/U_o = 3.934\times 10^{-4}$

$U_o = 2541.49$ W/m^{2}K assumed value of the overall heat transfer coefficient is 1881.8 W/m^{2}K

Therefore the design value is more than the assumed value.

5.25 PRESSURE DROP CALCULATIONS:

SHELL SIDE:

$T_{vap} =102^oC$

$\mu_{vap} = 0.0118$ cP

$$a_s= (ID)\times C'\times B/P_T$$

Where

C' = clearance between tubes= $P_T - D_o$

B=Baffle spacing

P_T=25.4 mm

By assuming baffle spacing as diameter of the shell pressure drop will be high and is more than the permissible limit.

Let $N_b+1=3$ i.e. number of baffles are taken as two for trial calculation.

Therefore B = 1.203 m

Then $a_s = 0.1296$ m^2

$D_e= 4\times[P_T/2\times 0.86\times P_T-0.5\times\pi\times D^2/4] / (\pi\times D_o/2)$

= 0.0182 m

$G_s= 2.512/ a_s$

$=2.512/0.0182$

$G_s = 19.38$ Kg/m^{2}s

Reynolds number:

$N_{Re}= G_s\times D_e /\mu_{vap}$

$=19.38\times 0.0182/(0.0118\times 10^{-3})$

$N_{Re} = 29595.56$

$$f = 1.87 \times (N_{Re})^{-0.2}$$
$$= 0.238$$

$$\Delta P_s = [4f\,(N_b+1) \times D_s \times G_s^2 \times g] \times 0.5/(2g \times D_e \times \rho_{vap})$$

$$= 4 \times 0.238 \times 3 \times 0.438 \times 19.38^2 \times 0.5/(2 \times 0.01802 \times 0.58)$$
$$= 11238.2\ N/m^2$$
$$\Delta P_s = 11.2382\ KN/m^2 < 14\ KN/m^2$$

Shell side pressure drop is less than the permissible value for the assumed number of baffles.

TUBE SIDE:

Velocity of liquid water in the tube side= 2.78m/s.
Properties at the average temperature 35 ^oC :

ρ_l=994.032Kg/m^3 C_p=4.187KJ/Kg K
k=0.578 W/mK μ=0.8cP

Reynolds number:

$$N_{Re} = \rho v D/\mu = 59655.09$$

Friction factor(f):

$$f = 0.079 \times (N_{Re})^{-0.25}$$
$$= 5.054 \times 10^{-4}$$

Pressure drop through the length:

$$\Delta P_l = 4fLV^2 \times \rho_l \times g/(2gD)$$
$$= 2f \times LG_t^2/(\rho_l \times D_i)$$
$$= 4 \times 5.54 \times 10^{-4} \times 3.66 \times 2763.4^2/(994.03 \times 0.01727)$$
$$\Delta P_l = 1645.66 N/m^2$$

Pressure drop:

$$\Delta P_R = 2.5 \times G_t^2/(2\rho)$$
$$= 9602.8\ N/m^2$$

Total pressure drop = $(\Delta P_l + \Delta P_R)$

$$\Delta P_T = 11248.48\ N/m^2 < 70000\ N/m^2$$

Pressure drop on both sides of the condenser are under the permissible limit. Hence the design is acceptable.

6.1 MECHANICAL DESIGN OF DISTILLATION COLUMN

a) SHELL:

Diameter (D_i)	1.99 m
Working/Operating Pressure	1.0329 kg/cm^2
Design pressure = 1.1×Operating Pressure	1.1×1.0329 = 1.1362 kg/cm^2
Working temperature	441 ^{0}K
Design temperature	457.8 ^{0}K

Shell material - IS: 2002-1962 Grade I Plain Carbon steel

Permissible tensile stress (f_t)	950 kg/cm^2
Elastic Modulus (E)	1.88×10^5 MN/m^2

Insulation material - asbestos

Insulation thickness	2”= 50.8 mm
Density of insulation	575 kg/m^3
Top disengaging space	0.3 m
Bottom separator space	0.4 m
Weir height	50 mm
Downcomer clearance	25 mm

b) HEAD - TORISPHERICAL DISHED HEAD:

