DESIGN OF EQUIPMENT

Process Design of Distillation Column:

The detailed process design of the Toluene column is given below. The pictorial representation of the column is given in fig. The feed to the column is a mixture of Toluene and xylene. The compositions of the components are given below. The distillate/top product is the required product consisting mainly of toluene.

I. Thermodynamics:

The primary requirement while designing mass transfer contact equipment is the thermodynamic equilibrium data. The data required is in the Vapor-Liquid Equilibrium (VLE) data for the Toluene-Xylene system. The X-Y curve is shown in the fig. To develop the VLE data, a model was used.

$$y_i \, p_t = \gamma_i \, x_i \, P_i^{sat} \qquad \text{--------------------------(1)}$$

Where,

y_i = mole fraction of component "i" in vapor.

p_t = total system pressure.

γ_i = activity coefficient of component "i" in liquid.

x_i = mole fraction of component "i" in liquid.

P_i^{sat} = saturation vapor pressure of component "i".

The equilibrium vapor pressure was evaluated using correlations given in literature. The correlation was based on the critical properties of the components. The two components Toluene and Xylene Alcohol form a highly non-ideal system. To accommodate this non-ideality, an activity coefficient term was used for the liquid phase. The activity coefficient was evaluated using the UNIFAC model. Since the evaluation of the VLE data is highly iterative, an algorithm was developed which was solved using a computer program. The gas phase was assumed to be ideal. This is a valid assumption since the column is at 1 atmosphere pressure (760 mm Hg. abs.). The boiling points of the two components requires the column to be operated at 1 atmosphere. The operating pressure was chosen to be 760 mm Hg (abs).

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 Tolune in liquid/Feed.

y_D = mole fraction of Toluene in Distillate.

x_W = mole fraction of Tolune 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.

II. Preliminary calculations:

Feed = 499.665 tons/day

= 20.819 tons/hr.

F = 211.014 kmol/hr, x_F = 0.5299, M_F = 98.66 kg/kmol.

D = 112.81 kmol/hr, x_D = 0.9767, M_D = 92.42 kg/kmol.

W= 98.19 kmol/hr, x_W = 0.0166, M_W =105.769 kg/kmol.

Basis: 1 Hour Operation.

From the graph

$x_D / (R_m+1) = 0.505$

$R_m+1 = x_D / 0.505$

$R_m = 1.146$

Thus, $R_m = \underline{1.146}$

Let, $R = 1.5*R_m$

Therefore,

$R = 1.5\times1.146 = \underline{1.719}$

Thus, $x_D / (R+1) = 0.9767 / (1.719+1)$

i.e., $x_D / (R+1) = 0.3592$

Number of Ideal trays = 19 (including the reboiler).

Reboiler is the last tray.

Number of Ideal trays in Enriching Section = 8

Number of Ideal trays in Stripping Section = 10

Now, we know that,

$R = L_o / D$

=> $Lo = R\times D$

i.e., $L_o = 1.719 * 111.83$

i.e., L_o =192.23 kmol/hr.

Therefore, Lo = 192.23 kmol/hr.

L= Liquid flow rate on the Top tray = 192.23 kmol/hr.

G = L + D

= (R+1)*D = 2.719 * 111.83 = 304.06 kmol/hr

G = Gas flow rate in the Enriching Section = 304.06 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 = $\underline{\infty}$

Now we know that,

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

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

$\bar{L} = F + L$

i.e., $\bar{L} = 211.014 + 192.23$

i.e., $\bar{L} = 403.24$ kmol/hr.

Therefore, liquid flow rate in the Stripping Section = <u>403.24</u> 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., $\bar{G} = 0 + G$

$\boldsymbol{\bar{G} = G}$

= 304.06 kmol/hr

Therefore, the flow rate of Vapor in the Stripping Section = <u>304.06</u> kmol/hr.

III. List of parameters used in calculation:

SECTION	ENRICHING SECTION	STRIPPING

PARAMETER	TOP	BOTTOM	TOP	BOTTOM
x	0.9767	0.5299	0.5299	0.0166
y	0.9767	0.735	0.735	0.0166
Liquid, L kmol/hr.	192.23	192.23	403.24	403.24
Vapor, G kmol/hr.	304.06	304.06	304.06	304.06
T_{liquid}, ^0C	111.0	123.5	123.5	143.5
T_{vapor}, ^0C	112.5	123.5	123.5	144.0
$M_{avg.\ liquid}$ kg/kmol	92.326	98.58	98.58	105.76
$M_{avg.\ Vapor}$ kmol/hr	92.326	95.78	95.78	105.76
Liquid, L kg/hr.	17747.8	18950.03	39751.39	42646.66
Vapor, G kg/hr	28072.6	29122.86	29122.86	32157.38
Density, ρ_l kg/m^3	788.86	776.98	776.98	768.06
Density, ρ_g kg/m^3	2.91	2.94	2.940	3.09
$(L/G)\ (\rho_g / \rho_l)^{0.5}$	0.0354	0.0358	0.0842	0.0868
$\sigma_{L(dynes/cm)}$	26.18	28.57	28.57	31.11
μ_L (Pa-sec)	0.252cp	0.261cp	0.261cp	0.258cp

Table 6.1 Parameters used in calculations.

IV. 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. The procedure for the evaluation of the tray parameters is iterative in nature. Several iterations were performed to optimize the design. The final iteration is presented here.

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

   Let t_s = 457mm(18in).

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

Let d_h = 5 mm.

3. Hole Pitch (l_p):

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):

Refer fig 6.3

Now, for a triangular pitch, we know that,

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., $(A_h/A_p) = 0.1$

Thus,

(A_h/A_p) = 0.1

6. Plate Diameter (D_c):

The plate diameter is calculated based on the flooding considerations

$L/G \{\rho_g/\rho_l\}^{0.5} = 0.0358$ ---------- (maximum value at bottom)

Now for,

$L/G \{\rho_g/\rho_l\}^{0.5} = 0.0358$ 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, $C_{sb,\ flood}$ = 0.28 ft/s = 0.0853 m/s.

Now,

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

---- {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 = 28.57 dyne/cm.

ρ_l = 776.98 kg/m^3.

ρ_g = 2.94 kg/m^3.

Therefore,

$U_{nf} = 0.28\times (28.57/20)^{0.2}\times [(766.980-2.94)/ 2.94]^{0.5}$

i.e., U_{nf} = 4.87 ft/s = 1.48 m/s.

Let

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

i.e., $U_n = 0.8\times1.48$

i.e., U_n = 3.884 ft/s

i.e, U_n = 1.184 m/s

Now,

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

= q_o = 29122.86 / (3600×2.94) = 2.75 m^3/s.

(max. at the bottom)

Now,

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, $A_n = q_o/ U_n$ = 2.75/1.184 = 2.322 m^2.

Let L_w / D_c = 0.75

Where, L_w = weir length, m

D_c = Column diameter, m

Now,

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

Now,

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

And,

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

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

i.e., $A_d = (0.2196\times D_c^2) - (0.1241\times D_c^2)$

i.e., $A_d = \underline{0.0955}\times D_c^2$, m^2

Since, $An = Ac - Ad$

$2.322 = (0.7854\times Dc^2) - (0.0955\times Dc^2)$

i .e., $0.6895\times D_c^2 = 2.322$

$\Rightarrow$ $D_c^2 = 2.322/ 0.6895 = 3.36$

$\Rightarrow$ $D_c = \sqrt{3.36}$

$D_c = \underline{1.8351}$ m

Take $D_c = \underline{1.9}$ m

Since $L_w / D_c = 0.75$,

$\Rightarrow$ $L_w = 0.75\times D_c = 0.75\times 1.90 = 1.425$ m.

Therefore, $L_w = \underline{1.425}$ m.

Now,

$A_c = 0.7854\times 1.9^2 = \underline{2.833}$ m^2

$A_d = 0.0879\times D_c^2 = 0.0879\times 1.9^2 = 0\underline{.344}$ m^2

$A_n = A_c - A_d$

i.e.,$A_n = 2.833- 0.344$

$\Rightarrow$ $A_n = 2.489$ m^2

7. Perforated plate area (A_p):

Acive area(A_a)

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

i.e., $A_a = 2.833 - (2\times0.344)$

$\Rightarrow \quad A_a = \underline{2.145}\ m^2$

Now,

$L_w / D_c = 1.425 / 1.9 = \underline{0.75}$

$\Theta_c = \underline{97.18}\ ^0$

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

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

$\Rightarrow \alpha = \underline{82.82}\ ^0$

Now,

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

$= 5 – 20\%$ of Ac

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

A_{cz} = taking 10% of Ac = $\underline{0.2833}m^2$

Also,

$A_{wz} = \{(\pi/4) \times D_c^2\times (\alpha/360\ ^0)\} - \{(\pi/4) \times (D_c - 0.05)^2\times (\alpha/360\ ^0)\}$

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

i.e., A_{wz} = 2 – 5 % of Ac, taking 5% of Ac,

i.e., $A_{wz} = \underline{0.14165}\ m^2$

Now,

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

i.e., $A_p = 2.833 - (2\times0.344) - 0.2833 - 0.14165$

Thus, $A_p = \underline{1.720}\ m^2$

8. Total Hole Area (A_h):

Since,

$A_h / A_p = 0.1$

$\Rightarrow A_h = 0.1\times A_p$

i.e., $A_h = 0.1\times1.72$

$\Rightarrow A_h = \underline{0.172}\ m^2$

Thus, Total Hole Area = $\underline{0.172}\ m^2$

Now we know that,

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

Where n_h = number of holes.

