DESIGN OF EQUIPMENTS

Process Design of Distillation Column

The detailed process design of the Monoethylene glycol column is given below. The pictorial representation of the column is given in fig 6.1. The feed to the column is a mixture of Monoethylene glycol(MEG), Diethylene glycol(DEG) and Triethylene glycol(TEG). The compositions of the components are shown in the figure. The distillate is the required product consisting of mainly MEG.

I. Thermodynamics:

The primary requirement while designing a mass transfer contact equipment is the thermodynamic equilibrium data. The data required is in the Vapor-Liquid Equilibrium (VLE) data for the MEG(1)-DEG(2) system. The quantity of TEG is small enough to be neglected. The X-Y curve is shown in the fig 6.2. To develop the VLE data, a model was used.

$$y_i \, p_t = \gamma_i \, x_i \, P_i^{sat}$$

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. Since the two components MEG and DEG are highly polar, they 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 a very low pressure (100 mmHg, abs). The high boiling points of the two components requires the column to be operated under vacuum. The operating pressure was chosen to be 100 mmHg(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 MEG in liquid

x_D = mole fraction of MEG in distillate

x_W = mole fraction of MEG 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, K

T_V = temperature of vapor, K

II. Preliminary calculations

F = 74.88 kmol/hr, x_F = 0.89, M_F = 66.84 kg/kmol

D = 66.96 kmol/hr, x_D = 0.99, M_D = 62.44 kg/kmol

W = 7.92 kmol/hr, x_W = 0.045, M_W = 104.02 kg/kmol

From the graph (Fig 6.3 and Fig 6.4)

$x_D/(R_m+1) = 0.5$, $R_m = 0.98$

$R = 1.5R_m = 1.5\times0.98 = 1.47$

$x_D/(R+1) = 0.4008$

L = RD = 98.4312 kmol/hr

G = L+D = (R+1)D = 165.3912 kmol/hr

$\overline{L}$ = L+qF = 98.4312 kmol/hr

$\overline{G}$ = G-(1-q)F = 90.5112 kmol/hr

III. List of parameters used in calculation.

	Enriching Section		Stripping Section	
PARAMETER	**TOP**	**BOTTOM**	**TOP**	**BOTTOM**
Liq, kmol/hr	98.4312	98.4312	98.432	98.4312
Vap, kmol/hr	165.3912	165.3912	90.5112	90.5112
X	0.99	0.83	0.83	0.045
Y	0.99	0.89	0.89	0.045
T_L, K	409.33	411.36	411.36	433.83
T_V, K	409.44	411.78	411.78	435.51

M_{LIQ}, kg/kmol	62.44	69.48	69.48	104.02
M_{VAP}, kg/kmol	62.44	66.84	66.84	104.02
Liq, kg/hr	6146.0441	6838.9998	6838.9998	10238.8134
Vap, kg/hr	10327.0265	11054.7478	6049.7686	9414.9750
ρ_L, kg/m^3	1052.2884	1054.2612	1054.2612	1062.5007
ρ_V, kg/m^3	0.2445	0.2603	0.2603	0.3830
μ_L, cP	0.7903	0.7259	0.7259	0.4300
q_L, m^3/s	1.6224×10^{-3}	1.8020×10^{-3}	1.8020×10^{-3}	2.6768×10^{-3}
q_V, m^3/s	11.7326	11.7970	6.4560	6.8284

IV. Design of Enriching Section

Tray Hydraulics

The design of a sieve plate tower is described below. The equations and correlations are borrowed form the 7th edition 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 (TS)

Choose tray spacing = 9" = 228.6mm

2.Hole Diameter (d_h)

Choose hole diameter = 5mm

3.Hole Pitch (l_p)

Choose hole pitch = 15mm, Δ pitch

4.Tray thickness (t_T)

Choose tray thickness = 3mm

5.Ratio of hole area to perforated area (A_h/A_p) (fig 6.3)

$$= \frac{1}{2}(\pi/4 \,.\, d_H^2)/[(\sqrt{3}/4).\, l_p^2]$$

$$= 0.1008$$

6.Plate Diameter (D_c)

The plate diameter is calculated based on the flooding considerations

$$L/G\{\rho_G/\rho_L\}^{0.5} = 0.0207$$

From the flooding curve, for a tray spacing of 228.6mm,

Flooding parameter, $C_{SB,F}$ = 0.0582m/s

$$Unf = Csb \times \{ \sigma / 20)^{0.2} [(\rho_L - \rho_G) / \rho_G]^{0.5}$$

$$Unf = 2.8102 \text{ m/s}$$

Actual velocity u_n= $0.8u_{n,f}$ = 0.8×4.4213 = 3.5370m/s

Net area available for gas flow (A_n)

Net area = Column cross sectional area – Downcomer area.

$A_n = A_c – A_d$

Choose weir length (L_w) = 0.60(Column diameter, D_c)

From the figure (fig 6.3),

Lw / Dc = 0.60

sin (θc/2) = [(Lw/2) / (Dc/2)] = 0.60

$$\Rightarrow \theta c = 73.74^0$$

$$Ac = (\pi/4) Dc^2 = 0.785Dc^2$$

$$Ad = (\pi/4) Dc^2 (\theta c/360^0) - (Lw/2) (Dc/2). \cos(\theta c/2)$$

$$= 0.1608 Dc^2 - Dc^2 \times 0.1200$$

$$= 0.0408 Dc^2$$

Since An = Ac -Ad

$$3.3352 = 0.785 Dc^2 - 0.0408 Dc^2$$

$$\Rightarrow Dc = 2.1164 \text{ m}$$

$Ac = (\pi/4) Dc^2 = 3.5179 \text{ m}^2$

$Ad = 0.1828 \text{ m}^2$

Lw = 1.2698 m

7.Perforated plate area (A_p)

Aa = Ac - 2Ad

= 3.1523m2

Perforated Area

Ap = Ac -2Ad - Acz - Awz

Ap = 2.6246 m^2

Total Hole Area

Ah / Ap = 0.1008

$\Rightarrow$ Ah = 0.2646 m^2

8.Total Hole Area

$A_h = 0.1008A_p = 0.1008\times2.6246 = 0.2646m^2$

Number of holes (n_h)

