5.1 PROCESS DESIGN OF DISTILLATION COLUMN:

5.1.1 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 Acetaldehyde in liquid/Feed.

y_D = mole fraction of Acetaldehyde in Distillate.

x_W = mole fraction of Acetaldehyde 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/hr.

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

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

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

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, ^{0}K.

T_V = Temperature of Vapor, ^{0}K

T – x- y data:

$T\ ^0C$	98.5	89.9	80	71	60.5	50	39
X	0.000	0.069	0.164	0.286	0.445	0.664	1.000
Y	0.000	0.317	0.578	0.761	0.879	0.954	1.000

Table 5.1 T-x-y data.

5.1.2 Preliminary calculations:

F = 152.798 kmol/hr, x_F = 0.938, M_F = 44.123 kg/kmol.

D = 144.7 kmol/hr, x_D = 0.99, M_D = 44.04 kg/kmol.

W = 8.0931 kmol/hr, x_W = 0.177, M_W = 45.64 kg/kmol.

Distillation column temperature = 40^0 C.

Distillation column pressure = 2.08 atm. = 1586.41 mm Hg.

Basis: One-hour operation.

From the graph,

$x_D / (R_m+1) = 0.94$

Thus, $R_m = 0.0476$

Let, $R = 1.5*R_m$

Therefore, R= 1.5*0.0476= 0.0714

Thus, $x_D/ (R+1) = 0.99/ (0.0714+1)$

i.e., $x_D/ (R+1) = 0.924$

Number of Ideal trays = 4 (including the reboiler).

Reboiler is the last tray.

Number of Ideal trays in Enriching Section = 2

Number of Ideal trays in Stripping Section = 2

Now, we know that,

$R = L_o/ D$

=> Lo = R*D

i.e., L_o= 0.0714*144.7

i.e., L_o =10.33 kmol/hr.

Therefore, Lo = 10.33 kmol/hr.

L= Liquid flow rate on the Top tray = 10.33 kmol/hr.

Since feed is Liquid, entering at bubble point,

$q = (H_V - H_F) / (H_V - H_L) = 1$

Now,

Slope of q-line = q/ (q-1)

$= 1/ (1-1) = 1/0 = \infty$

Now we know that,

$$\frac{(\bar{L} - L)}{F} = q = 1$$

$(\bar{L} - L) = F$

$\bar{L} = F + L$

i.e., $\bar{L} = 10.33 + 152.798$

i.e., $\bar{L} = 163.128$ kmol/hr.

Therefore, liquid flow rate in the Stripping Section = 163.128 kmol/hr.

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., $G = 10.33 + 144.7$

i.e., $G = 155.03$ kmol/hr.

Thus, the flow rate of Vapor in the Enriching Section = 155.03 kmol/hr.

Since $\bar{G} = G$

$\bar{G} = G = 155.03$ kmol/hr.

Therefore, the flow rate of Vapor in the Stripping Section = 155.03 kmol/hr.

5.1.3 List of parameters used in calculation:

SECTION	ENRICHING SECTION		STRIPPING SECTION	
PROPERTY	**TOP**	**BOTTOM**	**TOP**	**BOTTOM**
X	0.99	0.95	0.95	0.177
Y	0.99	0.97	0.97	0.177
Liquid, L kmol/hr.	10.33	10.33	163.128	163.128
Vapor, G kmol/hr.	155.03	155.03	155.03	155.03
T_{liquid}, ^0C	39.07	39.77	39.77	80.05
T_{vapor}, ^0C	53.00	54.01	54.01	94.13
$M_{avg.}$ liquid kg/kmol	44.02	44.1	44.1	45.646
$M_{avg.}$ Vapor kmol/hr	44.02	44.06	44.06	45.646
Liquid, L kg/hr.	454.726	455.55	7193,9	7446.14
Vapor, G kg/hr	6824.42	6830.02	6830.6	7076.5
Density, ρ_l kg/m^3	784.69	784.50	784.50	747.87
Density, ρ_g kg/m^3	3.4376	3.425	3.425	3.361
$(L/G)\ (\rho_g / \rho_l)^{0.5}$	0.0039	0.004	0.06958	0.0705

Table 5.2 Parameters used in calculations.

5.1.4 Design Specification:

a) Design of Enriching Section:

Tray Hydraulics,

The design of a sieve plate tower is described below. The equations and correlations are borrowed from the 6th and 7th editions of Perry's Chemical Engineers' Handbook.

1. **Tray Spacing, (t_s) :**

   Let t_s = 18" = 457 mm. (range 0.15 – 1.0 m).

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

   Let d_h = 5 mm. (range 2.5 – 12 mm).

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

   Let $l_p = 3^* d_h$ (range 2.5 to 4.0 times d_h).

   i.e., l_p = 3*5 = 15 mm.

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

   Let $t_T = 0.6^* d_h$ (range 0.4 to 0.7 times d_h).

   i.e., t_T = 0.6*5 = 3 mm.

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

   Refer fig 3

   Now, for a triangular pitch, we know that,

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

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

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

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

   Thus,

   $(A_h/A_p) = 0.1$

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

   The plate diameter is calculated based on entrainment flooding considerations

   $L/G \{\rho_g/\rho_l\}^{0.5} = 0.004$ ---------- (maximum value)

   Now for,

   $L/G \{\rho_g/\rho_l\}^{0.5} = 0.004$ and for a tray spacing of 500 mm.

We have,

From the flooding curve, ---------- (fig.18.10, page 18.7, 6th edition Perry.)

Flooding parameter, $C_{sb, flood}$ = <u>0.29</u> ft/s .

Now,

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

---- {eqn. 18.2, page 18.6, 6th edition Perry.}

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 = 19.325 mN/m = 19.325 dyne/cm.

ρ_l = 784.5 kg/m^3.

ρ_g = 3.425 kg/m^3.

Therefore,

$U_{nf} = 0.29*(19.325/20)^{0.2}*[(784.50-3.4250)/ 3.4250]^{0.5}$

i.e.,U_{nf} = 4.349 ft/s = 1.325 m/s.

Let,

Actual velocity, $U_n = 0.8*U_{nf}$

i.e., $U_n = 0.8*1.325$

i.e., U_n = 1.06 m/s

It is desired to design with volumetric flow rate maximum (therefore, actual is less than the maximum).

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

= q_o = 6830.62 / (3600*3.4250) = 0.554 m^3/s.

Now,

Net area available for gas flow (A_n)

Net area = (Column cross sectional area) - (Down comer area.)

$A_n = A_c - A_d$

Thus,

Net Active area, $A_n = t_o / U_n = 0.554 / 1.06 = 0.522\ m^2$.

Let $L_w / D_c =$ 0.77 (range 0.6 to 0.85 times D_c).

Where, L_w = weir length, m

D_c = Column diameter, m

Now,

$\Theta_c = 2*\sin^{-1}(L_w / D_c) = 2*\sin^{-1}(0.77) = 100.7^0$

Now,

$A_c = (\pi/4) * D_c^2 = 0.785*D_c^2$, m^2

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

i.e., $A_d = [0.785*Dc^2 *(100.7^0/360^0)]-[(1/4)* (L_w / D_c) * D_c^2 * \cos(100.7^0)]$

i.e., $A_d = (0.2196* D_c^2) - (0.1288* D_c^2)$

i.e., $A_d = 0.0968*D_c^2$, m^2

Since $An = Ac - Ad$

$0.522 = (0.785*Dc^2) - (0.0968* Dc^2)$

i.e., $0.6882* D_c^2 = 0.522$

$\Rightarrow D_c^2 = 0.522/ 0.6882 = 0.7585$

$\Rightarrow D_c = \sqrt{0.7585}$

$D_c = 0.87$ m

Since $L_w / D_c = 0.77$,

$\Rightarrow L_w = 0.77* D_c = 0.77*0.87 = 0.67$ m.

Therefore, $L_w = 0.67$ m.

Now,

$A_c = 0.785*0.87^2 = 0.5944\ m^2$

$A_d = 0.0968*D_c^2 = 0.0968*0.87^2 = 0.0724\ m^2$

$A_a = A_c - 2* A_d$

i.e., $A_a = 0.5944 - 2*0.0724 \Rightarrow A_a = 0.4496\ m^2$

7. Perforated plate area (A_p):

Now,

$L_w / D_c = 0.67/ 0.87 = 0.7701$

$\Theta_c = 100.73^0$

$\alpha = 180^0 - \Theta_c$

i.e., $\alpha = 180^0 - 100.73^0$

$\Rightarrow \alpha = 79.27^0$

Now,

$A_{cz} = 2^* L_w^*$ (thickness of distribution)

Where, A_{cz} = area of calming zone, m^2 (5 to 20% of A_c)

$A_{cz} = 2^*0.67^* (30\times10^{-3}) = 0.0402\ m^2$ -------- (which is 6.76% of A_c)

Also,

$A_{wz} = 2^*\{(\pi/4) * D_c^{2} * (\Theta_c /360^0) - (\pi/4) * (D_c - 30^*10^{-3})^2 * (\Theta_c /360^0)\}$

Where, A_{wz} = area of waste periphery, m^2 (range 2 to 5% of A_c)

i.e., $A_{wz} = 2^*\{(\pi/4) * 0.87^2 * (100.73^0/360^0 - (\pi/4) * (0.87-30^*10^{-3})^2 * (100.73^0/360^0)\}$

i.e., $A_{wz} = 0.0225\ m^2$ --------- (which is 3.8% of A_c)

Now,

$A_p = A_c - (2^*A_d) - A_{cz} - A_{wz}$

i.e., $A_p = 0.5944 - (2^*0.0724) - 0.0402 - 0.0225$

Thus, $A_p = 0.387\ m^2$.