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

i.e., $n_h = (4\times0.172)/ (\pi \times0.005^2)$

$\Rightarrow\ n_h = \underline{8759}$

Therefore, Number of holes = <u>8759.</u>

9. Weir Height (h_w):

Let h_w = <u>45</u> 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 downcomer apron, mm of liquid

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

c = Downcomer clearance, m

h_{dc} = Downcomer backup, mm of liquid

Calculations:

Head loss through dry hole

h_d = head loss across the 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 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) = 0.172/ 2.145 = 0.080

also t_T/d_h = 3/5 = 0.60

Thus for (A_h/A_a) = 0.07993 and t_T/d_h = 0.60

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

C_v = 0.730

⇒ $k_2 = 50.8 / 0.730^2$ = 95.3275

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

$= q_t$ = 28072.6/ (3600×2.910) = 2.679 m^3/s -------- (minimum at top)

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

$= q_o$ = 29122.86 / (3600×2.940) = 2.751 m^3/s. ---- (maximum at bottom)

Velocity through the hole area (U_h):

Now,

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

$= 2.679/0.172$

$= \underline{15.57}$ m/s

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

$= 2.751/0.172$

$= \underline{15.99}$ m/s

Velocity through hole area should be minimum because at low gas flow rate weeping is observed.

Now,

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

$$= 95.3275\times(2.91/788.86) \times 15.57^2$$

$\Rightarrow h_{d, top} = \underline{85.24}$ mm clear liquid. -------- (minimum at top)

also

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

$$= 95.3275\times(2.94/776.98)\times15.99^2$$

$\Rightarrow h_{d, bottom} = \underline{92.22}$ mm clear liquid ----- (maximum at bottom)

Head Loss Due to Bubble Formation

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

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

= (788.86 + 766.98)/2

= $\underline{777.92}$ kg/m^3

$h_\sigma = 409 [17.4565 / (777.92 \times 5)]$

$h_\sigma = \underline{2.714}$ mm clear liquid

Height of Liquid Crest over Weir:

$h_{ow} = 664 \square F_w \, [(q/L_w)^{2/3}]$-----------(eq$^{n.}$ 18.12.a, page 18.10, 6th edition Perry

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

= 17747.8/ (3600×788.86)

= $\underline{6.249\times10^{-3}}$ m^3/s

Thus, q' = $\underline{99.05}$ gal/min(or GPM).

L_w = weir length = $\underline{1.425}$ m = 4.675 ft

Now,

$q'/L_w^{2.5} = 99.05/(4.675)^{2.5} = \underline{2.096}$

now for $q'/L_w^{2.5}$ = 2.096 and L_w/D_c =0.75

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

F_w= correction factor =$\underline{1.025}$

Thus, $h_{ow} = 1.025\times664\times[(6.249\times10^{-3})/1.425]^{2/3}$

$\Rightarrow$ h_{ow} = $\underline{18.23}$ mm clear liquid.

Now,

$(h_d + h_\sigma)$ = 85.24 + 2.714 = $\underline{87.95}$ mm ------ Design value

$(h_w + h_{ow})$ = 45 + 18.23 = $\underline{63.23}$ mm

Also, A_h/A_a = $\underline{0.08}$ and $(h_w + h_{ow})$ = 63.23 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

$(h_d + h_\sigma)_{min}$ = $\underline{16.0}$ mm ------- Theoretical value.

The minimum value as found is $\underline{16.0}$ mm.

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

Downcomer 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.

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

= $18950.03/(3600\times776.98)$ = $\underline{6.774\times10^{-3}}$ m^3/s

Thus, $q' = (6.774\times10^{-3})/(6.309*10^{-3})$ = $\underline{107.37}$ gal/min

L_w = weir length = $\underline{1.425}$ m = $\underline{4.675}$ ft.

$q'/L_w^{2.5} = 107.37/(4.675)^{2.5}$ = $\underline{2.272}$

now for $q'/L_w^{2.5} = 2.272$ and $L_w/D_c = 0.75$

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

F_w= correction factor =$\underline{1.030}$

Thus, $h_{ow} = 1.03\times664\times[(6.774\times10^{-3})/1.425]^{2/3}$

$\Rightarrow$ h_{ow} = $\underline{19.33}$ mm clear liquid. ----- (maximum at the bottom of section).

Therefore, h_{ds} = 45 +19.33 = 64.33 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, $U_a = (G_b/\rho_g)/A_a = (28072/2.91)/(2.145\times3600)$ = $\underline{1.24}$ m/s

Thus, U_a = $\underline{4.06}$ ft/s

$\rho_g = 2.91\ kg/m^3 = 2.91/(1.601846\times10^{-1})$ = $\underline{0.181}$ lb/ft^3

therefore, $F_{ga} = 4.06\times (0.181)^{0.5}$

F_{ga} = $\underline{1.72}$

Now for F_{ga} = 1.72, we have from fig. 18.15, page 18.10 6th edition Perry)

Aeration factor = β = $\underline{0.6}$

Relative Froth Density = ϕ_t = $\underline{0.20}$

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

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

$\Rightarrow h_l^{'} = 0.6\times 64.33 = \underline{38.598}$ mm.

Now,

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

$\Rightarrow h_f = 38.598/ 0.20 = \underline{192.99}$ mm.

Head loss over downcomer apron:

$h_{da} = 165.2 \{q/ A_{da}\}^2$ ----- (eqn. 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,

$q = 18950.03/(3600\times776.98) = \underline{6.774\times10^{-3}}\ m^3/s$

Take clearance, C = $\underline{1}$" = $\underline{25.4}$ mm

$h_{ap} = h_{ds} - C = 64.33 - 25.4 = \underline{38.93}$ mm

$A_{da} = L_w \times h_{ap} = 1.425\times 38.93\times10^{-3} = \underline{55.47\times10^{-3}}$ m $h_{da}{}^2$

$\therefore h_{da} = 165.2[6.774\times10^{-3} / 55.47\times 10^{-3}]^2$

= 2.46 mm

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

$= h_d + h_l$`

= 85.24 + 38.598

= $\underline{123.838}$ 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)

where, h_{dc} = height in downcomer, mm liquid,

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

h_o =height of crest over the weir, mm liquid,

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

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

h_{dc} =123.83 + 45 + 19.33 + 2.46 + 0

= 190.62 mm

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

= 0.5

$h_{dc} = h_{dc} / \phi$

= 190.62/ 0.5 = 381.24 mm

which is less than the tray spacing of 457 mm.

Hence no flooding in the enriching section

b). Design of Stripping Section:

Tray Hydraulics

1. Tray Spacing, (t_s) :

Let t_s = 400mm(15.75in).

2. Hole Diameter, (d_h):

Let d_h = 5 mm.

3. Hole Pitch (l_p):

Let $l_p = 3\times d_h$

i.e., l_p = 3×5 = 15 mm.

4. Tray thickness (t_T):

Let $t_T = 0.6\times d_h$

i.e., t_T = 0.6×5 = 3 mm.

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

Now, for a triangular pitch, we know that, 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., $(A_h/A_p) = 0.1$

Thus,

$(A_h/A_p) = \underline{0.1}$

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

The plate diameter is calculated based on the flooding considerations

$L/G\ \{\rho_g/\rho_l\}^{0.5} = \underline{0.0868}$ ---------- (maximum value)

Now for,

$L/G\ \{\rho_g/\rho_l\}^{0.5} = \underline{0.0868}$ and for a tray spacing of 400 mm.

we have,

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

Flooding parameter, $C_{sb,\ flood} = \underline{0.23}$ ft/s = $\underline{0.070}$ m/s.

Now,

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

---- {eq$^{\underline{n}}$. 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,

$\sigma = \underline{31.11}$ dyne/cm.

$\rho_l = \underline{768.06}$ kg/m^3.

$\rho_g = \underline{3.09}$ kg/m^3.

Therefore,

$U_{nf} = 0.23\times (31.11/20)^{0.2}\times [(768.06-3.09)/ 3.09]^{0.5}$

i.e., U_{nf} = 3.953 ft/s = 1.20 m/s.

Let

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

i.e., $U_n = 0.8 \times 3.953$

i.e., U_n = 3.149 ft/s

U_n = 0.96 m/s

Now,

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

$= q_o = 32157.38/(3600 \times 3.09) = 2.89\ m^3/s.$

Now,

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, $A_n = q_o/U_n = 2.89/0.96 = \underline{3.01}\ m^2$.

Let $L_w / D_c = 0.75$

Where, L_w = weir length, m

D_c = Column diameter, m

Now,

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

Now,

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

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

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

i.e., $A_d = (0.2196 \times D_c^2) - (0.1241 \times D_c^2)$

i.e., $A_d = \underline{0.0955} \times D_c^2,\ m^2$

Since An = Ac -Ad

$3.01 = (0.7854 \times Dc^2) - (0.0955 \times Dc^2)$

$\Rightarrow$ D_c = 2.089 m

Take D_c = 2.09 m

Since $L_w / D_c = 0.75$,

$\Rightarrow$ $L_w = 0.75\times D_c = 0.75\times 2.09 = 1.567$ m.

Therefore, $L_w = \underline{1.567}$ m.