Material - IS: 2002-1962 Grade I Plain Carbon steel

Allowable tensile stress = 950 kg/cm^2

c) SUPPORT SKIRT:

Height of support 1 m

Material - Carbon Steel

d) TRAYS-SIEVE TYPE:

Number of trays = 9

Hole Diameter = 5mm

Number of holes:

Enriching section = 6981

Stripping section = 10726

Tray spacing:

Enriching section: 500 mm

Stripping section: 500 mm

Thickness = 3 mm

e) SUPPORT FOR TRAY:

Purlins - Channels and Angles

Material - Carbon Steel

Permissible Stress = 1275 kg/cm^2

1. Shell minimum thickness:

Considering the vessel as an internal pressure vessel.

$$t_s = ((P \times D_i) / ((2 \times f_t \times J) - P)) + C$$

where t_s = thickness of shell, mm

P = design pressure, kg/cm^2

D_i = diameter of shell, mm

f_t = permissible/allowable tensile stress, kg/cm^2

C = Corrosion allowance, mm

J = Joint factor

Considering double welded butt joint with backing strip

J= 85% = 0.85

Thus, $t_s = ((1.1362 \times 1990) / ((2 \times 950 \times 0.85) - 1.1362)) + 3 = \underline{4.556}$ mm

Taking the thickness of the shell as minimum specified value= 6 mm

2. Head Design- Shallow dished and Torispherical head:

Thickness of head = $t_h = (P \times R_c \times W) / (2 \times f \times J)$

P =internal design pressure, kg/cm^2

R_c = crown radius = diameter of shell, mm=1990mm

W=stress intensification factor or stress concentration factor for torispherical head

$W = \frac{1}{4} \times (3 + (R_c/R_k)^{0.5})$

R_k = knuckle radius, which is at least 6% of crown radius, m

$R_k = 6\% \times R_c = 0.06 \times 1990 = \underline{119.4}$ mm

$W = \frac{1}{4} \times (3 + (R_c/R_k)^{0.5}) = \frac{1}{4} \times (3 + (1/0.06)^{0.5}) = 1.7706$ mm

$t_h = (1.1362 \times 1990 \times 1.7706)/ (2 \times 950 \times 0.85) = \underline{2.7538}$ mm

including corrosion allowance thickness of head is taken as $\underline{6}$ mm

Pressure at which elastic deformation occurs

$P_{(elastic)} = 0.366 \times E \times (t/ R_c)^2$

$= 0.366 \times 1.88 \times 10^5 \times (6/1990)^2$

$= 0.6255$ MN/ m^2 = $\underline{6.3761}$ kg/cm^2

The pressure required for elastic deformation, $P_{(elastic)}$ > (Design Pressure)

Hence, the thickness is satisfactory. The thickness of the shell and the head are made equal for ease of fabrication.

Weight of Head:

Diameter = O.D + (O.D/24) + ($2 \times s_f$) + ($2 \times i_{cr}/3$) --- (eq$^{n.}$ 5.12 Brownell and Young)

Where O.D. = Outer diameter of the dish, inch

i_{cr} = inside cover radius, inch

s_f = straight flange length, inch

From table 5.7 and 5.8 of Brownell and Young

s_f =1”

i_{cr} = 1¼”

Also, O.D.= 1990 mm = 78.35”

Diameter = 78.35 + (78.35/24) + (2×1) + (2×1¼/3) =

d = 84.45” = 2144.97 mm

Weight of Head = $((\pi \times d^2 \times t)/4) \times (\rho/1728)$

$= ((\pi \times 84.45^2 \times 0.2362)/4) \times (590/1728) = 375.2$ lb

= 170.19 kg

3. Shell thickness at different heights

At a distance 'X'm from the top of the shell the stresses are:

3.1 Axial Tensile Stress due to Pressure:

$$f_{ap} = \frac{P \times D_i}{4(t_s - c)} = \frac{1.1362 \times 1990}{4(6 - 3)} = \underline{188.38} \text{ kg/cm}^2$$

This is the same through out the column height.