Number of holes N_h = 13476

9. Choose the weir height (h_W) as 12mm

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

$= k_1 + k_2 (\rho_g/\rho_l) \; U_h^2$

where U_h =gas velocity through hole area

k_1, k_2 are constants

For sieve plates

$k_1 = 0$ and $k_2 = 50.8 / (C_v)^2$

$C_v = 0.7419$

$\Rightarrow \quad k_2 = 50.8 / 0.7419^2 = 92.77$

Velocity through the hole area = U_h = 44.3409 m/s

$\Rightarrow \quad h_d = k_2 [\rho_g/\rho_l] U_h^2$

$= 42.16$ mm

Height of Liquid Crest over Weir

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

q = liquid flow rate at top = 1.6224×10^{-3} m^3/s

F_w= correction factor=1.01

L_w = weir length = 1.2698 m

$\Rightarrow \quad h_{ow}$ = 7.90 mm clear liquid

Head Loss Due to Bubble Formation

h_σ = 409 [σ / ($\rho_L . d_h$)]

where σ =surface tension(mN/m)

d_h =Hole dia

h_σ = 409 [48.5 / (1052.2884 x 5)]

h_σ = 3.77 mm clear liquid

($h_d + h_\sigma$) = 42.16 + 3.77 = 45.93 mm , this is the design value

(hw + how) = 12 + 2.676 = 7.90 mm

Also, A_h/A_a = 0.0839

The minimum value of ($h_d + h_\sigma$) required is calculated from a graph given in Perry ,plotted against A_h/A_a. The minimum value as found is 8 mm. Since the design value is greater than the minimum value**, there is no problem of weeping.**

Downcomer Backup

h_{dc} = $h_t + h_w + h_{ow} + h_{da} + h_{hg}$

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

= $h_d + h_l$`

Hydraulic Gradient

The hydraulic gradient was evaluated through an iterative procedure involving flow parameters of the liquid on the tray. The iteration yielded a value of 17.5mm. The large hydraulic gradient is a characteristic feature of vacuum operated towers where the additional hydraulic gradient is required to push the liquid hold up over the plate.

Head loss over downcomer apron

$$h_{da} = 165.2 \{q/ A_{da}\}^2$$

Take clearance, C = 0.5”

h_{ap} = h_{ds} - C = 28.9 – 25.4/2 = mm

A_{da} = Lw x h_{ap} = 0.0206 m^2

$\therefore$ hda = 165.2[1.802x 10^{-3}/ 0.0206] ^{2}

= 1.24 mm

h_t = h_d + h_l\`

= 42.16+8.60

= 50.76 mm

h_{dc} = h_t+ h_w + h_{ow} + h_{da} + h_{hg}

=50.76+12+7.90+1.24+17.5

= 89.40 mm

h\`$_{dc}$ = h_{dc} / ϕ , where ϕ is the froth density.

= 89.4/ 0.5 = 178.8 mm

which is less than the tray spacing of 228 mm.

Hence no flooding in the enriching section.

Column Efficiency

Point Efficiency

Average Vapor rate = 10690.8872 kg/hr

Average Vapor Density = 0.2524 kg/m^3

Active Area = 3.1523 m^2

Df = (Dc + Lw)/2 = 1.6931 m

Average Liquid rate = 6492.5220 kg/hr

Average Liquid Density =1053.2748 kg/m^3

$q = 1.7123 \times 10^{-3}\ m^3/s$

$\overline{T}_l = 410.34K$ and $\overline{T}g = 410.61K$

$\therefore\ (\mu_M)_L = 0.7851\ cp$

$(\mu_M)_G = 0.0143\ cp$

Diffusivity of the gas is calculated and is found out to be = $6.3003 \times 10^{-5} m^2/s$

Similarly the liquid diffusivity is calculated and found out to be

= $3.2411 \times 10^{-9}\ m^2/s$

Number of gas phase transfer units

$N_G = K_G.a.\theta_G$

$K_G.a = 316\ D_g^{\ 0.5}(1030f+867f^2)/\ h^{0.5}{}_L$

= 1184.4776 /s

$\theta_G = (1-\phi)h_L A_a/(1000\phi Q)$

$= 3.6652\times10^{-3}$ s

$N_G = 4.3414$

Number of liquid phase transfer units

$N_L = K_L.a.\theta_L$

$K_L.a = (3.875\times10^8 D_L)^{0.5}(0.4U_a\rho^{0.5}{}_G+0.17)$

= 1.0311 /s

$\theta_L = (1-\varepsilon)h_f A_a/(1000q) = 15.8263$ s

$\Rightarrow N_L = 16.3185$

Slope of equilibrium Curve

(m) top = 0.4933

(m) bottom = .6059

G_M/L_M = 165.3912/98.3412

$\lambda t = m_t\, G_M/L_M = 0.8289$

$\lambda b = m_b\, G_M/L_M = 1.0181 \quad \Rightarrow \quad \bar{\lambda} = 0.9235$

$$\therefore\ N_{OG} = \frac{1}{1/N_G + \lambda / N_L} = 3.4851$$

$E_{OG} = 1 - e^{-NOG} = 0.9694$

Murphree Plate Efficiency

θ_L = 15.8263 sec

$Z_L = D_C.\ \mathrm{Cos}\ (\theta c/2) = 1.6931\mathrm{m}$

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

$= 0.0397\ \mathrm{m}^2/\mathrm{s}$

Pecklet Number $N_{pe} = (\ z_L)^2/\ (\ D_E.\theta_L) = 4.5624$

$\bar{\lambda}\ \ E_{OG} = 0.9235 \times 0.9694 = 0.8952$

$E_{MV}/\ E_{OG} = 1.32$

$\Rightarrow\ E_{MV} = 1.32 \times 0.9694 = 1.2796$

Overall Efficiency (E_{OC})

$L/G\{\rho_G/\rho_L\}^{0.5} = 0.0094$

at 80 % of the flooding value we have $\psi = 0.40$

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

$\Rightarrow E_{\alpha} = 0.6905$

The overall efficiency is given by the equation :

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

$E_{OC} = 0.6819$

Hence the actual number of trays can be calculated as :

{ Theoretical number of trays   overall column efficiency }

$= 11 \quad 0.6819 \approx 16$

Height of the enriching section can be calculated as

{ Tray Spacing x Actual number of trays }

= 16 x 228 = 3657.6 mm.