8. Total Hole Area (A_h):

Since,

$A_h / A_p = 0.1$

$\Rightarrow A_h = 0.1^* A_p$

i.e., $A_h = 0.1^*0.387$

$\Rightarrow A_h = 0.0387\ m^2$

Thus, Total Hole Area = $0.0387\ m^2$

Now we know that,

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

Where, n_h = number of holes.

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

i.e., $n_h = (4^*0.0387)/ (\pi * 0.005^2)$

$\Rightarrow n_h \approx 1971$

Therefore, Number of holes = 1971.

9. Weir Height (h_w):

Let h_w = 50 mm.

10. Weeping Check

The static pressure below the tray should be capable enough to hold the liquid above the tray so that no liquid sweeps through the holes.

All the pressure drops calculated in this section are represented as mm head of liquid on the plate. This serves as a common basis for evaluating the pressure drops.

Notations used and their units:

h_d = Pressure drop through the dry plate, mm of liquid on the plate

u_h = Vapor velocity based on the hole area, m/s

h_{ow} = Height of liquid over weir, mm of liquid on the plate

h_σ = Pressure drop due to bubble formation, mm of liquid

h_{ds}= Dynamic seal of liquid, mm of liquid

h_l = Pressure drop due to foaming, mm of liquid

h_f = Pressure drop due to foaming, actual, mm of liquid

D_f = Average flow length of the liquid, m

R_h = Hydraulic radius of liquid flow, m

u_f = Velocity of foam, m/s

(N_{Re}) = Reynolds number of flow

f = Friction factor

h_{hg} = Hydraulic gradient, mm of liquid

h_{da} = Loss under down comer apron, mm of liquid

A_{ds} = Area under the down comer apron, m^2

c = Down comer clearance, m

h_{dc} = Down comer backup, mm of liquid

Calculations:

Head loss through dry hole

h_d = head loss across the dry hole

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

Where, 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 18.14, page 18.9 6th edition Perry.

Now,

$(A_h / A_a) = 0.0387/ 0.4496 = 0.086$

Also, $t_T/d_h = 3/5 = 0.60$

Thus for $(A_h/A_a) = 0.086$ and $t_T/d_h = 0.60$

We have from fig. edition 18.14, page 18.9 6th Perry.

$C_v = 0.74$

$\Rightarrow$ $k_2 = 50.8 / 0.74^2 = 92.77$

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

$= q_t = 1.8956/ (3.4376) = 0.5514\ m^3/s$ -------- (minimum at top)

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

$= q_o = 1.897 / (3.425) = 0.554\ m^3/s$. ---- (maximum at bottom)

Velocity through the hole area (U_h):

Now,

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

$= 0.5514/0.0387= 14.25$ m/s

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

$= 0.554/0.0387 = 14.31$ m/s

Now,

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

$= 92.77*(3.4376/784.69) *14.25^2$

$\Rightarrow h_{d, top}$ = 82.526 mm clear liquid. -------- (minimum at top)

Also,

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

$= 92.77 * (3.425/784.50) \times 14.31^2$

$\Rightarrow h_{d, bottom}$ = <u>82.94</u> mm clear liquid ----- (maximum at bottom)

Head Loss Due to Bubble Formation

$h_\sigma = 409 [\sigma / (\rho_{L*} d_h)]$

where σ =surface tension, mN/m (dyne/cm) = 19.325 dyne/cm.

d_h =Hole diameter, mm

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

= 784.69 kg/m^3

$h_\sigma = 409 [19.325/(784.69 *5)]$

h_σ = 2.014 mm clear liquid

Height of Liquid Crest over Weir:

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

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

= 0.1263*60/ (784.69)

= 0.009 m^3/min.

Thus, q' = 2.377 gal/min.

L_w = weir length = 0.67 m = 2.198 ft

Now,

$q'/L_w^{2.5} = 2.377/ (2.198)^{2.5} = 0.3318$

Now for $q'/L_w^{2.5}$ = 0.3318 and L_w/D_c =0.7701

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

F_w= correction factor =1.03

Thus, $h_{ow} = 1.03 * 664 * [0.00015/0.67]^{2/3}$

$\Rightarrow h_{ow}$ = 2.52 mm clear liquid.

Now,

$(h_d + h_\sigma)$ = 82.526 + 2.014 = 84.54 mm ------ Design value

$(h_w + h_{ow})$ = 50 + 2.52 = 52.52 mm

For, A_h/A_a = 0.086 and $(h_w + h_{ow})$ = 52.52 mm

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

i.e., we have from fig. 18.11, page 18.7, 6th edition Perry

$(h_d + h_\sigma)_{min}$ = 13.0 mm ------- Theoretical value.

The minimum value as found is 13.0 mm.

Since the design value is greater than the minimum value**, there is no problem of weeping.**

Down comer Flooding:

$h_{ds} = h_w + h_{ow} + (h_{hg}/2)$ ------- (eq^n 18.10, page 18.10, 6th edition Perry)

Where,

h_w = weir height, 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.

Hydraulic gradient, h_{hg}

Let h_{hg} = 0.5 mm.

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

= 50 + 2.52 + 0.5/2 = 52.77 mm.

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

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, $U_a = (G_b/\rho_g)/ A_a$ = 1.8974/(3.425 * 0.4496) = 1.232 m/s

Thus, U_a = 4.042 ft/s

ρ_g = 3.4250 kg/m^3 = 0.209 lb/ft^3

Therefore, $F_{ga} = 4.042*(0.209)^{0.5}$

$F_{ga} = 1.848$

Now for F_{ga} = 1.848, we have from fig. 18.15, page 18.10 6th edition Perry

Aeration factor = β = 0.6

Relative Froth Density = ϕ_t = 0.2

Now $h_l' = \beta * h_{ds}$ ---- (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,

$\Rightarrow h_l' = 0.6*52.77 = 31.662$ mm.

Now,

$h_f = h_l'/\phi_t$ ------- (eq$^{n.}$ 18.9, page 18.10, 6th edition Perry)

$\Rightarrow h_f = 31.662/ 0.2 = 158.31$ mm.

Average width of liquid flow path, $D_f = (D_c + L_w)/2$

$= (0.87 + 0.67)/2 = 0.77$ m.

Hydraulic radius of aerated mass $R_h = h_f * D_f /(2*h_f + 1000*D_f)$ (from eq. 18.23, page 18.12 6th edition Perry)

$R_h = 158.31*0.77/(2*158.31 + 1000*0.77)$

$= 0.112$ m.

Velocity of aerated mass, $U_f = 1000*q/ (h_l' * D_f)$

Volumetric flow rate, q = 1.6061*10^{-4} m^3/s.

$U_f = 1000* 1.6061*10^{-4} / (31.662* 0.77)$

$= 0.0066$ m/s.

Reynolds modulus $N_{Re} = R_h * U_f * \rho_l / \mu_{liq}$

$= 0.112 * 0.0066 * 784.5 /(1.03 * 10^{-3})$

$= 563.012$

$h_{hg} = 1000* f* U_f^2 *L_f/(g * R_h)$

f = 0.6 for h_w = 1.97” and N_{Re} = 563. 012

$L_f = 2 * D_c/2 \cos(\Theta_c / 2) = 0.5549$ m

$h_{hg} = 1000* 0.6 *0.0066^2*0.5549/(9.81* 0.112)$

$= 0.0132$ mm.

Head loss over down comer 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 down comer 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 down comer apron, m^2

Now,

$q = 1.6061 * 0^{-4}\ m^3/s$

Take clearance, C = 1” = 25.4 mm

$h_{ap} = h_{ds} - C = 52.77 - 25.4 = 27.37$ mm

$A_{da} = L_w * h_{ap} = 0.67 * 27.37 * 10^{-3} = 0.0183\ m^2$

$h_{da} = 165.2[(1.6061 * 10^{-4})/ (0.0183)]^2$

$h_{da} = 0.0127$ mm

Now,

$h_t = h_d + h_l`$

Here h_d and h_l' are calculated at bottom of the enriching section.

Now we have,

$h_{d, bottom} = 82.94$ mm

$h_{l, bottom} = 31.662$ mm

$h_t = h_d + h_l`$

$= 82.94+31.662$

$h_t = 114.602$ mm

Down comer Backup:

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

h_t = total pressure drop across the plate (mm liquid)

$= h_d + h_l`$

h_{dc} = height in down comer, mm liquid,

h_w = height of weir at the plate outlet, mm liquid,

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

h_{da} = head loss due to liquid flow under the down comer apron, mm liquid,

h_{hg} = liquid gradient across the plate, mm liquid.

h_{dc} = 114.602 +50 +2.52 + 0.0132 + 0.0127

h_{dc} = 167.148 mm.

Let ϕ_{dc} = average relative froth density (ratio of froth density to liquid density) =0.5

$h`_{dc} = h_{dc} / \phi_{dc}$ = 167.148/ 0.5

$h`_{dc}$ = 334.29 mm.

which is less than the tray spacing, t_s= 457 mm.

Hence no flooding in the enriching section and hence the design calculations are acceptable.

b). Design of Stripping Section:

Tray Hydraulics

The design of a sieve plate tower is described below. The equations and correlations are borrowed from the 6th and 7th editions of Perry's Chemical Engineers' Handbook.

1 **Tray Spacing, (t_s) :**

Let t_s = 18" = 457 mm.

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

Let d_h = 5 mm.

3 **Hole Pitch (l_p):**

Let $l_p = 3*d_h$

i.e., l_p = 3*5 = 15 mm.

4 **Tray thickness (t_T):**

Let $t_T = 0.6* d_h$

i.e., t_T = 0.6*5 = 3 mm.