3.2 Compressive stress due Dead Loads:

3.2a Compressive stress due to Weight of shell up to a distance 'X' meter from top.

f_{ds} = weight of shell/cross-section of shell

$= (\pi/4) \times (D_o^2 - D_i^2) \times \rho_s \times X / (\pi/4) \times (D_o^2 - D_i^2)$

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

Where D_o and D_i are external and internal diameter of shell.

ρ_s = density of shell material, kg/m^3

D_m = mean diameter of shell,

t_s = thickness of shell,

c = corrosion allowance

Now, $\rho_s = 8500 \text{ kg/m}^3 = 0.0085 \text{kg/cm}^3$

$f_{ds} = \rho_s \times x = (0.85 \times X) \text{ kg/cm}^2$

3.2b Compressive stress due to weight of insulation at a height X meter

$$f_{d(ins)} = \frac{\pi \times D_{ins} \times t_{ins} \times \rho_{ins} \times X}{\pi \times D_m \times (t_s - c)} = \frac{\text{weight of insulation per unit height X}}{\pi \times D_m \times (t_s - c)}$$

where D_{ins}, t_{ins}, ρ_{ins} are diameter, thickness and density of insulation respectively.

$D_m = (D_c + (D_c + 2t_s))/2$

$D_{ins} = D_c + 2t_s + 2t_{ins} = 199 + (2 \times 0.6) + (2 \times 5.08) = 201.216$ cm.

$D_m = (199 + (199 + (2 \times 0.6)))/2 = 199.6$ cm.

$$f_{d(ins)} = \frac{\pi \times 201.216 \times 5.08 \times 575 \times X}{\pi \times 199.6 \times (0.6 - 0.3)} = 9815.5 \times X \text{ kg/m}^2$$

$f_{d(ins)} = 0.98155 \times X \text{ kg/cm}^2$

3.2c Stress due to the weight of the liquid and tray in the column up to a height X meter.

$$f_{d,\,liq.} = \frac{\sum \text{weight of liquid and tray per unit height X}}{\pi \times D_m \times (t_s - c)}$$

The top chamber height is 0.3 m and it does not contain any liquid or tray. Tray spacing is 500 mm.

Average liquid density = 984.67 kg/m^3

Liquid and tray weight for X meter

$$f_{liq\text{-}tray} = [(X-0.3)/\ 0.5 + 1] \times (\pi \times D_i^2/4) \times \rho_l$$

$$= [(X-0.3)/\ 0.5 + 1] \times (\pi \times 1.99^2/4) \times 984.67$$

$$= [2X + 0.4] \times 3062.97 \text{ kg}$$

$$f_{d\,(liq)} = F_{liq\text{-}tray} \times 10/\ (\pi \times D_m \times (t_s - c))$$

$$= [2X + 0.4] \times 3062.97 \times 10/\ (\pi \times 1996 \times (6 - 3))$$

$$f_{d\,(liq)} = 3.26X + 0.653 \text{ kg/cm}^2$$

3.2d Compressive stress due to attachments such as internals, top head, platforms and ladder up to height X meter.

$$f_{d\,(attch.)} = \frac{\sum \text{weight of attachments per unit height X}}{\pi \times D_m \times (t_s - c)}$$

Now total weight up to height X meter = weight of top head + pipes +ladder, etc.,

Taking the weight of pipes, ladder and platforms as 25 kg/m = 0.25 kg/cm

Total weight up to height X meter = $\underline{(170.19+25X)}$ kg

$$f_{d\,(attch.)} = (170.19+25X) \times 10/\ \pi \times 199 \times (6 - 3) = \underline{0.907 + 0.133X} \text{ kg/cm}^2$$

Total compressive dead weight stress:

$$f_{dx} = f_{ds} + f_{ins} + f_{d\,(liq)} + f_{d\,(attch)}$$

$$= 0.85X + 0.98155X + [3.26X+0.653] + [0.907 +0.133X]$$

$$f_{dx} = 5.225X + 1.559 \text{ kg/cm}^2$$

4. Tensile stress due to wind load in self supporting vessels:

$$f_{wx} = M_w/Z$$

where M_w = bending moment due to wind load = (wind load× distance)/2

$= 0.7 \times P_w \times D \times X^2/2$

Z = modulus for the section for the area of shell $\approx \pi \times D_m^2 \times (t_s - c)/4$