V. Design of Stripping Section

Tray Spacing =t_s= 152.4mm=6 ”

Hole Diameter =d_h= 5 mm

Hole Pitch = l_p=15 mm

Tray Thickness = t_t =3 mm

Ah/Ap = $\dfrac{\text{Total Hole Area}}{\text{Perforated Area}}$

$= \underline{½\,(\pi/4 \,.\, d_H^2)}$

$(\sqrt{3}/4).\ l_p^2$

$= \quad 0.1008$

Plate Diameter (Dc)

Based on entrainment flooding, $L/G\{\rho_G/\rho_L\}^{0.5}$ has to be evaluated at a pt where the group is maximum

$L/G\{\rho_G/\rho_L\}^{0.5} = 0.0207$

$Unf = Csb \times \{ \sigma / 20)^{0.2} [(\rho_L - \rho_G) / \rho_G]^{0.5}$

$Unf = 2.8102$ m/s

U net vel. = Un = 0.7286 Unf = 2.0474 m /s

The odd value of the % flooding is taken so as to make the diameter of the stripping section equal to that of the enriching section. This ensures a considerable saving in mechanical design and fabrication without affecting the efficiency substantially.

Maximum flow rate of vapor = Vapor flow rate(max. at bottom) / vapor density = 6.8284 m/s

$\therefore$ An = 6.8284 / 2.0474 = 3.3352 m^2

Lw / Dc = 0.60

$\sin(\theta c/2) = [(Lw/2) / (Dc/2)] = 0.60$

$\Rightarrow \theta c = 73.74^0$

$Ac = (\pi/4) Dc^2 = 0.785Dc^2$

$Ad = (\pi/4) Dc^2 (\theta c/360^0) - (Lw/2) (Dc/2). \cos(\theta c/2)$

$= 0.1608\ Dc^2 - Dc^2 \times 0.1200$

$= 0.0408\ Dc^2$

Since An = Ac -Ad

$3.3352 = 0.785\ Dc^2 - 0.0408\ Dc^2$

$\Rightarrow Dc = 2.1164$ m

$Ac = (\pi/4)\ Dc^2 = 3.5179\ m^2$

$Ad = 0.1828\ m^2$

$Lw = 1.2698\ m$

Active Area (Aa)

$Aa = Ac - 2Ad$

$= 3.1523m2$

Perforated Area

$Ap = Ac - 2Ad - Acz - Awz$

$Ap = 2.6246\ m^2$

Total Hole Area

$Ah / Ap = 0.1008$

$\Rightarrow Ah = 0.2646\ m^2$

Number of holes $N_h = 13476$

Weir Height

Take a weir height of 12 mm.

Weeping check

hd = head loss across the dry hole

$= k_1 + k_2\ (\rho g/\rho l)\ Uh^2$

For sieve plates

$k_1 = 0$ and $k_2 = 50.8 / (\ Cv)^2$

$Cv = 0.7476$

$\Rightarrow \quad k_2 = 50.8 / 0.7476^2 = 90.89$

Weeping check is done at a point where the gas velocity is the least. Here the velocity of the vapor is minimum at the top of the enriching section.

Hence volumetric flow rate of the gas $= 6.456\ m^3/s$

$\therefore$ velocity through the hole area = U_h = 6.456 / hole are(A_h)

= 24.3991 m/s

$\Rightarrow$ hd = $k_2 [\rho g/\rho l] U_h^2$

= 12.77 mm

Height of Liquid Crest over Weir

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

q = liquid flow rate = 1.802×10^{-3} m^3/s

Lw = weir length = 1.2698 m

$\Rightarrow$ h_{ow} = 8.4691 mm clear liquid

Head Loss Due to Bubble Formation

$h_\sigma = 409 [\sigma / (\rho_L . d_H)]$

= 409 [48.50 / (1054.2612 x 5)]

h_σ = 3.76 mm clear liquid

(hd + hσ) = 16.52 mm , this is the design value

(hw + how) = 20.47 mm

Also, Ah/Aa = 0.0839

The minimum value of (hd + hσ) required is calculated from a graph plotted against Ah/Aa. The minimum value as found is 8 mm. Since the design value is greater than the minimum value we proceed using the same value for further calculations.

Downcomer Backup

$h_{dc} = h_t + h_w + h_{ow} + h_{da} + h_{hg}$

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

= $h_d + h_l$`

The hydraulic gradient was iteratively evaluated and found to be equal to 10.5 mm. The large gradient is again prominent as described before.

Loss under Downcomer

$h_{da} = 165.2 \{q/ A_{da}\}^2$

Take clearance = 0.5” = 12.70 mm

$h_{ap} = h_{ds} - c = 25.47-12.70 = 12.77$ mm

$A_{da} = Lw \text{ x } h_{ap} = 0.0162m2$

$\therefore$ hda = 4.51mm

$h_t = h_d + h_l`$

$=12.77 + 10.83$

$= 23.60$ mm

$h_{dc} = h_t + h_w + h_{ow} + h_{da} + h_{hg}$

$= 23.60+12+8.47+4.51+10.50$

$= 59.08$mm

$h`_{dc} = h_{dc} / \phi$, where ϕ is the froth density.

$= 59.08 / 0.5 = 118.2$ mm

which is less than the tray spacing of 152.4 mm. Thus flooding check is fulfilled satisfactorily for the enriching section.

Column Efficiency

Point Efficiency

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

$N_G = K_G.a.\theta_G$

$K_G.a = 316 D_g{}^{0.5}(1030f+867f^2)/ h^{0.5}{}_L$

$= 578.3924$ /s

$\theta_G = (1-\phi)h_L A_a/(1000\phi Q)$

$= 4.8271\times10^{-3}$ s

$N_G = 2.8180$

<u>Number of liquid phase transfer units:</u>

$N_L = K_L.a.\theta_L$

$K_L.a = (3.875\times10^8 D_L)^{0.5}(0.4U_a\rho^{0.5}{}_G+0.17)$

$= 0.9852$ /s

$\theta_L = (1-\varepsilon)h_f A_a/(1000q) = 15.2361$ s

$\Rightarrow N_L = 15.0161$

Slope of equilibrium Curve

(m)top = 0.6509

(m) bottom = 2.1875

$\lambda t = m_t\, G_M/L_M = 0.5572$

$\lambda b = m_b\, G_M/L_M = 2.4905 \quad \Rightarrow \quad \bar{\lambda} = 1.5238$

$$\therefore\ N_{OG} = \frac{1}{1/N_G + \lambda / N_L} = 2.1914$$

$E_{OG} = 1- e^{-NOG} = 0.8882$

Murphree Plate Efficiency

$\theta_L = 15.2361$ sec

$Z_L = D_C.\ \mathrm{Cos}\ (\theta c/2) = 1.6931$m

$D_E = 6.675 \times 10^{-3}(\mathrm{Ua})1.44 + 0.922 \times 10^{-4} \times h_L - 0.00562$