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

Refer fig 3

Now, for a triangular pitch, we know that,

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

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

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

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

Thus,

$(A_h/A_p) = 0.1$

6 Plate Diameter (D_c):

The plate diameter is calculated based on the flooding considerations

$L/G \{\rho_g/\rho_l\}^{0.5} = 0.0705$ ---------- (maximum value)

Now for,

$L/G \{\rho_g/\rho_l\}^{0.5} = 0.0705$ and for a tray spacing of 457 mm.

We have,

From the flooding curve, ---------- (fig.18.10, page 18.7, 6th edition Perry.)

Flooding parameter, $C_{sb,\ flood} = 0.27$ ft/s.

Now,

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

---- {eqn. 18.2, page 18.6, 6th edition Perry.}

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 = 18.330 mN/m = 18.330 dyne/cm.

ρ_l = 747.87 kg/m^3.

ρ_g = 3.361 kg/m^3.

Therefore,

$U_{nf} = 0.27* (18.33/20)^{0.2} \times [(747.87-3.361)/ 3.361]^{0.5}$

i.e., U_{nf} = 3.949 ft/s

Let,

Actual velocity, $U_n = 0.8*U_{nf}$

i.e., $U_n = 0.8*3.949$

i.e., $U_n = 3.159$ ft/s

$U_n = 0.9628$ m/s

Now,

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

$= q_o = 1.9657/ (3.361) = 0.5848$ m^3/s.

Now,

Net area available for gas flow (A_n)

Net area = (Column cross sectional area) - (Down comer area.)

$A_n = A_c - A_d$

Thus,

Net Active area, $A_n = q_o/ U_n = 0.5848/ 0.9628 = 0.6074$ m^2.

Let $L_w / D_c = 0.77$

Where, L_w = weir length, m

D_c = Column diameter, m

Now,

$\Theta_c = 2*\sin^{-1}(L_w / D_c) = 2*\sin^{-1}(0.77) = 100.7^0$

Now,

$A_c = (\pi/4) * D_c^2 = 0.785*D_c^2$, m^2

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

i.e., $A_d = [0.7854* Dc^2 * (100.7^0/360^0)]-[(1/4) * (L_w / D_c) * D_c^2 * \cos(100.7^0/2)]$

i.e., $A_d = (0.2196* D_c^2) - (0.1288* D_c^2)$

i.e., $A_d = 0.0968*D_c^2$, m^2

Since An = Ac -Ad

$0.6882 = (0.785*Dc^2) - (0.0968* Dc^2)$

i.e., $0.6882* D_c^2 = 0.6074$

$\Rightarrow D_c^2 = 0.6074/ 0.6882 = 0.8826$

$\Rightarrow D_c = \sqrt{0.8826}$

$D_c = 0.94$ m

Therefore, $D_c = 0.94$ m

Since $L_w / D_c = 0.77$

$\Rightarrow$ $L_w = 0.77* D_c = 0.77*0.94 = 0.724$ m.

Therefore, $L_w = 0.724$ m.

Now,

$A_c = 0.785*0.94^2 = 0.694\ m^2$

$A_d = 0.09688*D_c^{\ 2} = 0.0968*0.94^2 = 0.0866\ m^2$

$A_n = A_c - A_d$

i.e., $A_n = 0.694 - 0.0866$

$\Rightarrow$ $A_n = 0.6074\ m^2$

7 Perforated plate area (A_p):

$A_a = Ac - (2*A_d)$

i.e., $A_a = 0.694 - (2*0.0866)$

$\Rightarrow$ $A_a = 0.5208\ m^2$

Now,

$L_w / D_c = 0.724/ 0.94 = 0.7702$

$\Theta_c = 100.746\ ^0$

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

i.e., $\alpha = 180\ ^0 - 100.746\ ^0$

$\Rightarrow \alpha = 79.254\ ^0$

Now,

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

Where, A_{cz} = area of calming zone, m^2

$A_{cz} = 2*0.724* (30*10^{-3}) = 0.04344\ m^2$ -------- (which is 6.26% of A_c)

Also,

$A_{wz} = 2*\{(\pi/4) * D_c^{\ 2} * (\Theta_c /360\ ^0) - (\pi/4) * (D_c - 0.03)^{2} * (\Theta c /360\ ^0)\}$

Where, A_{wz} = area of waste periphery, m^2

i.e., $A_{wz} = 2*\{(\pi/4) * 0.94^2 * (100.746\ ^0/360\ ^0)$

$- (\pi/4) * (0.94-0.03)^{2} * (100.746\ ^0/360\ ^0)\}$

i.e., $A_{wz} = 0.0244\ m^2$ --------- (which is 3.515% of A_c)

Now,

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

i.e., $A_p = 0.694 - (2*0.0866) - 0.04344 - 0.0244$

Thus, $A_p = 0.453\ m^2$

8 Total Hole Area (A_h):

Since,

$A_h / A_p = 0.1$

$\Rightarrow A_h = 0.1 * A_p$

i.e., $A_h = 0.1*0.453$

$\Rightarrow A_h = 0.0453\ m^2$

Thus, Total Hole Area = 0.04147 m^2

Now we know that,

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

Where n_h = number of holes.

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

i.e., $n_h = (4*0.0453)/(\pi * 0.005^2)$

$\Rightarrow n_h = 2307.21 \approx 2308$

Therefore, Number of holes = 2308.

9 Weir Height (h_w):

Let, h_w = 50 mm.

10 Weeping Check

All the pressure drops calculated in this section are represented as mm head of liquid on the plate. This serves as a common basis for evaluating the pressure drops.

Notations used and their units:

h_d = Pressure drop through the dry plate, mm of liquid on the plate

u_h = Vapor velocity based on the hole area, m/s

h_{ow} = Height of liquid over weir, mm of liquid on the plate

h_σ = Pressure drop due to bubble formation, mm of liquid

h_{ds}= Dynamic seal of liquid, mm of liquid

h_l = Pressure drop due to foaming, mm of liquid

h_f = Pressure drop due to foaming, actual, mm of liquid

D_f = Average flow length of the liquid, m

R_h = Hydraulic radius of liquid flow, m

U_f = Velocity of foam, m/s

(N_{Re}) = Reynolds number of flow

f = Friction factor

h_{hg} = Hydraulic gradient, mm of liquid

h_{da} = Loss under down comer apron, mm of liquid

A_{da} = Area under the down comer apron, m^2

C = Down comer clearance, m

h_{dc} = Down comer backup, mm of liquid

Calculations:

Head loss through dry hole

h_d = head loss across the dry hole

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

where U_h =gas velocity through hole area

k_1, k_2 are constants

<u>For sieve plates</u>

k_1 = <u>0</u> and

$k_2 = 50.8 / (C_v)^2$

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

Now,

$(A_h/A_a) = 0.0453/ 0.5208 = 0.087$

also $t_T/d_h = 3/5 = 0.60$

Thus for $(A_h/A_a) = 0.087$ and $t_T/d_h = 0.60$

We have from fig. edition 18.14, page 18.9 6th Perry.

$$C_v = 0.73$$

$$\Rightarrow \quad k_2 = 50.8 / 0.73^2 = 95.327$$

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

$=q_t = 1.8974/ (3.425) = 0.554 m^3/s$ -------- (minimum at top)

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

$= q_o = 1.9657 / (3.361) = 0.5848\ m^3/s$. ------- (maximum at bottom).

Velocity through the hole area (U_h):

Now,

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

$= 0.554/0.0453 = 12.23$ m/s

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

$= 0.5848/0.0453 = 12.91$ m/s

Now,

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

$$= 95.327*(3.425/784.50)*12.23^2$$

$\Rightarrow h_{d,\ top} = 62.25$ mm clear liquid. -------- (minimum at top)

also

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

$$= 95.327*(3.361/747.87)*12.91^2$$

$\Rightarrow \quad h_{d,\ bottom} = 71.4$ mm clear liquid ----- (maximum at bottom)

Head Loss Due to Bubble Formation

$$h_\sigma = 409\ [\sigma / (\rho_{L*} d_h)]$$

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

d_h = Hole diameter, mm

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

$\rho_l = 784.5\ kg/m^3$

h_σ = 409 [18.33 / (784.5 * 5)]

h_σ = 1.911 mm clear liquid.

Height of Liquid Crest over Weir

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

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

= 0.0035 m^3/s.

q' = 1.998 * 60 / 7193.9 = 0.0166 m^3/min = 4.384 gal/min.

Thus, q' = 4.384 gal/min.

L_w = weir length = 0.724 m = 2.3753 ft

Now,

$q'/L_w^{2.5}$ = 4.384/ $(2.375)^{2.5}$ = 0.504

Now for $q'/L_w^{2.5}$ = 0.504 and L_w/D_c =0.7702

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

F_w = correction factor =1.02

Thus, $h_{ow} = 1.02 \times 664 \times [(0.00035)/0.724]^{2/3}$

$\Rightarrow$ h_{ow} = 4.17 mm clear liquid.

Now,

$(h_d + h_\sigma)$ = 62.25 + 1.911 = 64.161 mm ------ Design value

$(h_w + h_{ow})$ = 50 + 4.17 = 54.17mm

Also, A_h/A_a = 0.087 and $(h_w + h_{ow})$ =50 +4.17 = 54.17 mm

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

i.e., we have from fig. 18.11, page 18.7, 6th edition Perry

$(h_d + h_\sigma)_{min}$ = 12.0 mm ------- Theoretical value.

The minimum value as found is 12.0 mm.

Since the design value is greater than the minimum value**, there is no problem of weeping.**

Down comer Flooding:

$h_{ds} = h_w + h_{ow} + (h_{hg}/2)$ ------- (eq^n 18.10, page 18.10, 6th edition Perry)

Where,

h_w = weir height, 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.

Hydraulic gradient, h_{hg}

Let h_{hg} = 0.5 mm.

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

$= 50 + 4.17 + 0.5/2 = 54.42$ mm.