Thus, $f_{wx} = 1.4 \times P_w \times X^2/\ \pi \times D_m \times (t_s - c)$

Now $P_w = 25\ lb/ft^2$ --- (from table 9.1 Brownell and Young)

$= 122.06\ kg/m^2$

Bending moment due to wind load

$M_{wx} = 0.7 \times 122.06 \times 1.99 \times X^2/2 = 170.03$ kg-m

$f_{wx} = 1.4 \times 122.06 \times X^2/\ \pi \times 1.99 \times (6-3) = 3.075X^2\ \ kg/cm^2$

5. Stresses due to Seismic load:

$f_{sx} = M_{sx}/\pi \times D_m^2 \times (t_s - c)/4$

Where bending moment M_{sx} at a distance X meter is given by

$M_{sx} = [C \times W \times X^2/3] \times [(3H - X)/H^2]$

Where C = seismic coefficient,

W= total weight of column, kg

H = height of column

Total weight of column = $W = C_v \times \pi \times \rho_m \times D_m \times g \times (H_v + (0.8 \times D_m)) \times t_s \times 10^{-3}$

----- (eq$^{n.}$ 13.75, page 743, Coulson and Richardson 6th volume)

Where W = total weight of column, excluding the internal fittings like plates, N

C_v = a factor to account for the weight of nozzles, manways, internal supports, etc.

= 1.5 for distillation column with several manways, and with plate Support rings or equivalent fittings

H_v = height or length between tangent lines (length of cylindrical section)

g = gravitational acceleration = 9.81 m/s^2

t = wall thickness

ρ_m = density of vessel material, kg/m^3

D_m = mean diameter of vessel = $D_i + (t \times 10^{-3})$

$= 1.99 + (6 \times 10^{-3}) = 1.996$ m

$W = 1.5 \times \pi \times 8500 \times 1.996 \times 9.81 \times (4 + (0.8 \times 1.996)) \times 6 \times 10^{-3} = 26341.28$ N

= 2685.15 kg.

Weight of plates: ------- (Coulson and Richardson 6^{th} volume)

Plate area = $\pi\times1.99^2/4 - 0.331(\text{is } A_d) = 2.18\ m^2$

Weight of each plate = 1.2×2.18 =3.336 kN

Weight of 9 plates = 9×3.336 = 30.02 kN = 3060.55 kg.

Total weight of column = 2685.15 + 3060.55 = 5745.7 kg

Let C = seismic coefficient = 0.08

$M_{sx} = [0.08\times5745.7\times X^2/3] \times [((3\times4.5)-X)/4.5^2]$

$= 153.22X^2 \times [0.66-0.049X]$ kg-m

$f_{sx} = M_{sx}\times10^3/\pi\times D_m{}^2\times (t_s-c)/4$

$= 153.22X^2 \times [0.66-0.049X] \times10^3/(\pi\times199.6^2\times (6-3)/4)$

$= [1.0771X^2- 0.07997X^3]$, kg/cm^2

On the up wind side:

Total stress acting on the up wind side:

$f_{t,max} = (f_{wx} \text{ or } f_{sx}) + f_{ap} - f_{dx}$

Since the chances of, stresses due to wind load and seismic load, to occur together is rare hence it is assumed that the stresses due to wind load and earthquake load will not occur simultaneously and hence the maximum value of either is therefore accepted and considered for evaluation of combined stresses.

Thus,

$f_{t,max} = 0.908X^2 + 188.38- [5.225X + 1.559]$

i.e., $0.908X^2 - 5.225X -1.559+188.38-0.85 \times950 = 0$

$0.908X^2- 5.225X - 578.56 =0$

=> X = 28.28 m

On the down side:

Maximum stress acting on the down side is given by the following equation:

$f_{c,max} = (f_{wx} \text{ or } f_{sx}) - f_{ap} + f_{dx}$

$f_{t,max}$ =0.908X^2 - 188.38 + [5.225X + 1.559]

The column height is 4.5 m, for which the maximum value is

$f_{t,max}$ =0.908$(4.5)^2$ - 188.38+ [5.225(4.5) + 1.559]

= -144.92 kg/cm^2

This shows that the stress on the down wind side is tensile. Hence further calculation is done by taking $f_{t,max}$ as allowable stress to find the height up to that column can resist the maximum stress acting on it. If the height calculated is more than the actual height of the column, then selected material and hence the design will be acceptable.