$= 0.0151\ m^2/s$

Pecklet Number $N_{pe} = (z_L)^2/(D_E.\theta_L) = 12.4599$

$\bar{\lambda}\quad E_{OG} = 1.6314$

$E_{MV}/E_{OG} = 1.60$

$\Rightarrow E_{MV} = 1.4211$

Overall Efficiency (E_{OC})

$L/G\{\rho_G/\rho_L\}^{0.5} = 0.0193$

at 72.58 % of the flooding value we have $\psi = 0.35$

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

$$\Rightarrow E_{\alpha} = 0.8051$$

The overall efficiency is given by the equation :

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

$E_{OC} = 0.8354$

Hence the actual number of trays can be calculated as :

{ Theoretical number of trays   overall column efficiency }

= 8   0.8354 ≈ 10

Height of the enriching section can be calculated as

(Tray Spacing x Actual number of trays)

= 10 x 152.4 = 1524 mm.

Summary of the Distillation Column

Enriching section

Tray spacing = 228.6mm

Column diameter = 2.1164m

Weir length = 1.2698m

Weir height = 12mm

Hole diameter = 5mm

Hole pitch = 15mm, triangular

Tray thickness = 3mm

Number of holes = 13476

Flooding % = 80

Stripping section

Tray spacing = 152.4mm

Column diameter = 2.1164m

Weir length = 1.2698m

Weir height = 12mm

Hole diameter = 5mm

Hole pitch = 15mm, triangular

Tray thickness = 3mm

Number of holes = 13476

Flooding % = 72.58

VI. Mechanical Design of Distillation Column

Diameter of the tower D_i = 2.1164 m

Working pressure = 660 mmHg(abs)

Design pressure p_e = 0.1 N/ mm^2 (Total Vacuum)

Working temperature = 162.36 ^oC

Design temperature = 178.6 ^oC

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

Permissible tensile stress (f_t)= 93.195 MN/m^2

Elastic Modulus (E) = 1.88×10^5 MN/m^2

Insulation thickness = 75mm

Density of insulation = 5.64 kN/m^3

Tray spacing:

Enriching section: 9”

Stripping section: 6”

Top disengaging space = 0.5m

Bottom separator space = 1.0m

Weir height = 12mm

Downcomer clearance = 0.5”

Height of support = 2m

1. Shell minimum thickness

Considering a torispherical head, head dish:

h_i= 0.4101m

Tangent to tangent length = 6.4350+2/3(0.4101)

= 6.7048m

D/L = 0.3155 => K = 0.232, = 2.46

$P(\text{allowable}) = KE(t/D)^{2.46}$

$0.1 = (0.232)(1.88\times10^{5})(t/2.1164)^{2.46}$

t = 10.79mm, take 12mm (standard)

Check for Plastic deformation

P = 2f(t/D)(1+1.5U(1-0.2D/L))/(100t/D)

U = 1.5% (for new equipment)

Substituting the values, we get P(allowable) = 0.224MN/m^2

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

2. Head Design

A torispherical head of the following parameters is chosen:

R_c – crown radius, $R_c = D_i$ = 2.1164m

R_k - knuckle radius, R_k = 10% of R_c

= 0.21164 m

t = thickness of the head =12mm

Pressure at which elastic deformation occurs

$P(\text{elastic}) = 0.366E(t/ R_c)^2$

= 2.2121 MN/ m^2

The pressure required for elastic deformation, P(elastic)>3(Design Pressure)

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

3. Shell thickness at different heights

At a distance ‘X’ m from the top of the shell the stress are;

3.1. Axial Stress: (compressive)

$$f_{ap} = \frac{p_i D_i}{4(t_s - C)}$$

$$= 4.4 \text{ N/m}^2$$

3.2. Compressive stress due to weight of shell up to a distance 'X'

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

$$= \rho_s X$$

$$= 0.0077 X \text{ N/mm}^2$$

3.3. Compressive stress due to weight of insulation

$$f_{d(ins)} = \frac{\pi D_{ins} t_{in} \rho_{ins}}{\pi D_m (t_s - C)}$$

$$f_{d(ins)} = \frac{2290.4 * 75 * 0.0564X}{2174.9 * (12)}$$

$$= 0.0358 X \text{ N/mm}^2$$

3.4. Stress due to the weight of the liquid supported

$$f_l = \frac{W_l}{\pi t_s (D_i + t_s)}$$

Enriching section

F(liq) = ((X-top space)/TS+1) $(\pi d^2/4)\rho_L$

= 14157.8X – 3842.4

fd(liq) = 0.1727X – 0.0469

Stripping section

F(liq) = ((X-top space)/TS+1) $(\pi d^2/4)\rho_L$+ 14157.8X – 3842.4

= 35394.6X – 84145.2

fd(liq) = 0.4383X – 1.0250

3.5. Stress due to the weight of the attachments

The total weight of the attachments

$W_a = (26700+1400X)$ N

$$f_a = \frac{W_a}{\pi t_s (D_i + t_s)}$$

$= 0.3256 + 0.0171X$ N/mm^2

The total dead load stress, f_w acting along the axial direction of shell at point is given by:

$f_w = f_{ds} + f_d + f_l + f_a$

Enriching section: $f_w = 0.2787+0.2333X$

Stripping section: $f_w = -0.6994+0.4989X$

3.6. wind loads

Stress due to wind,

$$f_{wx} = \frac{1.4\, p_w X^2}{\pi D_o (t_s - C)}$$

where p_w is the wind pressure, which is ≅ 1300 N/mm^2

$$f_{wx} = \frac{1.4 * 1300\, X^2}{\pi * 21404 *(1.2\,)}$$

$= 0.0226\, X^2$ N/mm^2

Taking joint efficiency as 0.8

(Total force, tensile) = jf(max) = jf(allowable)

Enriching section

$0.0226\, X^2 + 4.4 -(0.2787+0.2333X) = f_{t\,max} = 0.8(93.195)$

$X = 64$m

Hence, the entire tower can be constructed keeping the same 12mm thickness

Stripping section

$0.0226X^2 - 4.4-(-0.6994+0.4989X) = 0.8(93.195)$

$X = 68.1$m

Hence, the 12mm thickness is sufficient for the stripping section also.