Now,

$A_c = 0.7854\times 2.09^2 = \underline{3.428}\ m^2$

$A_d = 0.0955\times D_c^2 = 0.0955\times 2.09^2 = \underline{0.417}\ m^2$

$A_n = A_c - A_d$

i.e., $A_n = 3.428 - 0.417$

$\Rightarrow$ $A_n = \underline{3.011}\ m^2$

1. **Perforated plate area (A_p):**

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

i.e., $A_a = 3.428 - (2\times 0.417)$

$\Rightarrow$ $A_a = \underline{2.594}\ m^2$

Now,

$L_w / D_c = 0.690/ 0.92 = \underline{0.75}$

$\Theta_c = \underline{97.18}\ ^0$

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

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

$\Rightarrow$ $\alpha = \underline{82.82}\ ^0$

Now,

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

Or 5% - 20% of A_c

Take 10% of A_c

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

$A_{cz} =$ o.1 *3.428

$= .3428\ m^2$

Also,

$A_{wz} =$ 2% - 5% of A_c

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

i.e., A_{wz} = o.o5* 3.428

i.e., A_{wz} = $\underline{0.1714}$ m^2

Now,

A_p = Perforated area

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

i.e., $A_p = 3.428 - (2\times 0.417) - 0.3428 - 0.1714$

Thus, A_p = $\underline{2.079}$$m^2$

8. Total Hole Area (A_h):

Since,

$A_h / A_p = 0.1$

$\Rightarrow A_h = 0.1\times A_p$

i.e., $A_h = 0.1\times 2.079$

$\Rightarrow A_h = \underline{0.2079}\ m^2$

Thus, Total Hole Area = $\underline{0.2079}$ m^2

Now we know that,

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

Where n_h = number of holes.

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

i.e., $n_h = (4\times 0.079)/ (\pi \times 0.005^2)$

$\Rightarrow \quad n_h = \underline{10180.2} \approx \underline{10180}$

Therefore, Number of holes = $\underline{10180.}$

11. Weir Height (h_w):

Let h_w = $\underline{45}$ mm.

12. 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 downcomer apron, mm of liquid

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

c = Downcomer clearance, m

h_{dc} = Downcomer backup, mm of liquid

Calculations:

Head loss through dry hole

h_d = head loss across the 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 U_h =gas velocity through hole area

k_1, k_2 are constants

For sieve plates

$k_1 = \underline{0}$ 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).

Now,

$(A_h/A_a) = 0.2079/ 2.594 = \underline{0.080}$

also $t_T/d_h = 3/5 = \underline{0.60}$

Thus for $(A_h/A_a) = 0.080$ and $t_T/d_h = 0.60$

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

$C_v = \underline{0.73}$

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

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

$=q_t = 29122.86/ (3600\times2.94) = \underline{2.779} m^3/s$ -------- (minimum at top)

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

$= q_o = 32157.39/ (3600\times3.09) = \underline{2.89}\ m^3/s$. ------- (maximum at bottom).

Velocity through the hole area (U_h):

Now,

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

$= 2.779/.2079$

$= \underline{13.36}$ m/s

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

$= 2.89/0.2079$

$= \underline{13.9}$ m/s

Now,

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

$= 95.327\times(2.779/776.98)\times13.36^2$

$\Rightarrow h_{d,\,top} = \underline{64.38}$ mm clear liquid. -------- (minimum at top)

also

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

$= 95.327\times(3.09/768.06)\times13.9^2$

$\Rightarrow \quad h_{d,\,bottom} = \underline{74.09}$ mm clear liquid ----- (maximum at bottom)

Head Loss Due to Bubble Formation

h_σ = 409 [σ / ($\rho_{L\times}d_h$)]

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

= (776.98 + 768.06)/2

= 772.52 kg/m^3

h_σ = 409 [28.57 / (772.52 x 5)]

h_σ = 3.00 mm clear liquid

Height of Liquid Crest over Weir

h_{ow} = 664□F_w [$(q/L_w)^{2/3}$]-------------- (eq$^{n.}$ 18.12, page 18.10, 6th edition Perry)

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

= 39751/ (3600×776.98)

= 0.0142 m^3/s

Thus, q' = 225.25 gal/min.

L_w = weir length = 1. 567 m = 5.141 ft

Now,

$q'/L_w^{2.5}$ = 225.25/ $(5.141)^{2.5}$ = 3.758

now for $q'/L_w^{2.5}$ = 73.758 and L_w/D_c =0.75

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

F_w= correction factor =1.03

Thus, h_{ow} = 1.03×664× $[(0.0142)/1.567]^{2/3}$

⇒ h_{ow} = 29.72 mm clear liquid.

Now,

(h_d + h_σ) = 64.38 + 3.0 = 67.38 mm ------ Design value

(h_w + h_{ow}) = 45 + 29.72 = 74.72 mm

Also, A_h/A_a = 0.080 and $(h_w + h_{ow})$ =74.72 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

$(h_d + h_\sigma)_{min}$ = 18.00 mm ------- Theoretical value.

The minimum value as found is 18.00 mm.

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

Downcomer 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.

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

= 42646.66/ (3600×768.06) = 0.0154 m^3/s

Thus, q' = (0.01540)/ (6.309×10^{-5}) = 244.48 gal/min

L_w = weir length = 1.567 m = 5.141 ft.

$q'/L_w^{2.5}$ = 244.48/ $(5.141)^{2.5}$ = 4.079

now for $q'/L_w^{2.5}$ = 4.079 and L_w/D_c =0.75

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

F_w= correction factor =1.042

Thus, $h_{ow} = 1.0420 \times 664 \times [(0.0154)/1.567]^{2/3}$

$\Rightarrow$ $h_{ow} = \underline{31.74}$ mm clear liquid. ----- (maximum at the bottom of section).

Therefore, $h_{ds} = 45 + 31.74 = 76.74$ 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, $U_a = (G_b/\rho_g)/ A_a = (32157/3.09) / (2.594 \times 3600) = \underline{1.114}$ m/s

Thus, $U_a = \underline{3.654}$ ft/s

$\rho_g = 3.09$ kg/m^3 = $\underline{0.1921}$ lb/ft^3

therefore, $F_{ga} = 3.654 \times (0.1921)^{0.5}$

$F_{ga} = \underline{1.60}$

Now for $F_{ga} = 1.60$, we have from fig. 18.15, page 18.10 6th edition Perry)

Aeration factor = $\beta = \underline{0.61}$

Relative Froth Density = $\phi_t = \underline{0.22}$

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,

$\Rightarrow h_l' = 0.60 \times 76.74 = \underline{46.044}$ mm.

Now,

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

$\Rightarrow h_f = 46.044/ 0.22 = \underline{209.29}$ 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,

$q = 42646.66/ (3600\times768.06) = \underline{0.0154}\ m^3/s$

Take clearance, C = $\underline{1}$” = $\underline{25.4}$ mm

$h_{ap} = h_{ds} - C = 76.74 - 25.4 = \underline{51.34}$ mm

$A_{da} = L_w \text{ x } h_{ap} = 1.567\times 51.34\times10^{-3} = \underline{0.0804}\ m^2$ ************************

$\therefore\ h_{da} = 165.2[0.0154\ /\ 0.0804]^2$

$= 6.053$ mm

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

$= h_d + h_l`$

$= 64.38 + 46.044$

$= \underline{110.424}$ 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)

where, h_{dc} = height in downcomer, mm liquid,

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

h_o =height of crest over the weir, mm liquid,

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

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

$h_{dc} = 110.424 + 45 + 31.74 + 6.053 + 0$

$= 193.217$ mm

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

$= 0.5$

$h_{dc} = h_{dc} / \phi$

$= 193.217/ 0.5 = 386.434$ mm

which is less than the tray spacing of 400 mm.

Hence no flooding in the Stripping section

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, ^0K,

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 ^0K

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 = $M/(0.34 + (\sum \blacktriangle P)^2)$

M = Molecular weight.

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

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.

Average Properties:

Enriching Section **Stripping Section**

Liquid Flow Rate (L)		
kmol/hr	192.23	403.24
kg/hr	18348.5	41198.5
Vapor Flow Rate (G)		
kmol/hr.	304.06	304.06
kg/hr.	28597.73	30639.5
Temperature (T)		
$T_{avg.,liquid}$ (^{0} C)	117.25	133.5
$T_{avg., vapor}$ (^{0} C)	118	133.75
Viscosity (μ)		
$\mu_{avg., liquid}$ (cP)	0.2565	0.2595
$\mu_{avg., vapor}$ (cP)	0.009	0.009
Density (ρ)		
$\rho_{avg., liquid}$ (kg/m^3)	782.92	772.52
$P_{avg., vapor}$ (kg/m^3)	2.925	3.015
Surface Tension (σ)		
σ_{mix} (dyne/cm)	27.375	29.84
Diffusivities (D)		
Liquid Diffusivity, D_L cm^2/s	8.08×10^{-5}	8.65×10^{-5}
Vapor Diffusivity, D_V cm^2/s	0.0465	0.049
Schimid number, $S_c=\mu/(\rho\times D)$		
Gas $N_{Sc, g}$	0.66	0.621
Liquid $N_{Sc, l}$	40.54	38.81

Table 6.2 Average Properties

V. EFFICENCIES: (AIChE Method)

A) **Enriching Section:**

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,

$\lambda = (m\times G_m)/ L_m$ = 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$^{n.}$ 18.36, page 18.15, 6th edition Perry)--- *

where h_w = weir height = 45.00 mm

U_a = Gas velocity through active area, m/s

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

= 28597.73/ (3600×2.145×2.925)

U_a = 1.266 m/s

$D_f = (L_w + D_c)/2 = (1.9 + 1.425)/2 = 1.6625$ m

Average Liquid rate = 18348.5 kg/hr

Average Liquid Density =782.92 kg/m^3

q = 18348.5/ (3600×782.92) =6.509×10^{-3} m^3/s

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

$= q/D_f = 6.509\times10^{-3}/1.6625 = 3.915\times10^{-3}$ m^3/ (s.m)