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

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, $U_a = (G_b/\rho_g)/ A_a = 1.9657 / (0.5208*3.361) = 1.123$ m/s

Thus, U_a = <u>3.684</u> ft/s

$\rho_g = 3.361$ kg/m^3 = 0.205 lb/ft^3

Therefore, $F_{ga} = 3.684* (0.205)^{0.5}$

$F_{ga} = 1.668$

Now for F_{ga} = 1.668, we have from fig. 18.15, page 18.10 6th edition Perry)

Aeration factor = β = 0.61

Relative Froth Density = ϕ_t = 0.21

Now $h_l' = \beta * h_{ds}$ ---- (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,

$\Rightarrow h_l' = 0.61* 54.42$ = <u>33.1962</u> mm.

Now,

$h_f = h_l'/\phi_t$ ------- (eq$^{n.}$ 18.9, page 18.10, 6th edition Perry)

$\Rightarrow h_f = 33.1962/ 0.21 = 158.07$ mm.

Average width of liquid flow path, $D_f = (D_c + L_w)/2$

$= (0.94 + 0.724)/2 = 0.832$ m.

Hydraulic radius of aerated mass $R_h = h_f * D_f /(2*h_f + 1000*D_f)$ (from eq. 18.23, page 18.12 6th edition Perry)

$R_h = 158.07*0.832/(2*158.07 + 1000*0.832)$

$= 0.1145$ m.

Velocity of aerated mass, $U_f = 1000*q/ (h_l' * D_f)$

Volumetric flow rate, q = 2.068/747.87 =0.00276 m^3/s.

$U_f = 1000* 0.00276 / (33.1962* 0.832)$

$= 0.0999$ m/s.

Reynolds modulus $N_{Re} = R_h * U_f * \rho_l / \mu_{liq}$

$= 0.1145 * 0.0999 * 747.87 /(0.924 * 10^{-3})$

$= 9257.17$

$h_{hg} = 1000* f* U_f^2 *L_f/(g * R_h)$

f = 0.18 for h_w =1.97" and $N_{Re} = 9257.17$

$L_f = 2 * D_c/2 \cos (\Theta_c / 2) = 0.5995$ m.

$h_{hg} = 1000* 0.18 *0.0999^2*0.5995/(9.81* 0.1145)$

$= 0.958$ mm.

Head loss over down comer 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 down comer 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 down comer apron, m^2

Now,

q = 0.00276 m^3/s

Take clearance, C = 1" = 25.4 mm

$h_{ap} = h_{ds} - C = 54.42 - 25.4 = 29.02$ mm

$A_{da} = L_w \times h_{ap} = 0.724 * 29.03*10^{-3} = 0.021\ m^2$

$h_{da} = 165.2[(0.00276)/ (0.021)]^2$

$h_{da} = 2.85$ mm

Now

$h_t = h_d + h_l`$

Here h_d and h_l' are calculated at bottom of the Stripping section.

Now we have,

$h_{d,\ bottom} = 71.4$ mm

$h_{l,\ bottom} = 33.1962$ mm

$h_t = h_d + h_l`$

$= 71.4+33.1962$

$h_t = 104.6$ mm

Down comer Backup:

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

h_t = total pressure drop across the plate (mm liquid)

$= h_d + h_l`$

h_{dc} = height in down comer, mm liquid,

h_w = height of weir at the plate outlet, mm liquid,

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

h_{da} = head loss due to liquid flow under the down comer apron, mm liquid,

h_{hg} = liquid gradient across the plate, mm liquid.

$h_{dc} = 104.6 + 50 + 4.17 + 0.958 + 2.85$

$h_{dc} = 162.58$ mm.

Let ϕ_{dc} = average relative froth density (ratio of froth density to liquid density) = 0.5

$h`_{dc} = h_{dc} / \phi_{dc} = 162.58/ 0.5$

$h`_{dc} = 325.16$ mm.

Which is less than the tray spacing, t_s= 457 mm.

Hence no flooding in the Stripping section and hence the design calculations are acceptable.

Formulas used in calculation of properties:

1 VISCOSITY:

(i). Average Liquid Viscosity:

$$(\mu_{liq})^{1/3} = [x_1 \times (\mu_1)^{1/3}] + [x_2 \times (\mu_2)^{1/3}]$$

2 DIFFUSIVITIES:

(i). Liquid Phase Diffusivity:

For the case of Organic solutes diffusing in Organic solvents

$$D_{AB} = (1.173*10^{-13}*(\Theta*M)^{0.5} * T) / [\eta_B \times (V_A)^{0.6}]$$ –(Richardson – coulson vol.6)

Where,

Θ = constant

M = molecular weight.

T = absolute temperature, ^{0}K,

η_B = viscosity of solvent B, cP,

V_A =molar volume of solute A at its normal boiling temperature, cm^3/g-mol.

D_{AB} =mutual diffusivity coefficient of solute A at very low concentration in solvent B, cm^2/s

(ii). Gas Phase Diffusivity:

$$D_{AB} = 1.013*10^{-7} \times T^{1.75} \times [(M_A+M_B)/ (M_A \times M_B)]^{1/2}\}/\{P \times [(\sum v_A)^{1/3} + (\sum v_B)^{1/3}]^2$$

------ (Richardson – coulson vol.6).

Where P = Pressure in atmospheres,

T = Temperature in ^{0}K

D_{AB} = Diffusivity, cm^2/s

$\sum v_A$ and $\sum v_B$ = summation of atomic diffusion volumes for components A and B respectively.

M_A and M_B = Molecular weights of components A and B respectively.

3. SURFACE TENSION:

$$\sigma = [P_{ch} \times (\rho_l - \rho_g)/M]^4 \times 10^{-12}$$ ----- (eq$^{n.}$ 8.23, page 293, Coulson and Richardson vol.6)

Where,

σ = surface tension, dyne/cm

P_{ch} =Sugden's Parachor,

ρ_l = liquid density, kg/m^3

ρ_g = density of saturated vapor, kg/m^3

M = Molecular weight

σ, ρ_l, and ρ_g are evaluated at system temperature.

$\sigma_{mix} = \sum (x_i \times \sigma_i)$ where i=1,2,3,……n.

4. LIQUID DENSITY:

$\rho = P_c / (R * T_c * Z_c^{[1 + (1 - T_r)^{2/7}]})$ (Coulson and Richardson vol.6)

Where,

P_c = critical pressure = $M/(0.34 + (\sum ▲P)^2)$

M = Molecular weight.

T_c = Critical temperature = $T_b / (0.567 + \sum ▲ T - (\sum ▲ T)^2)$

T_b = Normal boiling temperature ^{0}K.

$Z_c = P_c * V_c / (R * T_c)$

V_c = critical volume

R = universal gas constant.

5. GAS DENSITY:

$\rho = P * M /(R * T)$

P = pressure

M = Molecular weight.

R = universal gas constant.

T = temperature.

Enriching section:

Column efficiency (AIChe method)

1. 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,

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

m = slope of Equilibrium Curve,

G_m = Gas flow rate, mol/s

L_m = Liquid flow rate, mol/s

$N_g = (0.776 + (0.0045*h_w) - (0.238*U_a*\rho_g^{0.5}) + (105*W))/ (N_{Sc, g})^{0.5}$

----- (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

= 1.232 m/s.

U_a = 1.232 m/s

$D_f = (L_w + D_c)/2 = (0.87 + 0.67)/2 = 0.77$ m

$q = 161.30 * 10^{-6}$ m^3/s

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

$= q/D_f = 161.3*10^{-6}/0.77 = 209.48*10^{-6}$ m^3/ (s.m)

$N_{Sc, g}$ = Schmidt number $=\mu_g/ (\rho_g*D_g) = 0.6256$

D_g = Diffusivity = $4.433 * 10^{-6}$ m^2/s.

Now,

Number of gas phase transfer units,

$N_g=(0.776+(0.0045*50)-(0.238*1.232*3.425^{0.5})+(105*209.48*10^{-6}))/ (0.6256)^{0.5}$

10 $N_g = 0.6073$

Also,

Number of liquid phase transfer units,

$N_l = k_l * a * \theta_l$ ----- (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

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

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

$q = 161.30*10^{-6}\ m^3/s$

$h_l = h_l' = 31.662$ mm

$A_a = 0.4496\ m^2$

$\theta_l = 31.662*0.4496/ (1000*161.3*10^{-6}) = 88.25$ s

$k_l *a = (3.875*10^8*D_L)^{0.5}* ((0.40*U_a*\rho_g^{0.5}) + 0.17)$

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

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

$k_l *a = (3.875*10^8*2.002*10^{-9})^{0.5}* ((0.40*1.232*3.425^{0.5}) + 0.17)$

$k_l *a = 0.933$ m/s

$N_l = k_l * a*q_l$

i.e., N_l = 0..933*88.25

$\lambda_m = m_m * G_m/L_m$

$\lambda_b = 0.5990$

$\lambda_t = 0.3$

$\Rightarrow \lambda = 0.4495$

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

$= 1/ [(1/1.093) + (0.4495/82.33)]$

$N_{og} = 1.0865$

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

$= 1-e^{-1.0865} = 1-\exp(-1.0865)$

$E_{og} = 0.6626$

Point Efficiency = E_{og} = 0.6626

2 Murphree Plate Efficiency (E_{mv}):

Now, Peclet number $= N_{Pe} = Z_l^2 / (D_E * q_l)$

Z_l = length of liquid travel, m

$D_E = (6.675 * 10^{-3} * (U_a)^{1.44}) + (0.922 * 10^{-4} * h_l) - 0.00562$

----- (eq^n. 18.45, page 18.17, 6th edition Perry)

Where D_E = Eddy diffusion coefficient, m^2/s

$D_E = (6.675 * 10^{-3} * (1.232)^{1.44}) + (0.922 * 10^{-4} * 31.662) - 0.00562$

$D_E = 0.0063\ m^2/s$

Also,

$Z_l = D_c * \cos(\theta_c/2) = 0.87 * \cos(100.73^0/2) = 0.555$ m

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

$= 0.555^2 / (0.0063 * 88.25)$

$N_{Pe} = 0.554$

$\lambda * E_{og} = 0.4495 * 0.6626 = 0.2978$

Now, for $\lambda * E_{og} = 0.2978$ and $N_{Pe} = 0.554$

We have from fig.18.29a, page 18.18, 6th edition Perry

$E_{mv} / E_{og} = 1.09$

$E_{mv} = 1.09 * E_{og} = 1.09 * 0.6626 = 0.722$

Murphee Plate Efficiency = $E_{mv} = 0.722$

3 Overall Efficiency (E_{OC}):

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

----- (eq^n. 18.46, page 18.17, 6th edition Perry)

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

----- (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.