Design of Support

Skirt Support

D = 2.1164 m

Minimum weight of the vessel with attachments:

W(min) = $\pi(D+t)t(H)\gamma_s$+2(shell weight)

= 55.9773 kN

W(max) = W(shell) + W(insulation) + W(water during test) + W(attachments)

= 41.1913+18.4986+226.1696+29.7526

= 316kN

Period of vibration at minimum dead weight is:

T(min) = $6.35\times10^{-5}(H/D)^{1.5}(W(min)/t)^{0.5}$

= 0.0362 < 0.5s

$\therefore$K = 1.0

Period of vibration at maximum dead weight load:

T(max) = $6.35\times10^{-5}(H/D)^{1.5}(W(max)/t)^{0.5}$

= 0.0860 < 0.5

$\therefore$K = 1.0

Skirt

Stresses due to wind load

P(wind)=kKp(wind)HD

p(wind) = 1 kN/m^2

k = 0.7 for cylindrical surface.

For minimum weight condition, D = 2.1164m

P(wind), min = (0.7)(1)(1000)(8.7048)(2.1164)

= 12896 N

For maximum weight condition, D = 2.1164+2(0.075)

= 2.2664m

P(wind),max = (0.7)(1)(1000)(8.7048)(2.2664)

= 13810 N

Minimum wind moment

$M(wind), min = P(wind),min \times H/2$

$= 12896(8.7048/2)$

$= 56.13$ kJ

Maximum wind load

$M(wind),max = P(wind),max\times H/2$

$= 13810(8.7048/2)$

$= 60.11$ kJ

Assuming a small skirt thickness, D(in) = D(out) = 2.1164m

$\sigma zwm,min = 4(M(wind),min)/(\pi D^2 t)$

$= 4(56.13\times 10^{-3})/(\pi\times 2.1164^2\times t)$

$= 0.0160 / t$ MN/m^2

$\sigma zwm, max = 4(M(wind),max)/(\pi D^2 t)$

$= 4(60.11\times 10^{-3})/(\pi\times 2.1164^2\times t)$

$= 0.0171 / t$ MN/m^2

Minimum and maximum dead load stresses

$\sigma zw,min = W(min)/(3.14\times d\times t)$

$= 55.9773\times 10^{-3}/(3.14\times 2.1164\times t)$

$= 0.0084/t$ MN/m^2

$\sigma zw,max = W(max)/(3.14\times d\times t)$

$= 316\times 10^{-3}/(3.14\times 2.1164\times t)$

$= 0.0475/t$ MN/m^2

Maximum tensile stress without any eccentric load

σz (tensile) = $\sigma zwm, min - \sigma zw,min$

$= 0.016/t – 0.0084/t$

$= 0.076/t$ MN/ m^2

Taking a joint efficiency of 0.7 (Double welded butt joint, class 3 construction)

σz (tensile) = fJ

$= 93.195\times0.7$

$= 65.2365\ \text{MN/m}^2$

$65.2365 = 0.0076(1000/t)$

t = 0.11maintenance

Maximum compressive load

σz (compressive) = σzwm, max + σzw,max

$= 0.0171/t + 0.0475/t$

$= 0.0646/t$

substituting,

σz (compressive) = 0.125E(t/D)

$= 0.125(1.88\times10^5)(t/2.1164)$

$= 1.1104\times10^4 t$

equating,

$t^2 = 0.0646/(1.1104\times10^4)$

t = 2.4mm

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

Design of skirt bearing plate

Maximum compressive stress between bearing plate and foundation:

σ_C = W(max)/A + M(wind),max/Z

W(max) =319 kN

A = 3.14(D-l)l

D =outer diameter of skirt = 2.1164m

L = outer radius of bearing plate – outer radius of skirt

M(wind),max = 60.11 kJ

$Z = 3.14R^2 l$

R = (D-l)/2

In calculating A, it is assumed that the bearing plate ID is no much less than the ID os the skirt.

$\sigma_C = 0.316/(3.14l(2.1164-l)) + 0.06011\times4/(l(2.1164-l)^2)$

Allowable compressive strength of the concrete varies from 5.5 to 9.5 MN/m^2. Taking σ_C =5.5, and equating,

l = 11.8 mm

Since this is very small, a standard length of l=80mm is chosen.

Thickness of the bearing plate

$t(bp) = l(3\sigma_C/f)^{0.5}$

l = 80mm

σ_C = Maximum compressive load calculated for l = 80mm

= 0.848 MN/m^2

f = allowable stress = 93.195 MN/m^2

t(bp) = 13.2mm.

Take a standard thickness of 14mm

As the bearing plate thickness is less than 20mm, gussets are not required.

Rolled angle bearing plate of 14mm thickness is used. (80×80×14)

$\sigma(min) = W(min)/A – M(wind)/Z$

$= 0.056/(3.14(2.1164-0.08)(0.08) – 0.05613/(3.14(2.1164-0.08)^2(0.08))$

$= 0.1094-0.0539$

= 0.0555 MN/m^2

R = 0.42D(bp), where D(bp) is the outer diameter of the bearing plate.

j factor = W(min)R/(M(wind),min)

= (0.056)(0.42)(2.1164+2×0.08)/(0.05613)

= 0.9539

j < 1.5

hence, anchor bolts are required.

Design of anchor bolts

$P(bolt).N = \sigma(min)A$

$= (0.0555)(3.14\times(2.1164-0.08)\times0.08)$

$= 0.0284$ MN

Hot rolled plain carbon steel is selected for bolts.(f = 53.5 MN/m^2)

(area of bolts)f = P(bolt)N = 0.0284 MN

area of bolts = 0.0284/53.5 = 5.3084×10^{-4} m^2

Choose M16×1.5 bolts. Area = 133 mm^2

Number of bolts = 4.