$f_{t,max}$ =0.908X^2 - 188.38 + [8.852X + 1.559]

Let $f_{t,max}$ = 0.85 × 950 =807.5 kg/cm^2

Hence 0.908X^2 - 188.38 + [5.225X + 1.559] – 807.5=0

We get X=30.34 m

Actual height of the column is 4.5 m. Therefore the design is acceptable because of the height up to that it can resist the maximum permissible stress is much more larger than the actual height of the column.

Hence

Thickness of the shell	6.0	mm
Height of the head	0.4975	m (is Dc/4)
Skirt support height	1	m
Height of the tower	4.5	m

Design of Support:

a) Skirt Support:

The cylindrical shell of the skirt is designed for the combination of stresses due to vessel dead weight, wind load and seismic load. The thickness of skirt is uniform and is designed to withstand maximum values of tensile or compressive stresses.

Data available:

(i) Diameter =1990 mm.

(ii) Height = 4500 mm = 4.5 m

(iii) Weight of vessel, attachment =5745.7 kg.

(iv) Diameter of skirt (straight) = 1990 mm

(v) Height of skirt = 1.0 m

(vi) Wind pressure = 122.06 kg/m^2

1. Stresses due to dead Weight:

$f_d = \sum W/ (\pi \times D_{ok} \times t_{sk})$

f_d = stress,

$\sum W$ = dead weight of vessel contents and attachments,

D_{ok} = outside diameter of skirt,

t_{sk} = thickness of skirt,

$f_d = 5745.7/ (\pi \times 199.6 \times t_{sk}) = 91.6/ t_{sk}$ kg/cm^2

2. Stress due to wind load:

$p_w = k \times p_1 \times h_1 \times D_o$

$p_1 =$ wind pressure for the lower part of vessel,

k = coefficient depending on the shape factor

= 0.7 for cylindrical vessel.

D_o = outside diameter of vessel,

The bending moment due to wind at the base of the vessel is given by

$M_w = p_w \times H/2$

$f_{wb} = M_w/Z = 4 \times M_w/(\pi \times (D_{ok})^2 \times t_{sk}$

Z- Modulus of section of skirt cross-section

$p_w = 0.7 \times 122.06 \times 1.0 \times 1.99 = 765.13$ kg

$M_w = p_w \times H/2 = 765.13 \times 4.5/2 = 1721.5$ kg-m

Substituting the values we get,

$f_{wb} = 8.2/t_{sk}$ kg/cm^2

Stress due to seismic load:

Load = C×W

C = seismic coefficient,

W= total weight of column.

Stress at base, $f_{sb} = (2/3) \times (C\times H\times W)/ (\pi \times(R_{ok})^2 \times t_{sk}$

C=0.08

$f_{sb} = (2/3) \times (0.08\times450\times5745.7)/(\pi \times(199.6/2)^2 \times t_{sk} = 6.61/ t_{sk}$ kg/cm^2

Maximum tensile stress:

$f_{t, max} = (91.6/ t_{sk}) – (8.2/ t_{sk}) = (83.5/ t_{sk})$ kg/cm^2

Permissible tensile stress = 925 kg/cm^2

Thus, 925 = $(83.5/ t_{sk})$

=> t_{sk} = 0.0902 cm = 0.902 mm

Maximum compressive stress:

$f_{c, max} = (91.6/ t_{sk}) + (8.1/ t_{sk}) = (99.7/ t_{sk})$ kg/cm^2

Now,

$f_{c, (permissible)}$ <= (⅓) yield point

= 1500/ 3 = 500 kg/cm^2

Thus, t_{sk} = 99.7/500 = 0.1994 cm = 1.994 mm

As per IS 2825-1969, minimum corroded skirt thickness = 7 mm

Thus use a thickness of 7 mm for the skirt.