$(L/G)*\{\rho_g/\rho_l\}^{0.5} = 0.004$

Thus, for $(L/G)*\{\rho_g/\rho_l\}^{0.5} = 0.004$ 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 down flow = 0.095

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

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

$= 0.722/ (1+0.722[0.095/ (1-0.095)])$

$\Rightarrow E_\alpha = 0.6711$

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

$E_{OC} = \log [1+ 0.6711(0.4495-1)]/ \log 0.4495$

Overall Efficiency = $E_{OC} = 0.5767$

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

Where N_T = Theoretical plates,

N_{act} = actual trays

$N_{act} = 2/0.5767 = 3.47 \approx 4$

Thus, Actual trays in the Enriching Section = 4

Thus 4th tray is the feed tray.

Total Height of Enriching section = $4*t_s = 4*457 = 1828$ mm = 1.828 m $\approx$ 2 m.

B) Stripping Section:

1 Point Efficiency, (E_{og}):

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

Where N_{og} = Overall transfer units

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

Where N_l = Liquid phase transfer units,

N_g = Gas phase transfer units,

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

m = slope of Equilibrium Curve,

G_m = Gas flow rate, mol/s

L_m = Liquid flow rate, mol/s

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

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

where h_w = weir height = 50.00 mm

U_a = Gas velocity through active area, m/s

= (vapor flow rate in kg/hr)/ (vapor density ×active area)

= 1.123 m/s.

U_a = 1.123 m/s

$D_f = (L_w + D_c)/2 = (0.724 + 0.94)/2 = 0.832$ m

$q = 0.00276\ m^3/s$

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

$= q/D_f = 0.00276/0.832 = 0.0033\ m^3/ (s.m)$

$N_{Sc,\,g}$ = Schmidt number $=\mu_g/ (\rho_g*D_g) = 0.0095*10^{-3}/(3.361*4.433*10^{-6})$

= 0.6776

Now,

Number of gas phase transfer units,

$N_g = (0.776 + (0.00457*50) - (0.238*1.232*3.361^{0.5}) + (105*0.0033))/ (0.6776)^{0.5}$

$N_g = 1.046$

Also,

Number of liquid phase transfer units,

$N_l = k_l* a*\theta_l$ ----- (eq^n 18.36a, page 18.15, 6^{th} 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

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

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

$q = 0.00276\ m^3/s$

$h_l = h_l' = 33.1962$ mm

$A_a = 0.5208\ m^2$

$\theta_l = 33.1962*0.5208/ (1000*0.00276) = 6.264$ s

$k_l *a = (3.875*10^8*D_L)^{0.5}* ((0.40*U_a*\rho_g^{0.5}) + 0.17)$

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

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

$k_l *a = (3.875*10^8*2.002*10^{-9})^{0.5}* ((0.40*1.232*3.361^{0.5}) + 0.17)$

$k_l *a = 0.875$ m/s

$N_l = k_l* a*\theta_l$

i.e., $N_l = 0.875*6.264 =5.481$ m

<u>Slope of equilibrium Curve</u>

m_{top} = <u>0.2</u>

m_{bottom} = <u>0.3</u>

$\lambda t = m_t *G_m/L_m$ = <u>2.85</u>

$\lambda b = m_b*G_m/L_m$ = <u>0.19</u> $\Rightarrow$ λ = 1.52

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

$= 1/ [(1/1.046) + (1.52/5.481)]$

N_{og} = <u>0.8108</u>

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

$= 1-e^{-0.8108} = 1-\exp(-0.8108)$

$E_{og} = 0.5555$

Point Efficiency = E_{og} = 0.5555

2 Murphee Plate Efficiency (E_{mv}):

Now, Pelect number =$N_{Pe} = Z_l / (D_E* q_l)$

Z_l = length of liquid travel, m

$D_E = (6.675 * 10^{-3}* (U_a)^{1.44}) + (0.922 * 10^{-4}* h_l) - 0.00562$

----- (eq$^{n.}$ 18.45, page 18.17, 6th edition Perry)

Where, D_E = Eddy diffusion coefficient, m^2/s

$D_E = (6.675 * 10^{-3}* (1.123)^{1.44}) + (0.922 * 10^{-4}* 33.1962) - 0.00562$

$D_E = 0.0053\ m^2/s$

Also,

$Z_l = D_c* \cos(\theta_c/2) = 0.94* \cos(100.746^0/2) = 0.5995$ m

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

$= 0.5995^2 / (0.0053 * 6.264)$

$N_{Pe} = 10.82$

$\lambda * E_{og} = 1.52 * 0.5555 = 0.844$

Now for $\lambda * E_{og} = 0.844$ and $N_{Pe} = 10.82$

We have from fig.18.29a, page 18.18, 6th edition Perry

$E_{mv} / E_{og} = 1.49$

$E_{mv} = 1.49 * E_{og} = 1.49 * 0.5555 = 0.8276$

Murphree Plate Efficiency = $E_{mv} = 0.8276$

3 **Overall Efficiency (E_{OC}):**

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

----- (eq$^{n.}$ 18.46, page 18.17, 6th edition Perry)

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

----- (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.

$(L/G) * \{\rho_g / \rho_l\}^{0.5} = 0.0705$

thus, for $(L/G) * \{\rho_g / \rho_l\}^{0.5} = 0.0705$ 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 down flow = 0.04

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

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

$= 0.8276 / (1 + 0.8276[0.04 / (1 - 0.04)])$

$\Rightarrow E_\alpha = \underline{0.8}$

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

E_{OC} = log [1+ 0.8(1.52-1)]/ log 1.52

Overall Efficiency = E_{OC} = <u>0.83</u>

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

Where N_T = Theoretical plates,

N_{act} = actual trays

N_{act} = 2/0.83 = 2.41 ≈ 3

Thus, Actual trays in the Stripping Section = 3

Total Height of Stripping section = 3*t_s = 3*457 = 1371 mm = 1.371 m

Total Height of Column =H_C = Height of Enriching section + Height of Stripping section

= 2+ 1.371= 3.371 m ≈ 3.4 m

SUMMARY OF THE DISTILLATION COLUMN:

A) Enriching section

Tray spacing = 457 mm

Column diameter = 870 mm = 0.87 m

Weir length = 0.67 m

Weir height = 50 mm

Hole diameter = 5 mm

Hole pitch = 15 mm, triangular

Tray thickness = 3 mm

Number of holes = 1971

Flooding % = 80%

B) Stripping section

Tray spacing = 457 mm

Column diameter = 940 mm = 0.94 m

Weir length = 0.724 m

Weir height = 50 mm

Hole diameter = 5 mm

Hole pitch = 15 mm, triangular

Tray thickness = 3 mm

Number of holes = 2308, Flooding % = 80%

5.2 MECHANICAL DESIGN OF DISTILLATION COLUMN:

a) Shell:

Diameter of the tower =D_i = 940 mm =0.940 m

Working/Operating Pressure = 2.087 atmosphere = 2.1558 kg/cm^2

Design pressure = 1.1*Operating Pressure = 1.1*2.1558 = 2.37138 kg/cm^2

Working temperature = 95 ^{0}C = 368 ^{0}K

Design temperature = 104.5 ^{0}C = 377.5 ^{0}K

Shell material - IS: 2002-1962 Carbon steel (specific gravity 7.7)

Permissible tensile stress (f_t) = 95 MN/m^2 = 970 kg/cm^2

Insulation material - asbestos

Insulation thickness = 2”= 50.8 mm

Density of insulation = 2700 kg/m^3

Top disengaging space = 0.3 m

Bottom separator space = 0.4 m

Weir height = 50 mm

Down comer clearance = 1” = 25.4 mm

b) Head - torispherical dished head:

Material - IS: 2002-1962 Carbon steel

Allowable tensile stress = 95 MN/m^2 = 970 kg/cm^2

c) Support skirt:

Height of support = 1000 mm = 1.0 m

Material - Carbon Steel

d) Trays-sieve type:

Number of trays = 7

Hole Diameter = 5 mm

Number of holes:

Enriching section = 1971

Stripping section = 2308

Tray spacing:

Enriching section: 18” = 457 mm

Stripping section: 18” = 500 mm

Thickness = 3 mm

e) Support for tray:

Purlins - Channels and Angles

Material - Carbon Steel

Permissible Stress = 127.5 MN/m^2 =1299.7 k gf/cm^2

1. Shell minimum thickness:

Considering the vessel as an internal pressure vessel.