Trays

The trays are standard sieve plates throughout the column. The plates have 13476 holes of 5mm dia arranged on a 15mm triangular pitch. The trays are supported on purloins. The details of the trays are shown in fig 6.3

Nozzles

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

1.Vapor discharge

Nozzle diameter = 0.1D = 211.64mm.

t = 10mm

2.Reflux Inlet

Nozzle diameter = 126mm

t = 10mm

3.Feed Inlet

Nozzle diameter = 96mm

t = 10mm

4.Reboiled vapor Inlet

Nozzle diameter = 116mm

t = 10mm

5.Liquid Bottoms Outlet

Nozzle diameter = 126mm

t = 10mm

All nozzles are provided with a standard compensation pad of 30mm thickness. This small compensation is sufficient as the design pressure is low (0.1 N/mm^2)

Process Design of Condenser

The following is the detailed design of the total condenser for the Distillation column. The condenser is operated at the same pressure as that of the column. The vapor from the column is condensed and sent as reflux and product. Any changes in compensation are neglected. The optimization of the condenser is done in several iterative steps. The final trial is presented here. The design methods used here are from Chemical Engineering by Coulson and Richardson, vol.6

Shell side

Feed = 165.3912 kmol/hr

Average molecular weight M_f = 62.44

T = 409.44 K = 136.29 $^{\circ}$C

Mass flow rate = 10327.0265 kg/hr

Heat of vaporization = ΔH_V = 53191.7011 kJ/kmol

Heat Load, Q = 2443.7331 kW

Tube Side

Cooling water at 20 $^{\circ}$C

1. Heat Balance

Heat load = Q = 2443.7331 = m(4.187)(30-20)

m = 58.3648 kg/s, where m is the cooling water flow rate.

2. LMTD

LMTD = ((136.29-20)-(136.29-30))/ln((136.29-20)/(136.29-30)) = 111.22 °Constraint

3. Heat transfer area.

Choose the overall heat transfer coefficient (U) as 500 W/(m^2K)

Q = UA(LMTD)

$\therefore$ A = 2443.7331/(500×111.22)

= 43.9442 m^2

4. Tubes

Choose 1” OD, 16 BWG tubes of 6ft length laid in a 1.25” Square pitch

Tube OD = 25.4 mm

Tube ID = 22.098 mm

Flow Cross sectional area = 3.8353×10^{-4} m^2

Surface area/tube = 0.1459 m^2

Number of tubes (N_t) = 43.94415/0.1459 = 301 tubes

Bundle diameter $D_b = OD(N_t/k)^{1/n}$

For a TEMA 1-2 exchanger with tube pitch = 1.25 (OD),

K = 0.156; n = 2.291

$\therefore$ Bundle diameter D_b = 690.1 mm

Number of tubes in the central row (N_r) = $2/3(D_b/p_t)$ = 2/3(690.1/(1.25×25.4)) = 15

5. Shell side film transfer coefficient

The film temperature T_f is evaluated by an iterative procedure by first assuming a film coefficient and recalculating the film coefficient using the film temperature. The film temperature was calculated to be 71.62 °C. The corresponding wall temperature is 118.24 °C

The shell side film transfer coefficient is calculated by using a modified Nusselt’s equation:

Mass flow rate per unit length (Γ_h) = W/(L.N_t)

= 10327.0265/(3600×1.83×301)

= 5.2112×10^{-3} kg/(m.s)

Film transfer coefficient (h_C)

$h_C = 0.95k_L[\rho_L(\rho_L-\rho_V)g / (\mu\Gamma_h)]^{1/3}N_r^{-1/6}$

$= 0.95\times0.1935[1074.5432(1074.5432-0.2428)9.81/(4.4\times10^{-3}\times5.2112\times10^{-3})]^{1/3}15^{-1/6}$

= 919.0 W/(m^2K)

6. Tube Side Heat Transfer Coefficient

Tube velocity (u_t) = $58.3648/(995\times3.8353\times10^{-4}\times301/2)$

= 1.0162 m/s

Tube side coefficient, h_i

$h_i = 4200(1.35+0.02T_{av})u_t^{0.8}/d_i^{0.2}$

$= 4200(1.35 + 0.02\times25)(1.0162)^{0.8}/(22.098)^{0.2}$

= 4237.7348 W/(m^2K)

7. Overall Heat Transfer Coefficient

Assuming dirt coefficient as 6000 W/(m^2K) for both sides and k(wall) = 50 W/mK

$1/U = 1/919 + 1/6000 + 25.4\times10^{-3}\ln(25,4/22.098)/100 + 25.4/(22.098\times6000)$

$+ 25.4/(22.098\times4237.7348)$

U = 570.4902 W/(m^2K)

8. Pressure drop in tube side

Reynold's number

$Re = 22.098\times10^{-3}\times1.0162\times995/(0.9\times10^{-3})$

= 24826

Friction factor, $j_H = 3.8\times10^{-3}$

Pressure drop, ΔP_t

$\Delta P_t = N_P[8\ j_H(L/D)+2.5]\rho u_t^2/2$

$= 2[8\times3.8\times10^{-3}\times1.83/(22.098\times10^{-3})+2.5](995\times1.0162^2/2)$

$= 5.1538$ kPa

Pressure drop is acceptable.

9. Shell side pressure drop

Select baffle spacing (l_b) = shell diameter, baffles 45% cut

For TEMA Pull-Through Floating Head Heat Exchanger,

Clearance = 93 maintenance

Shell diameter = D_s = 783.1 mm

Cross Flow area:

$A_s = (p_t\text{-}D_o)D_s l_b/p_t$

$= (1\text{-}1/1.25)(0.7831)(0.7831)$

$= 0.1227\ m^2$

Equivalent diameter:

$d = 1.27/D_o(p_t^2\text{- } 0.785D_o^2)$

$= 1.27[(1.25\times25.4)^2\text{-}0.785(25.4)^2]$

$= 25.0806$ mm

Mass flux:

$G_S = w/A_s = 10327.0265/\ (3600\times0.1227) = 23.3791\ kg/(m^2s)$

Reynold's number:

$Re = dG_S/\ (A_s\mu)$

$= 25.0806\times23.3791/(0.1227\times9.4484\times10^{-4})$

$= 62107$

From the correlation, friction factor

$j_f = 2.5\times10^{-3}$

Vapor velocity:

$u_s = G_S/\rho_V$

$= 23.3791/0.2428$

$= 96.2895$ m/s

Pressure drop:

$\Delta P_S = 8j_f(D_S/d)(L/l_b)\rho u_S^2/2$

$= 8\times2.5\times10^{-3}(783.1/25.0806)\ (1.8288/0.7831)(0.2428\times96.2895^2/2)$

$= 0.82$ kPa

The maximum allowable pressure drop on the shell side for medium vacuum operation is 10% of the absolute pressure which is 1 kPa. Hence, the condenser pressure drop is within the limits.