$N_{Sc,\,g}$ = Schmidt number $=\mu_g/ (\rho_g\times D_g)$ = 0.66

Now,

Number of gas phase transfer units

$$N_g = \frac{(0.776 + (0.00457\times45) - (0.238\times1.266\times2.925^{0.5}) + (104.6\times3.915\times10^{-3}))/}{(0.66)^{0.5}}$$

N_g = 1.088

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

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

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

$$q = \frac{18348.5}{(3600\times782.92)} = 6.50\times10^{-3}\ m^3/s$$

$h_l = h_l'$ = 38.08 mm

A_a = 2.145 m^2

$$\therefore \theta_l = \frac{38.08\times2.145}{(1000\times6.5\times10^{-3})} = 12.566\ s$$

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

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

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

$k_l\times a = (3.875\times10^8\times8.08\times10^{-9})^{0.5}\times((0.40\times1.266\times2.925^{0.5}) + 0.17)$

$\therefore$ $k_l\times a$ = 1.833 m/s

$\therefore$ $N_l = k_l\times a\times\theta_l$

i.e., N_l = 1.833×12.566 =23.02 m

Slope of equilibrium Curve

m_{top} = 0.4375

m_{bottom} = 0.789

G_m/L_m = 1.7

$\lambda t = m_t \times G_m/L_m = \underline{0.743}$

$\lambda b = m_b \times G_m/L_m = \underline{1.341}$

$\Rightarrow \bar{\lambda} = \underline{1.0421}$

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

$$= \frac{1}{[(1/1.088) + (1.0421/23.02)]}$$

$N_{og} = \underline{1.037}$

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

$= 1 - e^{-1.037} = 1 - \exp(-1.037)$

$E_{og} = \underline{0.645}$

$\therefore$ **Point Efficiency = E_{og} = $\underline{0.645}$**

2. Murphree Plate Efficiency (E_{mv}):

Now,

Pelect number $= N_{Pe} = Z_l^2 / (D_E \times \theta_l)$

Where Z_l = length of liquid travel, m

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

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

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

$D_E = (6.675 \times 10^{-3} \times (1.266)^{1.44}) + (0.922 \times 10^{-4} \times 38.08) - 0.00562$

$D_E = \underline{7.265 \times 10^{-3}}\ m^2/s$

Also,

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

$= 1.9 \times \cos(97.18^0/2)$

$= \underline{1.257}$ m

$N_{Pe} = Z_l^2 / (D_E \times \theta_l)$
$= 1.257^2 / (7.265\times10^{-3} \times 12.566)$
$N_{Pe} = \underline{17.00}$

$\bar{\lambda} \times E_{og} = 1.0421 \text{ x } 0.645 = \underline{0.67}$

Now for $\lambda \times E_{og} = 0.67$ and $N_{Pe} = 17$

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

$E_{mv} / E_{og} = \underline{1.28}$

$\therefore E_{mv} = 1.28\times E_{og} = 1.28\times0.645 = \underline{0.8256}$

Murphree Plate Efficiency = E_{mv} = $\underline{0.8256}$

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

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

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

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.

$(L/G)\times \{\rho_g/\rho_l\}^{0.5} = (18348/28597)\times\{2.925/782.92\}^{0.5} = \underline{0.039}$

thus, for $(L/G)\times\{\rho_g/\rho_l\}^{0.5} = 0.039$ 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 = $\underline{0.076}$

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

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

$$= \frac{0.8256}{(1+0.82560[0.076/ (1-0.076)])}$$

$\Rightarrow E_\alpha = \underline{0.773}$

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

$$E_{OC} = \frac{\log [1+ 0.7730(1.0421-1)]}{\log 1.0421}$$

Overall Efficiency = E_{OC} = 0.777

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

Where N_T = Theoretical plates,

N_{act} = actual trays

N_{act} = 8/0.777 = 10.296 ≈ 11

Thus, Actual trays in the Stripping Section = 11

Total Height of Stripping section = $10 \times t_s = 10 \times 457$ = 5027 mm = 5.027 m

B) Stripping Section:

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

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

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

--------------------------- (eq$^{n.}$ 18.36, page 18.15, 6th edition Perry)--- *

where h_w = weir height = 45.00 mm

U_a = Gas velocity through active area, m/s

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

= 30639.5/ (3600×2.594×3.015)

U_a = 1.088 m/s

$D_f = (L_w + D_c)/2 = (2.09 + 1.567)/2 =$ 1.8285 m

Average Liquid rate = 41198.5 kg/hr

Average Liquid Density =772.52 kg/m^3

q = 41198.5/ (3600×772.52) =0.0147 m^3/s

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

= q/D_f = 0.0147/1.8285 = 8.039×10^{-3} m^3/ (s.m)

$N_{Sc,\,g}$ = Schmidt number =$\mu_g/(\rho_g\times D_g)$ = 0.621

Now,

Number of gas phase transfer units

$$N_g = \frac{(0.776 + (0.00457\times45) - (0.238\times1.088\times3.015^{0.5}) + (104.6\times8.039\times10^{-3}))}{(0.621)^{0.5}}$$

N_g = 1.60

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

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

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

$$q = \frac{41198.5}{(3600\times772.52)} = 0.0147 \text{ m}^3/\text{s}$$

$h_l = h_l'$ = 47.1 mm

A_a = 2.594 m^2

$$\therefore \theta_l = \frac{47.1 \times 2.594}{(1000 \times 0.0147)} = \underline{8.311}\ s$$

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

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

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

$k_l \times a = (3.875 \times 10^8 \times 8.65 \times 10^{-9})^{0.5} \times ((0.40 \times 1.088 \times 3.015^{0.5}) + 0.17)$

$\therefore$ $k_l \times a$ = $\underline{1.694}$ m/s

$\therefore$ $N_l = k_l \times a \times \theta_l$

i.e., N_l = 1.694×8.311 =$\underline{14.07}$ m

Slope of equilibrium Curve

$m_{top} = \underline{0.956}$

$m_{bottom} = \underline{2.55}$

G_m/L_m = 0.754

$\lambda t = m_t \times G_m/L_m = \underline{0.720}$

$\lambda b = m_b \times G_m/L_m = \underline{1.922}$

$\Rightarrow \bar{\lambda} = \underline{1.321}$

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

$$= \frac{1}{[(1/1.60) + (1.321/14.07)]}$$

$N_{og} = \underline{1.385}$

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

$= 1-e^{-1.385}$ = 1-exp (-1.385)

$E_{og} = \underline{0.749}$

$\therefore$ Point Efficiency = E_{og} = $\underline{0.749}$

4. Murphree Plate Efficiency (E_{mv}):

Now,

Pelect number $= N_{Pe} = Z_l^2 / (D_E \times \theta_l)$

Where Z_l = length of liquid travel, m

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

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

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

$D_E = (6.675 \times 10^{-3} \times (1.088)^{1.44}) + (0.922 \times 10^{-4} \times 47.1) - 0.00562$

$D_E = \underline{6.259 \times 10^{-3}}\ m^2/s$

Also,

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

$= 2.09 \times \cos(97.18^0/2)$

$= \underline{1.382}$ m

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

$= 1.382^2 / (6.259 \times 10^{-3} \times 8.311)$

$N_{Pe} = \underline{36.71}$

$\bar{\lambda} \times E_{og} = 1.321 \times 0.782 = \underline{1.033}$

Now for $\lambda \times E_{og} = 1.033$ and $N_{Pe} = 36.71$

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

$E_{mv}/ E_{og} = \underline{1.55}$

$\therefore E_{mv} = 1.55 \times E_{og} = 1.28 \times 0.749 = \underline{1.16}$

Murphree Plate Efficiency = E_{mv} = $\underline{1.16}$

5. Overall Efficiency (E_{OC}):

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

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

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

----- (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.

$(L/G)\times\{\rho_g/\rho_l\}^{0.5} = (41198.5/30639.9)\times\{3.015/777.05\}^{0.5} = \underline{0.0837}$

thus, for $(L/G)\times\{\rho_g/\rho_l\}^{0.5} = 0.0837$ 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 = $\underline{0.035}$

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

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

$$= \frac{1.16}{(1+1.16[0.035/(1-0.035)])}$$

$\Rightarrow E_\alpha = \underline{1.11}$

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

$$E_{OC} = \frac{\log[1+ 1.11(1.321-1)]}{\log 1.321}$$

Overall Efficiency = E_{OC} = $\underline{1.08}$

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

Where N_T = Theoretical plates,

N_{act} = actual trays

$N_{act} = 10/1.08 = \underline{9.25} \approx \underline{10}$

Thus, Actual trays in the Stripping Section = $\underline{10}$

Total Height of Stripping section = $10\times t_s = 10\times400$ = 4000 mm = $\underline{4.0}$ m

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

= 5027 + 4000 = $\underline{9027}$ mm = $\underline{9.027\text{m}}$

SUMMARY OF THE DISTILLATION COLUMN:

A) Enriching section

Tray spacing = 457 mm

Column diameter = 1900 mm = 1.90 m

Weir length = 1.425 m

Weir height = 45 mm

Hole diameter = 5 mm

Hole pitch = 15 mm, triangular

Tray thickness = 3 mm

Number of holes = 8759

Flooding % = 80

B) Stripping section

Tray spacing = 400 mm

Column diameter = 2090 mm = 2.09 m

Weir length = 1.567 m

Weir height = 45 mm

Hole diameter = 5 mm

Hole pitch = 15 mm, triangular

Tray thickness = 3 mm

Number of holes = 10180

Flooding % = 80

VI. Mechanical Design of Distillation Column

a) SHELL:

Diameter of the tower =D_i = 2090 mm =2.090 m

Working/Operating Pressure = 1 atmosphere = 1.033 kg/cm^2

Design pressure =1.1×Operating Pressure

= 1.1×1.033 = 1.1362 kg/cm^2

Working temperature = 145.6 ^0C = 418 ^0K

Design temperature = 159 ^0C = 432.5 ^0K

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

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

Elastic Modulus (E) = 1.88×10^5 MN/m^2 = 1.9164×10^6 kg/cm^2

Shell – double welded butt joints, stress relieved.