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

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, $t_s = ((2.37138*940)/((2*970*0.85)- 2.1558)) + 3 = 4.35$ mm

Taking the thickness of the shell = 6 mm (standard)

2. Head Design- Shallow dished and Torispherical head:

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

P =internal design pressure, kg/cm^2

R_c = crown radius = diameter of shell, mm

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

$W= ¼ * (3 + (R_c/R_k)^{0.5})$

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

Now, R_c = 940 mm

R_k = 6% of R_c = 0.06*940 = 56.4 mm

$W= ¼ * (3 + (R_c/R_k)^{0.5}) = ¼ * (3 + (940/56.4)^{0.5}) = 1.7706$ mm

t_h = (2.37138*940*1.7706)/ (2*970*0.85) = 2.39 mm

Including corrosion allowance take the thickness of head = 6 mm

Weight of Head:

Diameter = O.D + (O.D/24) + (2*s_f) + (2*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 =1.5"

i_{cr} = 2.31"

Also, O.D.= 940 mm = 37"

Diameter = 37+ (37/24) + (2*1.5)+(2/3*2.31)

d = 43.08" = 1094.23 mm.

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

$= ((\pi*43.08^2*0.2362)/4)*(7700/1728)$ = 1534.15 lb

= 695.87 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:

$$f_{ap} = \frac{P*D_i}{4(t_s - c)} = \frac{2.37138*940}{4(6-3)} = 185.758 \text{ kgf/cm}^2 .$$

This is the same through out the column height.

3.2 Circumferential stress

$2*f_{ap}$ = 2*185.758 = 371.516 kgf/cm^2

3.3 Compressive stress due Dead Loads:

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

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

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

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

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, $\rho_s = 7700 \ kg/m^3 = 0.0077 \ kg/cm^3$

$f_{ds} = \rho_s * X = (7700*X) \ kg/m^2 = (0.77*X) \ kg/cm^2$

The vessel contains manholes, nozzles etc., additional weight may be estimated 20% of the weight of the shell.

$f_{T,ds} = 1.2 * 7700*X = 0.924*(X) \ kg/cm^2$

3.3.2 Compressive stress due to weight of insulation at a height X meter:

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

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

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

Assuming asbestos is to be used as insulation material.

$\rho_{ins} = 2700 \ kg/m^3$

t_{ins} = 2” = 5.08 cm.

$D_{ins} = D_c + 2t_s + 2t_{ins} = 94 + (2*0.6) + (2*5.08) = 105.36$ cm.

$D_m = (94 + (94 + (2*0.6)))/2 = 94.60$ cm.

$$f_{d(ins)} = \frac{\pi * 105.36 * 5.08 * 2700 * X}{\pi * 94.6 * (0.6 - 0.3)} = 50920.28 * X \ kg/m^2$$

$= 5.092028*X \ kg/cm^3$

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

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

The top chamber height is 0.3 m and it does not contain any liquid or tray. Tray spacing is 457 mm.

Average liquid density = 775.45 kg/m^3

Liquid and tray weight for X meter

$F_{liq\text{-}tray}$ = [(X-0.3)/ 0.5 + 1] *(π *D_i^2/4) ×ρ_l

= [(X-0.3)/ 0.5 + 1] * (π *0.94^2/4) *775.4

= [2X + 0.4] * 538.11 kg

$f_{d\ (liq)}$ = $F_{liq\text{-}tray}$ *10/ (π*D_m* (t_s - c))

= [2X + 0.4] * 538.11 *10/ (π*946* (6 - 3))

= [2X + 0.4] * 0.6035

= 1.207*X + 0.2414 kg/cm^2

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

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

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 = (695.87+25X) kg

$f_{d\ (attch.)}$ = (695.87+25X) * 10/ π*946* (6 - 3) = 0.7805 + 0.028X kg/cm^2

Total compressive dead weight stress:

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

= 0.924X + 5.092X + [1.207X+0.2414] + [0.7805 +0.028X]

f_{dx} = 7.251X + 1.0219 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*P_w*D*X^2/2

Z = modulus for the section for the area of shell ≈ π*D_m^2* (t_s-c)/4

Thus, f_{wx} =1.4*P_w*X^2/ (π *D_m* (t_s-c))

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

= 37.204 kg/m^2

Bending moment due to wind load

$M_{wx} = 0.7*37.204*0.94*X^2/2 = \underline{12.24(X^2)}$ kg-m

$f_{wx} = 1.4*37.204*X^2/ (\pi *0.94* (6-3)*10^{-3}) = 0.58792(X^2)$ kg/cm^2

5. Stresses due to Seismic load:

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

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

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

Where, C = seismic coefficient,

W= total weight of column, kg

H = height of column

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

----- (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, man ways, internal supports, etc.

= 1.5 for distillation column with several man ways, 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 = $D_i + (t *10^{-3}) = 0.94+ (6 *10^{-3}) = 0.946$ m

W= $1.5*\pi*7700*0.946*9.81* (3.0+ (0.8*0.946))*6*10^{-3}$ =7590.341 N=773.73 kg.

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

Plate area = $\pi*0.94^2/4 = 0.694$ m^2

Weight of each plate = 1.2*0.694 = 0.8328 kN

Weight of 7 plates = 7*0.8328 = 5.8296 kN = 594.25 kg.

Total weight of column = 773.73 + 594.25 = 1367.98 kg.

Let, C = seismic coefficient = 0.08

$M_{sx} = [0.08*1367.98*X^2/3] * [((3*3.4)-X)/3.4^2]$

$= 36.48X^2 * [0.8823-0.086X]$ kg-m

$f_{sx} = M_{sx}*10^3/(\pi*D_m{}^2*(t_s-c)/4$

$=36.48X^2 * [0.8823-0.086X * 10^3/(\pi*94.6^2*(6-3)/4)$

$= [1.526X^2- 0.14878X^3]$, kg/cm^2

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,

$f_{t,max} = 0.58792X^2 + 168.871- [7.215X + 1.0129]$

i.e., $0.58792X^2- 7.251X + 168.871 - 1.0129- 824.5 = 0$

$0.58792X^2- 7.251X - 656.64 =0$

=> X = 40.15 m

On the down side:

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

$3.075X^2 - 86.1618+ [7.3580X + 0.6701] = f_{c,max}$

The column height is 3.4 m, for which the maximum value is

$f_{c,max} = 0.58792(3.4)^2 - 168.871+ [7.251(3.4) + 1.0129]$

= -136.408 kg/cm^2

this shows that the stress on the down wind side is tensile.

$f_{t,max}$ = 85% of allowable tensile stress.

$f_{t,max} = 970 * 0.85 = 824.5$ kg/cm^2.

$f_{t,max} = 0.58792(X)^2 – 168.871 + [7.251(X) + 1.0129] = 824.5$

Therefore, X = 35.38 m.

Hence we see that the design value of the column height is more than 3.4 m, which is the actual column height. So we conclude that the design is safe and thus the design calculations are acceptable.

Hence a thickness of 6 mm is taken throughout the length of shell.

Height of the head = $D_c/4 = 0.94/4 = 0.235$ m

Skirt support Height = 1.0 m

Total actual height = 3.4 + 1 + 0.235 = 4.635 m

5.2.1 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 = 940 mm.

(ii) Height = 3400 mm = 3.40 m

(iii) Weight of vessel, attachment = 2148.85 kg.

(iv) Diameter of skirt (straight) = 940 mm

(v) Height of skirt = 1.0 m

(vi) Wind pressure = 37.204 kg/m^2

1. **Stresses due to dead Weight:**

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

   f_d = stress,

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

   D_{ok} = outside diameter of skirt,

   t_{sk} = thickness of skirt,

   $f_d = 2148.85 / (\pi * 95.2 * t_{sk}) = 7.1848 / t_{sk}$ kg/cm^2

2. **Stress due to wind load:**

   $p_w = k * p_1 * h_1 * D_o$

   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

   $M_w = p_w * H/2$

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

Z- Modulus of section of skirt cross-section

$p_w = 0.7* 37.204*1.0*0.9 = 120.785$ kg

$M_w = p_w *H/2 = 120.795\times10/2 = 603.975$ kg-m

Substituting the values we get,

$f_{wb} = 708.4737/t_{sk}$ kg/cm^2

3. Stress due to seismic load:

Load = C*W

C = seismic coefficient,

W= total weight of column.

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

C=0.08

$f_{sb} = (2/3) * (0.08*2148.85*340)/(\pi \times(95.2/2)^2 * t_{sk} = 0.5474/ t_{sk}$ kg/cm^2

Maximum tensile stress:

$f_{t, max} = (8.9458/ t_{sk}) - (7.1848/ t_{sk}) = (1.761/ t_{sk})$ kg/cm^2

Permissible tensile stress = 925 kg/cm^2

Thus, $925 = (1.761/ t_{sk})$

=> $t_{sk} = 1.761/925 = 0.0019$ cm = 0.019 mm

Maximum compressive stress:

$f_{c, max} = (8.9458/ t_{sk}) + (7.1848/ t_{sk}) = (16.1306/ t_{sk})$ kg/cm^2

Now,

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

= 1500/ 3 = 500 kg/cm^2

Thus, $t_{sk} = 16.1306/500 = 0.03$ cm = 0.3 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 = 94+ 32.5 = 126.5 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,

$f_c = (2148.85*4)/(\pi*(126.5^2- 94^2))+(0.7*37.204*3*42.3^2*/(2*\pi*(126.5^4 -94^4)/(32*126.5))$

= 0.0954 + 0.506

f_c = 0.6014 kg/cm^2

Which is less than the permissible value for concrete.

Maximum bending moment in bearing plate

$M_{max} = (0.6014*16.25^2/2)$ = 79.4 kg-cm

Stress, $f = (6*0.6014* 16.25^2)/ (2 *t_B^2) = 476.42/ t_B^2$

Permissible stress in bending is 1000 kg/cm^2

Thus, $t_B^2 = 476.42/1000 \Rightarrow t_B$ = 0.6902 cm = 6.902 mm

Therefore, a bolted chair has to be used.