Summary of Condenser design

Shell outer diameter = 783.1 mm
Bundle diameter = 690.1 maintenance
Number of tubes = 301
Tube OD = 1”
Pitch = 1.25”
Tube length = 6ft
Shell side pressure drop = 0.82 kPa
Tube side pressure drop = 5.15 kPa
Condenser type: TEMA Pull-Through Floating Head 1-2 Heat Exchanger

Mechanical Design of Condenser

Design Temperature = T = 150 $^\circ$C
Design pressure = 0.1 N/mm^2 (external)
Number of tubes = 301
Bundle diameter = 690 mm
Shell diameter = 783 mm
Baffles: Spacing=783 mm, 45% cut

1.Shell Thickness

Material: IS 2825-1969 Grade I plain Carbon steel.

Assume shell thickness = t_S = 8mm

L/D = 2.36, D/t_S = 97.875

B factor = 2250 (Obtained from graphs in IS 2825)

Maximum allowable pressure = B/(14.22D/t) = 0.16 N/mm^2

Hence, the thickness is sufficient.

1. Nozzles

Take inlet and outlet nozzles as 100mm diameter.

Vent nozzle = 25mm diameter

Drain nozzle = 25mm diameter

Relief Valve = 50 mm diameter.

Only the inlet and outlet nozzles need compensation. The compensation required is minimum and is given by pads of 30mm thickness.

2. Head

Torispherical heads are taken for both ends.

R (Crown radius) = 783 mm

R (knuckle radius) = 78.3 mm

Head thickness = shell thickness = 8mm

3. Transverse Baffles

Baffle spacing = 783mm

Baffle cut = 45%

Baffle thickness = 6mm (standard)

6. Tie rods and spacers

Diameter of tie rods = 10mm

Diameter of Spacers = 8mm

7.Flange Design

Flange is ring type with plain face.

Design pressure = P = 0.1 MN/m^2 (external)

Flange material: IS 2004-1962 Class 2 Carbon Steel

Bolting steel: 5% Chromium, Molybdenum Steel

Gasket Material: Asbestos composition

Shell OD = 0.791m = B

Shell Thickness = 0.008m = g

Shell ID = 0.783m

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

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

(a) Determination of gasket width

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

Assume a gasket thickness of 1.6mm

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

m = gasket factor = 2.75

d_O/d_i = 1.002m

Let d_i = B+10 = 0.801m

Minimum gasket width = 0.801(1.002-1)/2 = 0.0008m = N

Choose N =0.04. d_o = 0.809m

Basic gasket seating width = 4/2 = 2mm =b

Diameter at location of gasket load reaction G = d_i + N = 0.805m

(b) Estimation of bolt loads

<u>Load due to design pressure</u>

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

= 0.5090 MN

where P is the design pressure

<u>Load to keep joint tight under operation:</u>

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

$= \pi(0.805)(0.004)(2.75)(0.1)$

$= 0.0028$ MN

Total Operating Load $W_o = H + H_T = 0.5118$ MN

Load to seat the gasket under bolting condition:

$W_g = \pi Gby$

$= 0.1290$ MN

$W_o > W_g$ Hence, the controlling load is $W_o = 0.5118$ MN

(c) Calculation of Minimum bolting area:

$A_m = A_o = W/S = 0.5118/S$

S_o = allowable stress for bolting material

$A_m = A_o = 0.5118/138 = 0.00371$ m

Calculation of optimum bolt size.

$g_1 = g/0.707 = 1.415g$

Choose M16×1.5 Bolts

Root area = 133 mm

Minimum number of bolts = 28

Radial clearance from bolt circle to point of connection of hub or nozzle and back of flange = R = 0.025 m

$B_s = 0.075$m (Bolt spacing)

$C = nB_s/\pi = 0.6690$

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

$= 0.783 + 2[(1.415)(0.008) + 0.025]$

$= 0.8566$

Choose C = 0.86m

Bolt circle diameter = 0.86m

(d) Flange outside diameter (A)

A = C +bolt dia + 0.02

= 0.896m

select A = 0.90m

(e) Check for gasket width

$A_b S_G / (\pi G N) = 50.80 < 2y$, where S_G is the Allowable stress for the gasket material

(f) Flange Moment Calculations

$M_o = W_1(a_1-a_3) + W_2(a_2-a_3)$

$a_1 = (C-B)/2 = 0.0385m$

$a_3 = (C-G)/2 = 0.0275m$

$a_2 = (a_1+a_3)/2 = 0.033m$

$M_o = 3.0646\times10^{-3}$ MJ

$M_g = Wa_3$

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

$A_b = 28(1.33\times10^{-4}) = 3.724\times10^{-4}$

$A_g = W_g/S_g = 0.129/138 = 9.35\times10^{-4}$

$W= 0.3215$ MN/m^2

$M_g = 8.8413\times10^{-3}$ MJ

$M_g > M_o$

Hence, M_g is controlling.

(g) Calculation of flange thickness

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

$K =A/B = 0.9/0.783 = 1.15$

For $K = 1.15$, $Y = 13$

Assuming $C_F =1$

$t^2 = 1.47\times10^{-3}$

$t = 0.038m$

Actual bolt spacing $B_S = \pi C/n = (3.14)(0.86)/(28) = 0.0965m$

Bolt Pitch Correction Factor

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

$= 1.1741$

$t(act) = t(C_F) = 0.0446m$

Select 45mm thick flange. Both flanges have the same thickness.