Design of skirt bearing plate:

Assume both circle diameter = skirt diameter + 32.5 =199+ 32.5 = 231.5 cm

Compressive stress between Bearing plate and concrete foundation:

$f_c = (\sum W/A) + (M_w/Z)$

$\sum W$ = dead weight of vessel contents and attachments,

A = area of contact between the bearing plate and foundation,

Z = Section Modulus of area,

M_w = the bending moment due to wind,

$f_c = (5745.7\times4)/(\pi\times(231.5^2-199^2))+(0.7\times122.06\times3\times42.3^2)/(2\times\pi\times(231.5^4-91^4)/(32\times231.5))$

= 0.133 + 0.138

f_c = 0.271 kg/cm^2

Which is less than the permissible value for concrete.

Maximum bending moment in bearing plate

Stress, $f = (6\times0.271\times 16.25^2)/ (2 \times t_B^2) = 214.68/ t_B^2$

Permissible stress in bending is 1000 kg/cm^2

Thus, $t_B^2 = 214.68/1000 \Rightarrow t_B = 0.463$ cm = 4.63

Therefore a bolted chair has to be used.

Anchor Bolts:

Minimum weight of Vessel = W_{min} = 3000 kg. ------ (assumed value)

$f_{c,min} = (W_{min}/A) - (M_w/Z)$

$= [(4\times3000)/ (\pi \times (231.5^2 - 199^2))] - (0.7\times 122.06\times 3 \times42.3^2\times/(2\times \pi\times(231.5^4 - 199^4)/(32\times231.5))$

$= 0.273 – 0.415 = - 0.142$ kg/cm^2

Since f_c is negative, the vessel skirt must be anchored to the concrete foundation by anchor bolts.

P_{bolts}=fc(min)A/n

Assuming there are 20 bolts,

$P_{bolts} = (0.142/20) \times ((\pi \times (231.5^2 -199^2))/4) = 78.01$ kg

Trays:

The trays are standard sieve plates throughout the column. The plates have 6981 holes in Enriching section and 10726.11 holes in the Stripping section of 5mm diameter arranged on a 15mm triangular pitch. The trays are supported on purloins.

6.2 MECHANICAL DESIGN OF CONDENSER

Fluid in the shell side is water vapor and in the tube side is liquid water.
Data available:

SHELL SIDE:

Material	carbon steel
One shell–one tube	pass exchanger.
Fluid	water vapor
Working pressure	1 atmosphere
Design pressure	0.1114 N/m^2
Temperature	102^oC
Diameter	438 mm

Permissible stress for carbon steel is 95 N/mm^2

TUBE SIDE:

Number of tubes	208
Number of passes	one
Inside diameter	17.27 mm
Outside diameter	19.05 mm
Length	12 ft, 3.66 m
Triangular pitch	1”

Working and operating pressures are same as that of shell side.
Fluid on the tube side is water:

Inlet temperature	30^oC
Outlet temperature	$40\,^oC$

1. SHELL THICKNESS:

$t_s = PD/(2fJ+P)$
let J=85%
$= 0.1114\times438/(2\times0.85\times95+0.1114)$
$= 0.31$

Minimum thickness of shell including corrosion resistance is taken as 8 mm

2. HEAD THICKNESS:

Shallow dished and torispherical head.

$t_h = PR_e/2fJ$
$W = \frac{1}{4}\times(3+\sqrt{(Re/Rk)}$
$= 1.77$
$t_h = 0.535$ mm

IS:4503-1967:

Minimum thickness including corrosion allowance must be 10mm hence t_h = 10 mm

3. TANSVERS BAFFLES:

Baffle spacing =1.203 m
Thickness of baffles(t_s) = 6mm

4. TIE RODS AND SPACERS:

These are provided to retain all cross baffles and tube support plates in position. From IS:4503-1967

For shell diameter 400-700 mm
Diameter of rod is 10 mm and number of rods = 6

5. FLANGE DESIGN:

Flange is ring type with plain face.