Anchor Bolts:

Minimum weight of Vessel = W_{min} = 1400 kg. ------ (assumed value)

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

$= [(4*1400)/(\pi*(126.5^2-94^2))]-(0.7*37.204*3*42.3^2*/(2*\pi*(126.5^4-94^4)/(32*126.5))$

= 0.2487 – 0.5059 = - 0.2572 kg/cm^2

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

Assuming there are 24 bolts,

P_{bolts} = (0.2572/24) * ((π * (126.5^2 - 94^2))/4) = 19.199 kg

Trays:

The trays are standard sieve plates throughout the column. The plates have 1971 holes in Enriching section and 2308 holes in the Stripping section of 5mm diameter arranged on a 15mm triangular pitch. The trays are supported on purloins.

5.2.2 Nozzle Design:

Nozzles are required for compensation where a hole is made in the shell. The following nozzles are required:

1. Feed Nozzle:

Liquid Velocity = V_L= 2 m/s

Area of Nozzle = (Mass of liquid in)/ (ρ_L * V_L)

Mass of liquid in = 6741.976 kg/hr.

= 1.87277 kg/s

Thus, Area of Nozzle = (1.87277)/ (784.50 * 2) = 1.1936×10^{-3} m^2

Now, Area of Nozzle = $\pi * d_N^2/4 = 1.1936 * 10^{-3}$ m^2

$d_N^2 = (4*1.1936 *10^{-3}/\pi)$

d_N = 0.03898 m = 38.98 mm.

2. Nozzle for distillate:

Gas Velocity = V_G= 25.0 m/s

Area of Nozzle = (Mass of liquid in)/ (ρ_G * V_G)

Mass of vapor in = 6372.56 kg/hr.

= 1.77 kg/s

Thus, Area of Nozzle = (1.77)/ (3.4376 * 25) = 0.0206 m^2

Now, Area of Nozzle = $\pi * d_N^2/4$ = 0.0206 m^2

$d_N^2 = (4*0.0206/\pi)$

d_N = 0.1619 m = 16.19 cm.

3. Nozzle for residue:

Liquid Velocity = V_L= 1.0 m/s

Area of Nozzle = (Mass of liquid in)/ (ρ_L * V_L)

Mass of liquid in = 369.416 kg/hr.

= 0.1026 kg/s

Thus, Area of Nozzle = (0.1026)/ (784.87 * 1) = 1.3072 *10^{-4} m^2

Now, Area of Nozzle = π *d_N^2/4 = 1.3072 m^2

d_N^2 = (4*1.3072*10^{-4}/π)

d_N = 0.0129 m = 12.9 mm.

5.3 Process Design of Heat exchanger

Heat exchanger used is shell and tube.

The ethanol entering from vaporizer must be heated from 100^0C to 200^0C using ethanol, acetaldehyde and hydrogen mixture available at 310^0C.

Shell side:

Feed (m_h)=2.008 kg/sec

Inlet temperature (T1)= 100^0C

Outlet temperature (T2)= 200^0C

Tube side:

Inlet temperature (t1)= 310^0C

Outlet temperature (t2)= 232.690^0C

1) Heat balance

Qh=m_h C_p (T2-T1)

= 2.008*1.97*(200-100)

= 395.576 KW

2) LMTD

LMTD=120.99^{0}C

F_T=LMTD correction factor.

R=0.7731 & S=0.476

From graph of F_T Vs S

F_T =0.91

LMTD (corrected)= 110.1009^0 C.

3) Heat transfer area:

Choose overall heat transfer coefficient= 120 W/(m^{2}K)

Q = UA(LMTD)

A=395576 / (120*120.99*0.91)

A=29.94m^2

4) Tube selection:

¾ in OD ,10 BWG Tubes

OD=3/4 in=19.05 mm

ID=0.685 in=17.399 mm

Length of tube =L=16ft=4.88m

Heat transfer area per tube =0.292 m^2

Number of tubes= 29.94/0.292=102.53

TEMA P or S, Floating head type:

Nearest tube count from tube count table

N_T= 102

2 tube passes and 1 shell pass

¾ in tubes arranged in triangular pitch

Shell ID (D_f)=305mm=12in

Corrected heat transfer area=0.292*102=29.784 m^2

Corrected over all heat transfer coefficient (U)=120.63 W/(m^{2}K)

5) Average properties of fluids

a) Shell side (ammoniated brine) at 150^{0}C

ρ=3.98 kg/m^3

μ=1300*10^{-8} mNs/m^2

Cp=1.97KJ/kg.K

k=0.0256 w/m.k

b) Tube side (water) at 25^{0}C

ρ=2.965 kg/m^3

μ=4.7577*10^{-5} mNs/m^2

Cp=1.7117 KJ/kg.K

k=0.081w/m.k

6) Tube side velocity

Number of passes N_P=2

Flow area =(Π*ID^2/4)*N_T/N_P

=(3.14*0.017399^2/4)*102/2

A_a=0.012 m^2

V_t=m_c/ (A_a ρ)

=2.008/(0.012*2.965)

=56.43 m/s.

Velocity is with the range (for vapor

7) Shell side velocity

S_m=[(P^l-D_o)L_s]D_s/ P^l

S_m → cross flow area at center of shell.

N_b→Number of baffles.

L→Tube length.

(P^1-D_o)*L_S→Flow area between two adjacent tube rows.

D_S/P^1→Number of tube rows.

S_m =[(25.4-19.05)*244] 305/25.4

=0.018605 m^2.

V_s =m_h/(ρ S_m)

=2.008/(3.8*0.018605)

=28.4 m/s

P^1 =25.4 mm.

L_S = 0.8 * D_S

= 0.244 m.

$N_b+1=L/L_S$

$=4.88/0.244$

$N_b=19$ baffles

8) Shell side heat transfer coefficient:

$N_{NU}=j_H\ N_{re}(N_{Pr})^{1/3}$ N_{Nu}=nusselt number

$N_{Re}=V_sD_o\rho/\mu$ N_{Re}=Reynolds number

$=28.40*19.05*^{10-}3*3.98/(1300 * 10^{-8})$.

$=165635$

$j_h= 3*10^{-3}$

$N_{Pr}=\mu C_p/k$

$=1300*10^{-8} *1.97/(2.855 * 10^{-4}) = 0.09$

$N_{NU}=3*10^{-3} *165635 * 0.09^{0.33} =222.68$

$h_o=222.68* 0.0256 / 0.01905 = 299.244$ W / m^2 K.

9) Tube side heat transfer coefficient:

$N_{Nu}=0.023(N_{Re})^{0.8}\ (N_{Pr})^{0.3}$

$N_{Re}=61187.4$

$N_{Pr}=0.796$

$N_{Nu}=0.023(61187.4)^{0.8}\ (0.796)^{0.3}$ =2 26.82

$h_i=1055.9$ w/m^2.K

10) Overall heat transfer coefficient:

Dirt coefficient =$3.522*10^{-4}$ w/m^2.K

$1/U=1/h_o+(D_o/D_i)(1/h_i)+D_o\ln(D_o/D_i)/(2*K_W)$+dirt coefficient

$1/U=1/299.24+(19.05/17.399)(1/1055.9)+0.01905*\ln(19.05/17.399)/(2*50)+$

$+3.522*10^{-4}$

$U=210.608$ w/m^2.K

Designed value is greater than the assumed value.

11) Pressure drop calculation:

11a) Tube side pressure drop:

Tube side Reynolds number=N_{Re}= 61187.4

Friction factor=f=0.079$(N_{Re})^{-1/4}$ = 0.079$(61187.4)^{-1/4}$ = 5.023*10^{-3}

ΔP_L= $(4fLv_t^2/2gD_i)*\rho_t g$

= $(4*5.023*10^{-3}*4.88*56.43^2/2*9.8*17.399*10^{-3})*2.965*9.8$

= 20603.08 N/m^2

ΔP_E= $2.5(\rho_t v_t^2/2)$

= $2.5(2.965*56.43^2/2)$

= 11802 N/m^2

$(\Delta P)_T = N_p(\Delta P_L+\Delta P_E)$

= 2*(20603.08 +11802) = 64810 N/m^2 = 64.810 kPa.

11b) Shell side pressure drop (Bell's method):

Shell side Reynolds number=N_{Re}=165635

f_k=0.1

Pressure drop for cross flow zones

$\Delta P_C = (bf_k w^2 N_C/\rho_f S_m^2)(\mu_w/\mu_f)$

N_c= number of tube rows crossed in one cross flow section.

$N_c=D_s[1-2(L_C/D_s)]/P_P$

Where, L_c baffle cut,25% of D_s

$P_P=((\surd 3)/2)P^I$

N_c=0.305*[1-2*0.5]/0.022

N_c= 7

$\Delta P_C = (2*10^{-3}*0.1*2.008^2*7)/(3.98*0.018605^2)$

ΔP_C = 0.076 K Pa

Pressure drop in end zones:

$\Delta P_E = \Delta P_C(1+N_{cw}/N_c)$

$N_{cw}=0.8L_C/P_P$, number of cross flow rows in each window.

N_{cw}= 3

ΔP_E= 0.076*(1+3/7)

ΔP_E= 0.10857 kPa.

Pressure drop in window zones:

$\Delta P_w = bw^2(2+0.6N_{cw})/(S_m S_w \rho)$

$S_w = S_{wg} - S_{wt}$

S_w=area for flow through window zone.

S_{wg}= gross window area

S_{wt}= area occupied by tubes

S_{wg}= 25 in^2 =0.01613 m^2, for D_S=12in & L_C/D_S=0.25

$S_{wt} = (N_T/8)(1- F_C)\ \Pi D_O^2$

F_C =0.63 for L_C/D_S=0.25

S_{wt}= (102/8)(1-0.63) *Π *0.01905^2

S_{wt}= 5.378*10^{-3} m^2.