Insulation material - asbestos

Insulation thickness = 2”= 50.8 mm

Density of insulation = 2700 kg/m^3

Top disengaging space = 0.3 m = 30 cm

Bottom separator space = 0.40 m= 40 cm

Weir height = 45 mm

Downcomer clearance = 1” = 25.4 mm

b) HEAD - TORISPHERICAL DISHED HEAD:

Material - IS: 2002-1962 Grade I Plain 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 = 21

Hole Diameter = 5 mm

Number of holes:

Enriching section = 8759

Stripping section = 10180

Tray spacing:

Enriching section: 18” = 457 mm

Stripping section: 15.75” = 400 mm

Thickness = 3 mm

e) SUPPORT FOR TRAY:

Purlins - Channels and Angles

Material - Carbon Steel

Permissible Stress = 1275 kg/cm^2

Materials for trays, downcomers and weirs – stainless steel.

f) nozzles:

No. of nozzles = 4.

1. Shell minimum thickness:

Considering the vessel as an internal pressure vessel.

$$t_s = \frac{(P \times D_i)}{(2 \times f_t \times J) - P} + C$$

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, $t_s = \frac{(1.1363 \times 2090)}{(2 \times 970 \times 0.85) - 1.1363} + 3 = 4.4411$ m

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

Check for Plastic deformation

$$P = \frac{2 \times f_t \times (t/D) * (1+1.5U(1-0.2D/L))}{(100t/D)}$$

U = 1.5% (for new equipment)

$$P = \frac{2\times95\times(6/2090)*(1+(1.5\times0.015)*(1-(0.2\times(2090/9027)))}{(100\times6/2090)}$$

$P = \underline{1.852}\ MN/m^2 = \underline{18.17}\ kg/cm^2$

$P_{(allowable)} = \underline{1.852}\ MN/m^2 = \underline{18.17}\ kg/cm^2$

The allowable pressure is greater than the design pressure. Hence, the thickness is satisfactory with respect to plastic deformation.

2. Head Design- Shallow dished and Torispherical head:

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

P =internal design pressure, kg/cm^2

R_c = crown radius = diameter of shell, mm

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

$W = ¼ \times (3 + (R_c/R_k)^{0.5})$

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

Now, $R_c = \underline{2090}$ mm

$R_k = 6\% \times R_c = 0.06\times2090 = \underline{125.4}$ mm

$W = ¼ \times (3 + (R_c/R_k)^{0.5}) = ¼ \times (3 + (2090/125.4)^{0.5}) = \underline{1.7706}$ mm

$t_h = \frac{(1.1363\times2090\times1.7706)}{(2\times970\times0.85)} = \underline{2.5499}$ mm = 2.55mm

including corrosion allowance take the thickness of head = $\underline{6}$ mm

Pressure at which elastic deformation occurs

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

$= 0.366\times1.88\times10^5\times (6/2090)^2$

$= \underline{1.022}\ MN/ m^2 = \underline{10.034}\ kg/cm^2$

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 = 1.5”

i_{cr} = 4.75”

also, O.D.= 2090 mm = 82.28”

Diameter = 82.28 + (82.28/24) + (2×1.5) + (3/2*19/4) =

d = 95.83” = 2434.1 mm

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

$= ((\pi\times 95.83^2 \times 0.2362)/4) \times (7700/1728)$ = 7591 lb

= 3443 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:

$$f_{ap} = \frac{P\times D_i}{4(t_s - c)} = \frac{1.1363\times 2090}{4(6 - 3)} = 237.38 \text{ kg/cm}^2$$

This is the same through out the column height.

Circumferencial stress = 2x 237.38 = 474.7

3.2 Compressive stress due Dead Loads:

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

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

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

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

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, $\rho_s = \underline{7700}\ kg/m^3$

$f_{ds} = \rho_s \times X = \underline{(7700\times X)}\ kg/m^2 = \underline{(0.0077\times X)}\ kg/cm^2$

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

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

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

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

$t_{ins} = 2'' = 5.08cm$

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

$D_{ins} = D_c + 2t_s + 2t_{ins}$

$= 209 + (2\times 0.6) + (2\times 5.08) = \underline{220.6}$ cm.

$D_m = (209 + (209 + (2\times 0.6)))/2 = \underline{209.6}$ cm.

$$f_{d(ins)} = \frac{\pi \times 220.36 \times 5.08 \times 2700 \times X}{\pi \times 209.0 \times (0.6 - 0.3)} = \underline{48067.07 \times X}\ kg/m^2$$

$= \underline{4.8067 \times X}\ kg/cm^2$

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 450 mm.

Average liquid density = 777.72 kg/m^3

Liquid and tray weight for X meter

$F_{liq\text{-}tray} = [(X-0.3)/\ 0.6 + 1] \times (\pi \times D_i^2/4) \times \rho_l$

$= [(X-0.3)/ 0.6 + 1] \times (\pi \times 2.09^2/4) \times 777.72$

$= \underline{[2X + 0.4] \times 2668.12}$ kg

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

$= [2X + 0.4] \times 2668.12 \times 10/ (\pi \times 2090 \times (6 - 3))$

$= \underline{2.709X + 0.541}$ 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 = $\underline{(3443 + 25X)}$ kg

$$f_{d\ (attch.)} = \frac{(3443+25X) \times 10}{\pi \times 2090 \times (6 - 3)} = \underline{1.747 + 0.0126X} \text{ kg/cm}^2$$

Total compressive dead weight stress:

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

$= 0.9246X + 4.8067X + [2.709X+0.541] + [1.747 +0.0126X]$

$f_{dx} = \underline{8.4523X + 2.288}$ 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

$\approx \pi \times D_m^2 \times (t_s-c)/4$

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

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

$= 37.204$ kg/m^2

Bending moment due to wind load

$= M_{wx} = 0.7\times37.204 \times 2.09\times X^2/2 = \underline{27.71X^2}$ kg-m

$f_{wx} = 1.4\times37.204\times X^2/\ \pi \times2.09\times (6\text{-}3) = \underline{0.264423X^2}$ kg/cm^2

5. Stresses due to Seismic load:

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

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

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

Where C = seismic coefficient,

W= total weight of column, kg

H = height of column

Total weight of column = $W= C_v\times\pi\times\rho_m\times D_m\times g\times (H_v+ (0.8\times D_m))\times t_s\times10^{-3}$

----- (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 = $D_i + (t \times10^{-3})$

$= 2.09+ (6 \times10^{-3}) = \underline{2.096}$ m

$W= 1.5\times\pi\times7700\times2.096\times9.81\times (8.267 + (0.8\times2.096))\times6\times10^{-3} = 46125.47$ N =

= 4701.9 kg .

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

Plate area = $\pi\times2.09^2/4 = \underline{3.43}$ m^2

Weight of each plate = 1.2×3.43 = <u>4.11</u> kN

Weight of 21 plates = 21×4.11 = <u>86,31</u> kN = $\underline{86.31\times10^3}$ N = <u>8798.1</u> kg.

Total weight of column = 4701.9+8798.1= 13500 kg

Let C = seismic coefficient = 0.08

$M_{sx} = [0.08\times13500\times X^2/3] \times [((3\times9.027-X)/9.027^2]$

$= \underline{360X^2 \times [0.3323-0.01227X]}$ kg-m

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

$= 360X^2 \times [0.3323-0.01227X \times10^3/\pi\times209.0^2\times (6-3)/4$

$= \underline{[1.162X^2- 0.0429X^3]}$, 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,

$0.264423X^2 + 237.38- [8.4523X + 2.288] = f_{t,max}$

LET $f_{t,max = 970 * 0.85}$

$0.2644X^2- 8.4523X – 592.4 =0$

=> X = 65.92 m

On the down side:

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

$0.2644X^2 –237.38+ [8.4523X + 2.288] = f_{c,max}$

The column height is 9.027 m, for which the maximum value is

$f_{c,max} =$ 0.2644(9.O27^2 –237.38+ [8.4523(9.027 + 2.288]

= $\underline{-137.24}$ kg/cm^2

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

therefore

$0.2644X^2–237.38+[8.4523X+2.288]=f_{t,max}$

$f_{t,max}$ = 824.5 kg/cm^{2,}

$0.2644X^2–237.38+[8.4523X+2.288]- 824.5 =0$

i.e, $0.2644X^2–8.4523X- 1059.5 =0$

$$X = \frac{-8.4523 \pm \sqrt{(8.4523^2 + 4 * 0.2644 * 1059.5)}}{2 * 0.2644}$$

$= \underline{49.27m}$.

Hence we see that the design value of the column height is more than 9.027 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 = $D_c/4$ = 2.09/4 = 0.5225 m

Skirt support Height = 1.0 m

Total actual height = 9.027 + (2×0.5225) + 1.0 = 11.072 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 = 910 mm.

(ii) Height = 10000 mm = 10 m

(iii) Weight of vessel, attachment = 204845.7489 kg.