Design pressure = P = 0.1114 N/mm^2 (external)

Flange material: IS 2004-1962 Class 2 Carbon Steel

Bolting steel: 5% Chromium, Molybdenum Steel

Gasket Material: Asbestos composition

Shell OD = 0.446m = B

Shell Thickness = 0.008m = g

Shell ID = 0.438m

Allowable stress for flange material = 100 MN/m^2

Allowable stress of bolting material = 138 MN/m^2

(a) Determination of gasket width

$d_O/d_i = [(y-Pm)/(y-P(m+1))]^{0.5}$

Assume a gasket thickness of 0.6mm

y = minimum design yield seating stress = 44.85 MN/m^2

m = gasket factor = 3.5

d_O/d_i = 1.001m

do=0.4385 m

Minimum gasket width = (0.4385-0.438)/2 = 0.000275m = N

Taking minimum width as 10 mm

Then d_o = 0.458m

Basic gasket seating width = 6 mm =b

Diameter at location of gasket load reaction G = d_i + N = 448m

(b) Estimation of bolt loads

Load due to design pressure

$H = \pi G^2 P/4$

= 0.01755 MN

where P is the design pressure

Load to keep joint tight under operation:

$H_p = \pi G(2b)mp$

$= \pi(0.448)(0.00612)(3.5)(0.1114)$

H_p = 0.00672 MN

Total Operating Load $W_o = H+H_T$ = 0.0241 MN

Load to seat the gasket under bolting condition:

$W_g = \pi Gby$

= 0.862 MN

$W_g > W_o$ Hence, the controlling load is W_g = 0.862 MN

(c) Calculation of Minimum bolting area:

$A_m = A_g$ = W/S = 0.862/S

S_o = allowable stress for bolting material

$A_m = A_g$ = 0.862/138 = 0.006246 m

Calculation of optimum bolt size.

g_1 = g/0.707 = 1.415g

Choose M18×2 Bolts

Minimum number of bolts = 44

Radial clearance from bolt circle to point of connection of hub or nozzle and back of flange = R = 0.027 m

B_s = 0.045m (Bolt spacing)

$C = nB_s/\pi = 0.63$

$C = ID + 2(1.415g + R)$

$= 0.438 + 2[(1.415)(0.008)+0.027]$

$= 0.726$ m

Choose C = 0.726m

Bolt circle diameter = 0.726m

(d) Flange outside diameter (A)

A = C +bolt dia + 0.02

= 0.764m

(e) Check for gasket width

$A_b S_G / (\pi GN)$

where S_G is the Allowable stress for the gasket material=138

A_b is actual bolt area=$44\times1.54\times10^{-4}$=0.006776 m^2

$A_b S_G / (\pi GN)$=89.7MN/m^2<2y condition is satisfied.

(f) Flange Moment Calculations

For operating condition:

$W_{o=}W_1 + W_2 + W_3$ -----equation(17.6.6)

$W_1=\pi\times B^2\times P/4$=0.01739 MN

W_2=H- W_1=0.00016 MN

W_3= W_o-H=0.00672 MN

$M_o = W_1\times a_1 + W_2\times a_2 + W_3\times a_3$ ---- equation(7.6.7)

For loose type lap joint flanges,

a_1 = (C-B)/2 = 0.14m

a_3 = (C -G)/2 = 0.1395m

$a_2 = (a_1+a_3)/2 = 0.139$m

$\underline{M_o = 3.39\times10^{-3}\text{ MJ}}$

For bolting up condition:

$M_g = Wa_3$------equation(7.6.8)

$W =(A_b+A_g)S_g/2$

$A_g = W_g/S_g = 0.862/138 = 6.246\times10^{-4}m^2$

$A_g=6.776\times10^{-3}$

W= 897 MN/m^2

M_g = 0.125 MJ

$M_g > M_o$

Hence, M_g is controlling.