S_W = (0.01613-5.378*10^{-3}) = 0.010752 m^2

$$\Delta P_W = \frac{5*10^{-5}*2.008^2*(2+0.6*8)}{0.018605*0.010752*3.98}$$

ΔP_W = 0.962 kPa

$(\Delta P_S)_T = 2\Delta P_E + (N_b-1)\Delta P_C + N_b\ \Delta P_w$

$(\Delta P_S)_T$ = 2*1.69 + (8-1)*1.19 + 8*1.127

$(\Delta P_S)_T$ = 21.8174 kPa

5.4 Mechanical design of Heat Exchanger:

(a) Shell side details:

Material: carbon steel

Number of shell passes: one

Working pressure: 0.3N/mm^2

Design pressure: 0.33N/mm^2

Inlet temperature: 100^{0}C

Out let temperature:200^{0}C

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

(b) Tube side details:

Number tubes: 102

Number of passes: 2

Outside diameter: 19.05mm

Inside diameter: 17.399 mm.

Length: 4.88m

Pitch triangular:1 inch

Working pressure: 0.3 N/mm^2

Design pressure: 0.33N/mm^2

Inlet temperature: 310^0C

Outlet temperature: 232.69^0C

Shell side:

(1) Shell thickness:

t_s= PD/(2fJ+P)

= 0.33*305/(2*95*0.85+0.33) = 0.57

Minimum thickness of shell must be=6.0 mm

Including corrosion allowance shell thickness is 8mm

(2) Head thickness:

Shallow dished and torispherical

$t_s = PR_cW/2fJ$

= 0.33*305*1.77/(2*95*0.85)

= 1.103 mm.

Minimum shell thickness should be 10mm including corrosion allowance.

(3) Transverse Baffles:

Baffle spacing =0.8*D_c = 244mm

Number of baffles,

$N_b+1=L/L_S$=4.88/0.244=20

N_b=19

Thickness of baffles, t_b=6mm

(4) Tie Rods and spacers

For shell diameter, 300-500mm

Diameter of Rod = 9mm

Number of rods=4

(5) Flanges

Design pressure=0.33 N/mm^2

Flange material IS: 2004-1962,class 2

Bolting steel: 5% Cr-Mo steel

Gasket material: asbestos composition

Shell thickness: 8mm=g_o

Outside diameter of shell: 305 mm

Allowable stress of flange material: 100MN/m^2

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

Shell thickness = 10 mm.

Outside diameter = 325 mm.

Determination of gasket width:

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

Assume a gasket thickness of 10 mm

y = minimum design yield seating stress = 25.5 MN/m^2

m = gasket factor = 2.75

$d_O/d_i = [(25.5-0.33*2.75)/(25.5-0.33(2.75+1))]^{0.5}$

$d_O/d_i = 1.0067$

Let, d_i of gasket equal 335mm

$d_o= 1.002*d_i$

d_o= 0.33724 m

Minimum gasket width = (337.24-335)/2 = 1.12mm =0.00112 m.

Taking gasket width of N= 0.010m

d_o=0.35924 m.

Basic gasket seating width, b_o=5mm

Diameter of location of gasket load reaction is

$G= d_i + N = 0.335 + 0.01 = 0.345$ m

Estimation of Bolt loads:

Load due to design pressure

$H = \pi G^2 P/4 = 3.14*0.345^2*0.33/4 = 0.03085MN$

Load to keep joint tight under operation

$b = 2.5\ (b_0)^{0.5} = 5.59$ mm.

$H_p=\pi*G*(2b)*m*p = 3.14*0.345*(2*0.00559)*2.75*0.33 = 0.011$ MN

Total operating load,

$W_o= H + H_p = 0.03085 + 0.011 = 0.04185$ MN.

Load to seat gasket under bolting condition

$W_g = \pi*G*b*y = 3.14*0.345*5.59*10^{-3}*25.5 = 0.1545$ MN.

$W_g>W_o$, controlling load=0.1545 MN

Calculation of optimum bolting area:

$A_m = A_g = W_g/S_g = 0.1545 /138 = 1.12*10^{-3}\ m^2$

Calculation of optimum bolt size:

Bolt size, M18 X 2

Actual number of bolts =20

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

$C =ID + 2(1.415g + R) = 325 +2[11.315+0.027*10^3] = 401.63mm = 0.40163$

Bolt circle diameter = 0.40163 m.

Calculation of flange outside diameter

Let, bolt diameter = 18 mm.

A=C+ bolt diameter +0.02 = 0.40163 +0.018+0.02 = 0.43963 m.

Check for gasket width,

$A_b S_G / (\pi GN) = 1.54*10^{-4}*20*138/(3.14*0.345*10^{-2}) = 39.21 < 2*y.$

Where, S_G is the Allowable stress for the gasket material.

Flange moment computation:

(a) For operating condition

$W_o=W_1+W_2+W_3$

$W_1 = \prod * B^2 * P/4 = \prod * 0.325^2 * 0.33/4 = 0.027$ MN

$W_2 = H - W_1 = 0.03085 - 0.027 = 0.00385$ MN.

$W_3 = W_o - H = H_p = 0.011$ MN.

M_o=Total flange moment

$M_o = W_1 a_1 + W_2 a_2 + W_3 a_3$

$a_1 = (C-B)/2 = (0.40163-0.325)/2$

$a_1 = 0.038315$ m

$a_3 = (C-G)/2 = (0.40163-0.345)/2$

$a_3 = 0.028315$ m

$a_2 = (a_1 + a_3)/2 = (0.038315 + 0.028315)/2 = 0.033315$ m

$M_o = 0.027 * 0.038315 + 0.00385 * 0.033315 + 0.011 * 0.028315$

$M_o = 1.474 * 10^{-3}$ MN-m

(b) For bolting condition

$M_g = W a_3$

$W = (A_m + A_b) * S_g / 2$

$A_b = 20 * 1.54 * 10^{-4} = 3.08 * 10^{-3}\ m^2$

$A_m = 1.12 * 10^{-03}\ m^2$

$W = (1.12 * 10^{-03} + 3.08 * 10^{-3}) * 138/2$

$W = 0.2898$ MN

$M_g = 0.2898 * 0.028315 = 8.205 * 10^{-3}$ MN-m

$M_g > M_o$,Hence moment under operating condition M_g is controlling, $M_g = M$

Calculation of flange thickness

$t^2 = M\ C_F\ Y / (B\ S_F)$, S_F is the allowable stress for the flange material

K =A/B = 0.43963/0.325 = 1.3527

For K = 1.3527, Y = 10

Assuming C_F =1

$t^2 = 8.205 * 10^{-3} * 1 * 10(0.325 * 100)$

t= 0.0502 m=50.2 mm

Actual bolt spacing $B_S = \pi * C/n = (3.14 * 0.40613)/(20) = 0.063$m

Bolt Pitch Correction Factor

$C_F = [B_s / (2d+t)]^{0.5} = (0.063/(2*0.018+0.0502)^{1/2} = 0.855$

$\sqrt{C_F}=0.9246$

Actual flange thickness = $\sqrt{C_F}*t = 0.9246*0.063 = 0.04713$ m

= 0.0464 m.

Standard flange thickness available is 50 mm

Channel and channel Cover

$t_h=G_c\sqrt{(K*P/f)} = 0.345*\sqrt{(0.3*0.33/95)} = 0.01114m = 11.14mm$

t_h=14mm including corrosion allowance

Tube sheet thickness

$t_{ts}=F*G\sqrt{(0.25*P/f)} = 1*0.345\sqrt{(0.25*0.33/95)} = 0.0101m=10.1$ mm

t_{ts}=13 mm including corrosion allowance.

Nozzle design:

1. **Tube side Nozzle:**

Velocity = V_G = 28 m/s

Area of Nozzle = (Mass of vapor in)/ ($\rho_G * V_G$)

Mass of liquid in = 2.008 kg/s

Thus, Area of Nozzle = (2.008)/ (2.965 * 28) = 0.024187 m^2

Now, Area of Nozzle = $\pi *d_N^2/4 = 0.024187$ m^2

$d_N^2 = (4*0.024187/\pi)$

d_N = 0.17548 m = 17.548 cm.

2. **Shell side Nozzle:**

Velocity = V_G = 27 m/s

Area of Nozzle = (Mass of vapor in)/ ($\rho_G * V_G$)

Mass of liquid in = 2.008 kg/s

Thus, Area of Nozzle = (2.008)/ (3.8 * 27) = 0.01957 m^2

Now, Area of Nozzle = $\pi *d_N^2/4 = 0.01957$ m^2

$d_N^2 = (4*0.024187/\pi)$

$d_N = 0.1578$ m = 15.78 cm.

Saddle support

Material: low carbon steel

Total length of shell: 4.88 m

Diameter of shell: 325 mm

Knuckle radius: 18.3 mm

Total depth of head (H)= $\sqrt{(D_o r_o/2)} = \sqrt{(325*18.3/2)} = 54.53$ mm

Density of the steel = 7600 kg/m^3.

Weight of steel vessel = 3707. 21 kg.

R=D/2=162.5 mm

Distance of saddle center line from shell end = A =0.5R=81.25 mm

Longitudinal Bending Moment

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

Q = W/2(L+4H/3) = 3707.21/2*(5.88 +4*0.03085/3) = 10975.44 kg m

M_1 = 18.6 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 =15706.74 kg-m.

Stresses in shell at the saddle

(a) At the top most fiber of the cross section

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

$= 18.6/(3.14*0.1625^2*0.01) = 0.02242$ kg/mm^2

Stress in the shell at mid point

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

= 9.9656 kg/mm^2

Axial stress in the shell due to internal pressure

f_p= PD/4t

= 3.4089*940/(4*8) = 100.136 kg/cm^2 = 1.00136 kg/mm^2

$f_2 + f_p$ = 10.96696 kg/mm^2

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