(iv) Diameter of skirt (straight) = 910 mm

(v) Height of skirt = 1.6 m

(vi) Wind pressure = 189.631 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,

$f_d = 204845.7489/(\pi \times 91.6 \times t_{sk}) = \underline{711.8387/t_{sk}}$ 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

$p_w = 0.7 \times 37.204 \times 1.0 \times 2.090 = \underline{54.42}$ kg

$M_w = p_w \times H/2 = 54.74 \times 9.027/2 = \underline{245.66}$ kg-m

Substituting the values we get,

$f_{wb} = \underline{578/t_{sk}}$ kg/cm^2

3. **Stress due to seismic load:**

Load = C×W

C = seismic coefficient,

W= total weight of column.

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

C=0.08

$f_{sb} = (2/3) \times (0.08 \times 2090 \times 13500)/(\pi \times (210.2/2)^2 \times t_{sk} = \underline{0.433/t_{sk}}$ kg/cm^2

Maximum tensile stress:

$f_{t,\,max} = (25{,}99/t_{sk}) - (0.433/t_{sk}) = \underline{(25.557/t_{sk})}$ kg/cm^2

Permissible tensile stress = $\underline{925}$ kg/cm^2

Thus, $925 = (25.557/t_{sk})$

=> t_{sk} = 0.0027 cm = 0.27 mm

Maximum compressive stress:

$f_{c, max} = (25.99/ t_{sk}) + (0.433/ t_{sk}) = (26.423/ t_{sk})$ kg/cm^2

Now,

$f_{c, (permissible)} <= (1/3)$ yield point

= 1500/ 3 = 500 kg/cm^2

Thus, t_{sk} = 26.423/500 = 0.0528 cm = 0.528 mm

As per IS 2825-1969, minimum corroded skirt thickness = 6 mm

Thus use a thickness of 6 mm for the skirt.

Design of skirt bearing plate:

Assume both circle diameter = skirt diameter + 32.5 = 210.2+ 32.5 = 242.7 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,

$f_c = (17168\times4)/ (\pi \times (243.7^2- 210.2^2)) + (0.7\times37.204 \times 3 \times42.3^2\times/(2\times \pi\times(242.7^4 - 210.2^4)/(32\times231.5$

f_c = 0.4873 kg/cm^2

which is less than the permissible value for concrete.

Maximum bending moment in bearing plate

$M_{max} = (0.9351\times16.25^2/2)$ = 123.4624 kg-cm

Stress, $f = (6\times0.4873\times 16.25^2)/ (2 \times t_B^2) = 386.03/ t_B^2$

Permissible stress in bending is 1000 kg/cm^2

Thus, t_B^2 = 386.03/1000 => t_B = 0.6213 cm = 6.213 mm

Therefore a bolted chair has to be used.

Anchor Bolts:

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

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

$= [(4\times3000)/ (\pi \times (242.7^2 - 210^2))] - (0.7\times 37.204\times 3 \times42.3^2\times/(2\times \pi\times(242.7^4 - 210^4)/(32\times242.7))$

$= - 0.1447$ kg/cm^2

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

Assuming there are 8 bolts,

$P_{bolts} = (0.1447/20) \times ((\pi \times (242.7^2 - 210^2))/4) = 84.11$ kg

Trays:

The trays are standard sieve plates throughout the column. The plates have 8759 holes in Enriching section and 10180 holes in the Stripping section of 5mm diameter arranged on a 15mm triangular pitch. The trays are supported on purloins. The details of the trays are shown in fig 6.3

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)/ ($\rho_L \times V_L$)

Mass of liquid in = [(molar flow rate) × (molecular weight of liquid)]/3600

= [211.0`14 × 98.66]/3600 = 5.783 kg/s

Thus, Area of Nozzle = (5.783)/ (788.86 × 2) = 3.66×10^{-3} m^2

Now, Area of Nozzle = $\pi \times d_N^2/4$ = 0.683 m^2

d_N = 0.683 m = 6,83 mm.

2. Liquid Outlet Nozzel:

Liquid Velocity = V_L= 2 m/s

Area of Nozzle = (Mass of liquid in)/ ($\rho_L \times V_L$)

Mass of liquid in = [(molar flow rate) × (molecular weight of liquid)]/3600

= [112.81 ×92.42]/3600 = 2.89 kg/s

Thus, Area of Nozzle = (2.89)/ (788 × 2) = 1.837×10^{-3} m^2

Now, Area of Nozzle = $\pi \times d_N^2/4$ = 1.837×10^{-3} m^2

d_N = 0.0483 m = 48.3 mm.

3. Vapor Outlet Nozzel:

Vapor Velocity = V_G= 1.2180 m/s

Area of Nozzle = (Mass of liquid in)/ ($\rho_G \times V_G$)

Mass of liquid in = [(molar flow rate) × (molecular weight of vapor)]/3600

= [65.6690 ×86.6048]/3600 = 1.5798 kg/s

Thus, Area of Nozzle = (1.5798)/ (2.9150 × 1.2180) = 0.4450 m^2

Now, Area of Nozzle = $\pi \times d_N^2/4$ = 0.4450 m^2

17 $d_N^2 = (4 \times 0.4450/\pi)$

18 d_N = 0.7527 m = 752.7 mm.

4. Reboiler Vapor Outlet:

Vapor Velocity = V_G= 1.2637 m/s

Area of Nozzle = (Mass of liquid in)/ ($\rho_G \times V_G$)

Mass of liquid in = [(molar flow rate) × (molecular weight of vapor)]/3600

= [65.6690 ×88.1293]/3600 = 1.6076 kg/s

Thus, Area of Nozzle = (1.60760)/ (2.6672 × 1.2637) = 0.4770 m^2

Now, Area of Nozzle = $\pi \times d_N^2/4$ = 0.4770 m^2

19 $d_N^2 = (4 \times 0.4770/\pi)$

20 d_N = 0.7793 m = 779.3 mm.

5. Reflux Liquid Inlet:

Liquid Velocity = V_L= 2 m/s

Area of Nozzle = (Mass of liquid in)/ ($\rho_L \times V_L$)

Mass of liquid in = [(molar flow rate) × (molecular weight of liquid)]/3600

= [57.2858 ×86.6048]/3600 = 1.3781 kg/s

Thus, Area of Nozzle = (1.3781)/ (750.65 × 2) = 9.2113×10^{-4} m^2

Now, Area of Nozzle = $\pi \times d_N^2/4$ = 9.2113×10^{-4} m^2

21 $d_N^2 = (4 \times 9.2113 \times 10^{-4} / \pi)$

22 d_N = 0.0343 m = 34.3 mm.

All nozzles are provided with a standard compensation pad of 36 mm thickness. This small compensation is sufficient as the design pressure is 1.1362 kg/cm^2

CONDENDER DESIGN

The condenser is used to condense the vapor leaving the distillation tower. Part of the vapor condensed is sent back to the tower as reflux. Assume that the vapor entering is saturated and the condenser removes only the latent heat. i.e. the liquid leaving is a saturated liquid. The vapor comprises of acetic acid and water with a saturation temperature of 112.5ºC. The cooling fluid used is treated water in the tube side.

Feed to the condenser = 28072.6 Kg/Hr

m = 7.79 Kg/s

C_P = 1.405 KJ/Kg K

$\bar{\lambda}$ = 363.17 KJ/Kg K

Heat of vapor = 7.79 x 363.17

Q =**2829.09 KW**

To calculate the amount of Cooling water Required:

Cooling water is untreated water and assume that the water leaves the condenser at a temperature of 35 ºC.

$Q = mC_P \Delta T$

$$m = \frac{2829.09}{4.187\ (35 - 25)}$$

The Cooling water required = **67.56 Kg/s**

To find the LMTD:

$$(\Delta T)_{lmtd} = \frac{(112.5 - 25) - (112.5 - 35)}{\ln\left[\frac{112.5-25}{112.5-35}\right]}$$

$(\Delta T)_{lmtd}$ = **82.39 ºC**

To Calculate the Heat Transfer Area:

From the table assume the heat transfer coefficient = 500 W/m^2K

$Q = U_a\, A\, (\Delta T)_{lmtd}$

$$A = \frac{2829.09 \times 10^{3}}{500 \times 82.39}$$

$= \mathbf{68.67\ m^2}$

To Calculate the Number of Tubes:

Take the pipe to be a 16 BWG pipe with 0.75”

O.D. = 0.75” = 19.05mm,

I.D. = 0.745” = 15.75mm,

Length = 4.88 m , a = 0.0598 m^2

Number of tubes N_t = A/(a x L)

N_t = (68.67/(0.0598 x 4.88))

= **235**

To find the dimensions of the Shell:

From the table 11-3 (Perry – page no.11-14)

Triangular pitch 1”, 1-2 pass Heat Exchanger

N_t = **314**

Shell ID = **540 mm**

Corrected Heat transfer Area = 314 x 0.05987 x 4.88

= **91.66 m^2**

Corrected Heat transfer coefficient = $U_o = \dfrac{Q}{A \times \Delta T} = \dfrac{2829.09 \times 10^{3}}{191.66 \times 82.39}$

$(U_o)_{assumed}$ = **374.6 W/m^2K**

Calculation Of Film Transfer Coefficient:

T_w = (112.5 + (35+25)/2)/2 = 71.25 ºC

T_f = (112.5 + 71.25)/2 = 91.875 ºC

*Properties of shell side fluid(toluene)***:**

ρ_l = 791.3 Kg/m^3

$\mu_l = 0.246 \times 10^{-3}$ N-s/m^2

k = 0.1488 W/m^{2}K

Shell Side FTC:

$$N_{Re} = \frac{4\,W}{\mu(N_t\,\Pi\,D_o)}$$

$$= \frac{4 \times 7.79}{(0.246 \times 10^{-3} \times 314 \times \Pi \times 1.905 \times 10^{-2})} = \mathbf{6740}$$

$$h_o = 1.51\left[\frac{k^3\ \rho^2\ g}{\mu^2}\right]^{1/3} (N_{Re})^{-1/3}$$

$$h_o = 1.51\left[\frac{0.1488^3 \times 791.3^2 \times 9.81}{(0.246 \times 10^{-3})^2}\right]^{1/3} (6740)^{-1/3}$$