(g) Calculation of flange thickness

$t^2 = M\ C_F\ Y / (B\ S_F)$ --- equation(7.6.12)

S_F is the allowable stress for the flange material= 100MN/m^2

K =A/B = 0.764/0.446= 1.71

For K = 1.71, Y = 4.4

Assuming C_F =1

t^2 = 0.0123

t = 0.11m

Actual bolt spacing $B_S = \pi C/n$ = (3.14)(0.726)/(44) = 0.052m

Bolt Pitch Correction Factor

$C_F = [B_s / (2d+t)]^{0.5}$

= 0.596

•C_F =0.772

t(act) = t×•C_F = 0.085m

Select 85mm thick flange. Both flanges have the same thickness.

6. SADDLE SUPPORT DESIGN:

Material : Carbon Steel

Shell diameter = 438mm

R = D/2

l = 3660mm

Torispherical Head:

Crown radius = D, knuckle radius = 0.06×D

Total Head Depth = •(Do×ro/2)= 75.86mm = H

Shell Thickness = Head Thickness = 8mm

f_t = 95 MN/m^2

Weight of the shell and its contents = 1542.34 kg = W

Distance of saddle center line from shell end = A = R/4=109.5mm

Longitudinal Bending Moment

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

Q = W/2(L+4H/3) = 5800.96 Nm

M_1 = 621.2 kg-m

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

= 4965.9 kg-m

Stresses in shell at the saddle

$f_1 = M_1/(\pi R^2 t)$ = 41.22 kg/cm^2

$f_2 = M_2/(k_2\pi R^2 t)$ = 329.5kg/cm^2

$f_3 = M_2/(\pi R^2 t)$ = 329.5kg/cm^2

since $k_1=k_2=1$

All stresses are within allowable limits. Hence, the given parameters can be considered for design.

Axial stress in the shell due to internal pressure:

f_p= PD/(4t)

$= 24.87\ kg/cm^2$

sum of f_p and f_3 is well within the limit of permissible stress.

NOZZLE DESIGN:

FOR CONDENSER:

1. **Feed nozzle for cooling liquid:**

Assumed liquid velocity v = 3 m/s
Mass of liquid in M = 134.9 kg/s
Area of nozzle required $A = M/(\rho \times v)$
$= 0.04645 m^2$
Therefore diameter of the nozzle = $\sqrt{0.04645 \times 4/\pi}$
$d_N = 24.3$ cm

2. **Cooling liquid outlet nozzle:**

It is same as that of inlet nozzle, hence the diameter of the nozzle = 24.3 cm

3. **Vapor inlet nozzle:**

Vapor velocity is assumed as 45 m/s
Mass of vapor in is 2.51 kg/s
Density of vapor entering $0.58\ kg/m^3$
Area of nozzle required $0.096\ m^2$
Therefore
Diameter of the nozzle 34.9cm

4. **Condenser liquid outlet nozzle:**

Velocity of liquid is assumed as 2.00m/s
Mass flow rate of liquid 2.51 kg/s
Density of the condensed liquid $956.8\ kg/m^3$
Area of nozzle required $0.00131\ m^2$
Hence,
Diameter of nozzle 40.86 mm

FOR DISTILLATION COLUMN:

1. Feed nozzle:

Mass flow rate of liquid	4.823 kg/s
Density of the condensed liquid	987.8 kg/m^3
Velocity of liquid is assumed as	2.00m/s
Area of nozzle required	0.00244 m^2

Hence,

Diameter of nozzle	55.70 mm

2. Nozzle for distillate:

Mass flow rate of liquid	2.286 kg/s
Density of the liquid	956.97 kg/m^3
Velocity of liquid is assumed as	2.00m/s
Area of nozzle required	0.0012 m^2

Hence,

Diameter of nozzle	38.99 mm

3. Nozzle for residue:

Mass flow rate of residue	4.823 kg/s
Density of the residue	1016.7 kg/m^3
Velocity of liquid is assumed as	2.00m/s
Area of nozzle required	0.00123 m^2

Hence,

Diameter of nozzle	39.57 mm

Reflux liquid inlet nozzle:

Liquid flow rate	0.2285 kg/s
Density of the reflux	956.8 kg/m^3
Liquid velocity through nozzle	1.5 m/s (assumed)
Area required for assumed velocity	1.59×10^{-4}

Hence,

Diameter of the nozzle	14.23 mm