8. Saddle Support Design

Material : Carbon Steel

Shell diameter = 783mm

R = D/2

l = 200mm

Torispherical Head: Crown radius = D, knuckle radius = 0.1D

Total Head Depth = 152mm = H

Shell Thickness = Head Thickness = 8mm

$f_t = 95\ MN/m^2$

Weight of the shell and its contents = 12100 N = W

Distance of saddle center line from shell end = A = 200mm

Longitudinal Bending Moment

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

$Q = W/2(L+4H/3) = 49626$ Nm

$M_1 = 49626(1-0.9649) = 1741.8726$ Nm

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

= 24813(0.5671)

= 14071.4523 Nm

Stresses in shell at the saddle

$f_1 = M_1/(\pi R^2 t) = 0.4522$ N/mm

$f_2 = 0.4522$ N/mm

$f_3 = M_2/(\pi R^2 t) = 3.65$ N/mm

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

Process Design of Reboiler

The following is the design of a kettle reboiler for the MEG column. The reboiler is operated as the same pressure as that of the column. Any enhancement of the vapor in the reboiler is neglected.

Feed = 10238.8134 kg/hr

Quantity of liquid to be vaporized = 9414.9750 kg/hr

Feed Temperature = 433.83 K

Vaporization Temperature = 435.51 K

Average temperature = 434.67 K = 161.52 °C

Properties at the average temperature

Latent heat of vaporization = 550.2221 kJ/kg

Cp = 2.3298 kJ/(kgK)

Critical pressure = 4.66 MPa

(a) Heat Loads

Maximum sensible heat = 2.3298(435.51-433.83) = 3.9141 kJ/kg

Total Heat Load = 3.9141(10328.8134/3600) + 9414.9750/3699(550.2211)

= 1450.1094 kW

Adding 5% losses, Maximum heat load (duty) = 1.05(1450.1094)

= 1522.6148 kW

(b)Heat Balance and number of tubes

Assume U =1000 W/(m^2K)

Choose steam at 15.55 bar, T(sat) = 200 °C, λ = 1938.6 kJ/kg

LMTD = [(200.160.68)-(200-162.36)]/ln[(200-160.68)-(200-162.36)]

= 38.47 °C

Area required = (1522.6148×1000)/(38.47×1000) = 39.5798 m^2

Select 25mm ID, 30mm OD plain carbon U-tubes, l = 4.8m

No. of tubes = 88

Use square pitch, $p_t = 1.5(30) = 45$mm

Minimum bend radius = 3(OD) = 90mm

From the tube layout, for 88 tubes, outer diameter limit = 502mm

(c) Boiling Heat Transfer Coefficient

$q = 1522.6148/39.5793 = 38.47$ kW/m^2

$h_{nb} = 0.104\ (P_C)^{0.69}\ (q)^{0.7}\ [1.8(P/P_C)^{0.17} + 4(P/P_C)^{1.2} + 10(P/P_C)^{10}]$

$= 1595.8582$ W/(m^2 K)

This is acceptable.

(e) Maximum allowable heat flux

$\sigma = 48.4\times10^{-3}$ N/m

$\rho_L = 1062.5007$ kg/m^3

$\rho_V = 0.3830$ kg/m^3

$N = 88$

$K = 0.44$

$q(\max) = k\ (p_t/d)\ (\lambda/N^{0.5})\ [\sigma g\ (\rho_L-\rho_V)\ \rho_V^2\ ]^{0.25}$

$= 113.53$ kW/m^2

Applying a factor of 0.7,maimum flux should not exceed $0.7\times113.53 = 79.471$ kW/m^2

$q < q(\max)$. Hence, the design is within permissible limits.

(f). Velocity Check

Bundle diameter = 502mm

Take shell diameter = 2(bundle diameter) ~1010mm

Taking liquid level as 600mm from base (see fig)

Free board = D_S – 600 = 1010-600 = 410mm

Width at liquid level = 984.7maintenance

Surface area of liquid = $A = 984.7\times10^{-3}(4.8/2) = 2.3632$ m^2

Vapor velocity at the surface = $9414.9750/(3600\times A\times0.3038) = 3.6427$ m/s

Maximum allowable velocity

$u(max) = 0.2[(\rho_L-\rho_V)/\rho_V]^{0.5}$

$= 11.826$ m/s

Hence, the velocity is permissible.

Summary of Reboiler design

Type: Kettle Reboiler (TEMA AKT)

Number of Tubes = 88

Tubes: U- Tube, 30mm OD laid on 45mm square pitch.

Shell diameter = 1010mm

Free board = 410mm

Process Design of Reactor

The reactor for the hydrolysis of ethylene oxide is a high pressure adiabatic Plug Flow Reactor. The rectors initially used were stirred tank reactors or distillation column reactors. But literature shows that these are rapidly being replaced by Tubular Plug Flow Reactors. Since there is a large heat of reaction, no catalyst is required and the reaction goes to completion. The following assumptions are made for the design of the reactor.

(a) Since the molar ratio of water to other components is large, all properties are taken for pure water.

(b) The heat of reaction if assumed to remain constant over the temperature range. However, the variation of specific heat is considered.

(c) The pressure in the reactor is maintained such that there is no flashing of ethylene oxide. The reactor is thus a liquid-liquid reactor.

(d) The operation is purely adiabatic.

<u>Reactor conditions:</u>

Feed: 9.3182 kg/s of reactant mixture containing:

Ethylene oxide: 10.8905 wt%

Water: 89.1095 wt%

Temperature of Feed = 200 °C

Operating pressure = 20atm

Heat of reaction = 21.8 kcal/mol of ethylene oxide

The reaction follows first order kinetics. The kinetics of the reaction are represented in fig 3.2.

Reactor Design

Design equation:

$\gamma X_A(-\Delta H_R) = \int (C_P dT)$

Where, γ is the molar ratio of ethylene oxide

X_A is the conversion of ethylene oxide

$F_{Ao}\, dX_A/dV = -r_A(X_A,T)$

Where, $-r_A(X_A,T) = kC_A= [k_o e^{-E/(RT)}][C_{Ao}(1-X_A)]$

Solving the two equations,

$V/ F_{Ao} = \int[dX_A/\{k(T)C_{Ao}(1-X_A)]$

From the kinetic data, the value of the kinetic constants are as follows:

$k_o = 6.3856\times10^9$ min

Activation energy = E = 8.1668×10^4 J/mol

Solving the integral using Simpson's 1/3rd rule, we get the reactor volume as:

$V =3.0034\ m^3$

For Plug Flow, Re>10000 and L/d > 100

Take L/d = 150.

L = 44.15m, d= 0.2943m

Take L = 45m and hence, d = 0.2915m

The reactor can be arranged in 9 tube lengths of 5 meters each. The line representation of the PFR is shown in fig 6.4.