= **554.86 W/m^{2}K**

Tube Side FTC:

Properties:

ρ = 1000 Kg/m^3

$\mu = 1 \times 10^{-3}$ N-s/m^2

k = 0.578 W/m^{2}K

C_p = 4.187 KJ/Kg ºC

Flow area = 194.7×10^{-6} m^2/m

$a_t = (250 \times 194.7 \times 10^{-6})/2$

= **0.0243**

G_t = 67.56/0.0243) = **2776.8 kg/m^2 s**

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

$= \frac{4.187 \times 10^3 \times 1 \times 10^{-3}}{}$

$$= \frac{\quad}{0.578}$$

$= \mathbf{7.244}$

$N_{Re} = D\,G_t / \mu$

$$= \frac{2276.8 \times 1.575 \times 10^{-2}}{1 \times 10^{-3}}$$

$= \mathbf{43734.6}$

$$\frac{h_i D_i}{k} = 0.023 \times (N_{Re})^{0.8} (N_{Pr})^{0.3}$$

$$h_i = \frac{0.023 \times (43734.6)^{0.8} \times (7.244)^{0.3} \times 0.578}{1.575 \times 10^{-2}}$$

$= \mathbf{7887.8\ W/m^2K}$

Overall Outside Heat Transfer Coefficient:

$$\frac{1}{U_o} = \frac{D_o}{D_i}\frac{1}{h_i} + \frac{1}{h_o} + \frac{1}{h_{dirt}}$$

$$\frac{1}{U_o} = \frac{0.75}{0.62}\frac{1}{7887.8} + \frac{1}{554.86} + 5.3 \times 10^{-3}$$

$U_o = \mathbf{402.31\ W/m^2K}$

$(U_o)_{calculated} > (U_o)_{assumed}$

Therefore the above value of shell and tube dimension can be accepted

<u>Pressure drop ccalculatons:</u>

Shell side pressure drop (Bell's method)

shell side Reynolds number=N_{Re} =9282.87

O.D = 0.75"

Therefore from fig.10-25, page 10-31,

f_k=0.15

pressure drop for cross flow zones

$$\Delta P_C = \frac{(b f_k w^2 N_C}{\rho_f S_m^2)} \frac{(\mu_w)^{0.14}}{\mu_f}$$

where,

b = constant = 0.002

w = 7.79 Kg/s

S_m = cross flow area = 0.02916

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

$$N_c = \frac{D_s[1-2(L_C/D_s)]}{P_P}$$

Where L_c baffle cut,25% of D_s

$P_P=((\sqrt{3})/2)P^I$

= 22mm

$$N_c = \frac{540\ [1-2*(135/540)]}{22}$$

N_c= 12

$$\Delta P_C = \frac{(2*10^{-3}*0.18*58.216^2*19}{(987*0.1404^2)}$$

ΔP_C = 0.324K Pa

pressure drop in end zones

$\Delta P_E = \Delta P_C(1+N_{cw}/N_c)$ Kn.m^2

N_{cw}= number of effective cross flow rows in each window

= $0.8L_C/P_P$.

N_{cw}= **5**

ΔP_E= 0.324*(1+5/12)

ΔP_E= 0.459 K Pa

pressure drop in window zones

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

b = 0.002

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

S_w=area for flow through window zone.

S_{wg}= gross window area

S_{wt}= area occupied by tubes

S_{wg}= 70 in^2, for D_S=21.25in & L_C/D_S=0.25

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

$S_{wt}= (314/8)(1-0.66)\ \Pi x\ 0.01905^2$

S_{wt}= 0.0152 m^2

S_W=(0.0.0451-0.0152)=0.0299 m^2

$$\Delta P_W = \frac{5*10^{-4}*7.79^2*(2+0.6*5)}{0.02916*0.0299*791.3}$$

ΔP_W = 0.22 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*0.459 + (17-1)*0.324 + 8*0.22

$(\Delta P_S)_T$ = 9.842 Kpa

The Pressure drop in the shell side is well within the allowed limit therefore the dimensions of the shell also can be accepted.

Tube Side:

$f = 0.079\ (Re)^{-0.25}$

$= 0.079\ (43734.6)^{-0.25}$

$= \mathbf{0.00546}$

$$\Delta P_l = \left[\frac{4\ f\ L\ V_t^2}{2\ g\ D_i} \right] x\ g\ x$$

$V_t = 2276.8/1000 = \mathbf{2.2768\ m/s}$

$$\Delta P_l = \left[\frac{4 \times 5.46 \times 10^{-3} \times 4.88 \times 2.27^2}{2 \times 9.81 \times 1.575 \times 10^{-2}} \right]$$

$= \mathbf{17.434\ KPa}$

$$\Delta P_t = \frac{2.5}{2} (\ \rho_t \ x\ \ V_t^2)$$

$$\Delta P_t = \frac{2.5}{2} (\ 1000 \times 2.27^2)$$

$= \mathbf{6.41\ KPa}$

$\Delta P_{total} = N_b\ (\Delta P_l + \Delta P_t)$

$= 2\ (17.434 + 6.41)$

$= \mathbf{47.71\ KPa}$

The Pressure drop in the tube side is also well within the allowed limit therefore the dimensions of the tube also can be accepted.

CONDENSER DETAILS

Type Of Condenser : 1-2 Pass Counter Current Floating Head Condenser

Heat Load on the Condenser: 2829.09 KW

Shell Side: toluene vapors

Tube Side: UnTreated Cooling Water

Mass Flow Rate on the Shell Side: 7.79 Kg/s

Mass Flow Rate on the Tube Side:67.56   Kg/s

Logarithmic Mean Temperature Difference: 82.39 ºC

Heat Transfer Area: 91.66 m^2

Diameter of the Shell : 540 mm

Number of Tubes: 716

Type of Tube Used : 16BWG Tubes

Inner Diameter of the Tube: 0.745”

Outer Diameter of the Tube: 0.75”

Length of the Tube: 4.88 m

Pitch of the Tubes: 1” Δ

Heat Transfer Coefficient: 402.31 W/m^2K

Number of Baffles: 17

Pressure Drop on Shell Side: 9.842 KPa

Pressure Drop on Tube Side: 47.14 KPa

Mechanical design of Condenser

(a) Shell side details

Material of construction: Carbon steel

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

Fluid: ttoluene

Working pressure: 0.101325 N/mm^2

Design pressure: 0.1115 N/mm^2

Inlet temperature: 112.5 ^0C

Out let temperature: 112.5 ^0C

Design temperature: 123.75 ^0C

Number of shell passes: one

Number of shells: one

Shell Diameter : 540mm

(b) Tube side details

Material of construction: Stainless Steel

IS- grade 10

Permissible stress for carbon steel: 10.06 kg/mm^2

Number tubes: 314

Number of passes: 2

Number of tubes per pass: 157

Outside diameter: 19.05 mm

Inside diameter: 15.75 mm

Length of each tube: 4.88 m

Pitch square: 1 inch

Working pressure: 0.101325 N/mm^2

Design pressure: 0.1115 N/mm^2

Inlet temperature: 25 ^0C

Outlet temperature: 35 ^0C

SHELL SIDE

(1) Shell thickness:

$$t_s = \frac{(P_d \times D_s)}{((2 \times f \times J) - P_d)}$$

Where P_d = design pressure

D_s = shell diameter

f = allowable tensile stress

J = joint factor = 0.85

$$t_s = \frac{(0.1115 \times 540)}{((2 \times 95 \times 0.85) - 0.1115)}$$

= 0.37 mm

Minimum thickness of shell of 254 mm diameter, must be= 6 mm - (IS-4503, Table 4)

Including corrosion allowance of 3 mm, take shell thickness = 9 mm

(2) Nozzles:

Inlet and outlet diameter = 100 mm

Vent = 50 mm

Drain = 50 mm

Opening for relief valve = 75 mm

Material of construction: carbon steel

Permissible stress for Carbon steel = 950 kg/cm^2

Diameter = 100 mm = 10 cm

$t_n = (P_d \times D) / ((2 \times f \times J) - P_d)$

Let J= 1, seamless pipe

$t_n = (1.1362 \times 10) / ((2 \times 950 \times 1) - 1.1362)$

$t_n = 5.9836 \times 10^{-3}$ cm = 5.9836×10^{-2} mm

Including a corrosion allowance use thickness of 4 mm

(3) Head thickness.

Shallow dished and torispherical

$R_{(\text{Crown radius})}$ = 540 mm

$R_{(\text{knuckle radius})}$ = 6% $R_{(\text{Crown radius})}$ = 0.06×540 = 32.4 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

$$t_h = \frac{(P \times Rc \times W)}{(2 \times f \times J)}$$

$$= \frac{(0.1115 \times 540 \times 1.7706)}{(2 \times 95 \times 1)}$$

$= 0.65$ mm

Minimum shell thickness should be 10 mm including corrosion allowance.

(4) Transverse Baffles

Baffle spacing, $l_b = 0.5D_s$

$= 270$ mm

Number of baffles,

$N_b + 1 = L/l_b = 4.88/0.27 = 18$

$N_b = 18$

Use baffles of thickness= t_b= 6 mm(from IS : 4503 – 1967)

(5) Tie Rods and spacers

Tie rods and spacers shall be provided to retain all cross baffles and tube support plates accurately in position(from IS: 4503- 1967).

For shell diameter, 500-700mm

Diameter of Rod = 11 mm

Number of rods= 5

(6) Flanges

Design pressure= 0.1115 N/mm^2

Flange material IS: 2004-1962, class 2

Bolting steel: 5% Cr-Mo steel

Gasket material: Asbestos composition

Shell thickness: 9 mm=g_o

Outside diameter of shell: 558 mm = B

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

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

Determination of gasket width:

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

Assume a gasket thickness of 10 mm

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

m = gasket factor = 2.75

$d_O/d_i = [(25.5-(0.1115\times 2.75))/(25.5-(0.1115\times (2.75+1)))]^{0.5}$

d_O/d_i = 1.0022

let d_i of gasket equal 568 mm

$d_o = 1.0022\times d_i = 1.002\times 0.568$

d_o= 0.5691 m

Minimum gasket width = N = (0.5691-0.568)/2 = 0.00054 m

Taking gasket width of 10 mm = 0.011 m

i.e., N= 0.011 m

d_o= 0.5911 m

Basic gasket seating width, b_o= 5 mm

Diameter of location of gasket load reaction is

$G=d_i + N$

=0.568 + 0.010

= 0.578 m

Estimation of Bolt loads:

Load due to design pressure

$H = (\pi \times G^2 \times P)/4$

$= (\pi \times 0.578^2 \times 0.1115)/4 = \underline{29 \times 10^{-3}}$ MN

Load to keep joint tight under operation

$H_p = \pi G \times (2b) \times m \times p$ ($b = 2.5 \text{ x}(b_0)^{0.5}$)

$= \pi \times 0.568 \times (2 \times 0.00559) \times 2.75 \times 0.1115$

$= \underline{6.03 \times 10^{-3}}$ MN

Total operating load

$W_o = H + H_p$

$= (29 \times 10^{-3}) + (6.03 \times 10^{-3})$

$= \underline{35 \times 10^{-3}}$ MN

Load to seat gasket under bolting condition

$W_g = \pi \times G \times b \times y$

$= \pi \times 0.568 \times 0.00559 \times 25.5$

$= \underline{0.254}$ MN

$W_g > W_o$, => Controlling load= $\underline{0.254}$ MN

Calculation of optimum bolting area

$A_m = A_o = W_o/S_o$ (since the controlling load is wg)

S_o = allowable stress for bolting material at design pressure.

= 138

Calculation of optimum bolt size

Bolt size, M18 X 2

Actual 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

$C = n \times B_s/\pi = \underline{0.9243}$

C =ID + 2(1.415g + R)

= 0.558 +2[(1.415×0.009) +0.027]

= <u>0.6374</u> m

Choose C = <u>0.63</u>m

Bolt circle diameter = <u>0.63</u> m

<u>Calculation of flange outside diameter</u>

A=C+ bolt diameter +0.02

=0.6374 + 0.018+0.02

= <u>0.6754</u> m(selected)

<u>Check for gasket width</u>

$(A_b S_G) / (\pi \times G \times N) = (1.54 \times 10^{-4} \times 138) / (\pi \times 0.578 \times 0.010) = \underline{46.8} < 2y$,

where S_G is the Allowable stress for the gasket material

Hence condition satisfied.

Flange moment computation

(a) For operating condition

$W_o = W_1 + W_2 + W_3$

$W_1 = (\pi \times B^2 \times P)/4$

$= (\pi \times 0.558^2 \times 0.1115)/4$

$= \underline{26.9 \times 10^{-3}}$ MN

W_2=H-W1

$= (29 \times 10^{-3}) - (26.9 \times 10^{-3})$

$= \underline{2.1 \times 10^{-3}}$ MN

$W_3 = W_o - H = H_p$

$= \underline{6.03 \times 10^{-3}}$ MN

M_o=Total flange moment

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

$a_1 = (C-B)/2 = (0.6374-0.558)/2$

$a_1 = \underline{0.0397}$ m

$a_3 = (C-G)/2 = (0.6374-0.578)/2$

$a_3 = \underline{0.0297}$ m

$a_2 = (a_1 + a_3)/2 = (0.0397+0.0297)/2 = \underline{0.0347}$ m

$M_o = (0.0397\times0.027) + (0.0347\times0.0021) + (0.0297\times0.00603)$

$M_o = \underline{1.323\times10^{-3}}$ MN-m

(b) For bolting condition

$M_g = W\times a_3$

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

$A_b = 40\times1.54\times10^{-4} = \underline{6.16\times10^{-3}}\ m^2$

$A_m = \underline{1.84\times10^{-3}}\ m^2$

$W = ((1.84\times10^{-3}) + (6.18x10^{-3}))\times138/2$

$W = \underline{0.553}$ MN

$M_g = 0.553\times0.0297$

$= \underline{0.0164}$ 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

$K = A/B = 0.6754/0.558 = \underline{1.21}$

For K = 1.21, Y = 13

Assuming $C_F = 1$

$t^2 = 0.0164\times1\times13/ (0.558\times100)$

$t = \underline{0.0618}$ m= 61.8 mm

Actual bolt spacing, $B_S = \pi\times C/n = (\pi\times0.6374)/ 40 = \underline{0.050}$ m

<u>Bolt Pitch Correction Factor</u>

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

$= [0.05/ ((2\times0.018)+0.0618)]^{1/2}$

$= \underline{0.715}$

$\sqrt{C_F} = \underline{0.845}$

Actual flange thickness $= \sqrt{C_F}\times t$

$= 0.845\times0.0618 = \underline{0.0522}$ m = $\underline{52.2}$ mm

Standard flange thickness available is 60 mm

TUBE SIDE:

(1) Thickness of tube:

$t_t = (P_d \times D_s) / ((2 \times f \times J) + P_d)$

$t_t = (0.1115 \times 19.05) / ((2 \times 98.6886 \times 1) + 0.1115)$

$t_t = \underline{0.01076}$ mm

since the tube is a stainless steel tube there is no need of corrosion allowance, take the thickness of tube as 3 mm

(2) Tube sheet thickness:

$t_{ts} = F \times G \times (0.25 \times P/f)^{0.5}$

$t_{ts} = 1 \times 0.568 \times (0.25 \times 0.1115/95)^{0.5}$

$t_{ts} = \underline{9.67 \times 10^{-3}}$ m

$t_{ts} = \underline{9.67}$ mm

Including the corrosion allowance take $t_{ts} = \underline{13}$ mm

(3) Channel and channel Cover:

Since the pressure on the tube side is high and the velocity is well within the range, it is proposed to make the channel and cover out of a single plate.

$t_h = G_c \sqrt{(KP/f)}$

$= 0.578 \times \sqrt{(0.3 \times 0.1115/95)}$

$= \underline{10.7 \times 10^{-3}}$ m ≈ 11 mm

$t_h = \underline{14}$ mm including corrosion allowance

(4) Nozzles:

Inlet and Outlet diameter = 100 mm

Thickness of nozzle,

$t_n = (P_d \times D) / ((2 \times f \times J) - P_d)$

Let J= 1, seamless pipe

$t_n = (5.088 \times 100) / ((2 \times 93.175 \times 0.85) - 5.088)$

$t_n = \underline{0.33186}$ cm = $\underline{3.3186}$ mm

Including a corrosion allowance use thickness of 8 mm.

Considering the size of nozzle and the pressure rating it is necessary to provide a reinforcing pad on the channel cover.

Area required to compensate for each nozzle is = A= $d \times t_h$ = 100 × 8 = 800 mm^2
Compensation will be available from the additional thickness of channel cover and nozzle. Hence it is proposed to use a 10 mm thick pad.

Saddle support

Material: low carbon steel

Total length of shell: 5.88 m

Diameter of shell: 588 mm

Knuckle radius: 32.4 mm

Shallow dished and torispherical head

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

$= \sqrt{(558 \times 32.4/2)}$

= 95.07 mm

Weight of the shell and its contents = W = 10928.2 kg

R=D/2= 558/2 = 279 mm

Distance of saddle center line from shell end = A = 0.5×R= 0.5×279 = 139.5 mm

Longitudinal Bending Moment

$$M_1 = Q \times A \times \left[1 - \frac{\left(1 - A/L + (R^2 - H_d^2)/(2AL)\right)}{\left(1 + 4H_d/(3L)\right)}\right]$$

$Q = W/2(L+4H_d/3)$

= 10928.2× (5.88+ (4×0.029/3))/2

= 32340 kg-m

$M_1 = 32340.01 \times 0.1395 \Big[1 - \Big(\dfrac{1 - 0.1395/5.88 + (0.279^2 - 0.0029^2)/(2 \times 5.88 \times 0.1395)}{1 + 4 \times 0.029/(3 \times 5.88)} \Big) \Big]$

(

= <u>131.7</u>kg-m

Bending moment at center of the span

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

$M_2 =$ <u>46354.4</u>kg-m

Stresses in shell at the saddle

(a) <u>At the topmost fiber of the cross section</u>

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

$=131.7/(3.14\times0.279^2\times0.010)$

= <u>5.3855</u> kg/cm²

the stresses are well within the permissible values.

(b) <u>Stress in the shell at mid point</u>

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

= <u>528.8</u> kg/cm²

(c) <u>Axial stress in the shell due to internal pressure</u>

$f_p = PD/4t$

$= 10.06\times254/4\times10$

= <u>63.8810</u> kg/cm²

$f_2 + f_p = 537.1579 + 63.8810 =$ <u>601.0389</u> kg/cm²

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