6. DESIGN OF EQUIPMENTS

(A) MAJOR EQUIPMENT

Basis: 1hour of operation

Vapor-pressure data of cumene-Diispropylbenzene:

1/T 10^3 °C	2.35	2.3	2.25	2.2	2.15	2.10
P_A	760	943	1211.9	1480.2	1998.1	2440.6
P_B	190.56	257.2	314.1	403.4	518.0	760
LnP_A	6.633	6.85	7.1	7.3	7.6	7.8
LnP_B	5.25	5.55	5.75	6.0	6.25	6.63

T-xy data for cumene – Diispropylbenzene system :

T °C	152.4	160	170	180	190	202
X_A	1	0.733	0.496	0.331	0.163	0
Y_A	1	0.909	0.791	0.644	0.429	0

Vapour-pressure data from Perry's Chemical Engineers handbook 6th edition pg2-52

Splitting the feed into two towers of equal capacity as the feed rate of the distillation tower is too high .The production rate in our case is almost ten times more than the normal production rate.

Feed: F = 138190.5/2 Kg/hr ; weight fraction ; mole fractions

$X_F = 0.932$ $X_F = 0.948$

= 69095.25 Kg/hr

D = 129051/2 Kg/hr $X_D = 0.995$ $X_D = 0.996$

= 64525.5 Kg/hr

= 536.8 Kmoles/hr

W = 9139.5/2 Kg/hr $X_W = 0.01$ $X_W = 0.013$

= 4569.5 Kg/hr

= 29 Kmoles/hr

[From material balance equation we find that if X_F, X_D & X_W are kept same , then on reducing the feed rate to half , both distillate and residue are also reduced to half their original value .]

F_{molar} = (0.932 x 69095.25)/120.19 + (0.068 x 69095.25)/162

= 546.79 Kmols/hr

M_{Feed} = 69095/546.8 = 126.5 Kg/kmol

Taking feed as saturated liquid , q=1
Slope of q-line = q/(q-1)= oo
Therefore q-line is vertical.
From the X-Y diagram , $X_D/(R_m+1) = 0.72$
Hence R_m =0.38
Assuming a reflux ratio of 1.4 times the R_m value we get
R = 1.4 x 0.38 = 0.532

Now total number of stages including reboiler = 10
Therefore actual number of stages in the tower = 9
Number of stages in the enriching section = 3
Number of stages in the stripping section = 6

L = RD =0.532 x 536.8 = 285.6 Kmoles/hr
G = (R+1)D = 1.532 x 536.8 = 822.4 Kmoles/hr

$\underline{L}$ = L+qF = 285.6 + 1x546.79 = 832.39 Kmoles/hr
$\underline{G}$ = G+(q-1)F = 822.47+0 = 822.47 Kmoles/hr

Plate Hydraulics :

Enriching Section **Stripping Section**

	Top	_Bottom	Top	Bottom
Liquid Kgmoles/hr	285.6	285.6	832.39	832.39
Vapor Kgmoles/hr	822.47	822.47	822.47	822.47
X	0.996	0.948	0.948	0.013
Y	0.996	0.97	0.97	0.013
M_{avg}(Liq)	120.34	122.36	122.36	161.45
M_{avg}(Gas)	120.34	121.44	121.44	161.45
Liq, Kg/hr	34369.1	34946	101851.2	134389.36
Vap,Kg/hr	98976	99880.75	99880.75	132787.78

T_{liquid} , ^oC	152	153	153	202
T_{vapour} , ^oC	154	155	155	202
ρ_L , (kg/m^3)	746.3	745	745	600
ρ_G ,(kg/m^3)	3.436	3.826	3.826	4.072
$(L/G)^*$ $(\rho_G/\rho_L)^{0.5}$	0.0235	0.0250	0.0730	0.0830

ENRICHING SECTION

Plate Calculations:

1. Plate spacing t_s = 500mm
2. Hole diameter d_h =5mm
3. Hole pitch $L_p = 3d_h$ = 15mm
4. Tray thickness $t_T = 0.6d_h$ = 3mm

5. $$\frac{\text{Total hole area}}{\text{Perforated area}} = (A_h / A_p)$$

= 0.1 for triangular pitch

6. Plate diameter

From above table , $L/G\,(\rho_g / \rho_L)^{0.5} = 0.025$

From Perry's handbook 6th edition for ts = 18 inches

Csb flood = 0.28

We have,

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

$$= 0.28(37.3/20)^{0.2}\ \ ((745\text{-}3.826) / 3.826)^{0.5}$$

$$= 4.41 ft/sec$$

Let us take Un= 0.8 Unf (% flooding = 80%)

= 0.8 * 4.41ft/sec

= 1.158 m/sec

Volume rate of vapour = 99880.75/(3600*3.826)

= 7.2516 m^3/sec

Net area for gas flow, An = volumetric flow rate of vapor/Un

= 7.2516/1.1586

= 6.2589 m^2

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

L_w = Weir Length
D_c = Column Diameter

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

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

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

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

$= (0.212 - 0.1239)\ D_c^2$

$= \underline{0.0879\ D_c^2}$

Area for gas flow , An = Ac-Ad

$= 0.785\ Dc^2 - 0.0879\ Dc^2$

$= 0.6971Dc^2$

$6.2589 = 0.6911Dc^2$

Dc =2.996m

$A_c = \pi/4\ D_C^2$

$= 0.785 \times 2.996^2$

$= 7.046m^2$

$A_d = 0.7889m^2$

Active area, $A_a = A_c - 2A_d$

$= 7.046 - 2(0.7889) = 5.468m^2$

7. Perforated area Ap:

Lw/Dc = 0.75

where Lw is the wier length

Lw = 0.75*2.996 = 2.247m

θc = 97.2 °

$\alpha = 180 - \theta c = 180 - 97.2 = 82.8°$

Periphery waste = 50mm = $50*10^{-3}$

Area of the calming zone $A_{cz} = 2[\ Lw *50*10^{-3}]$
= 2[2.247*50*10-3]
= 0.2247m2

Area of the periphery waste ,

$A_{wz} = 2[\pi/4*2.99^2(82.8/360)- \pi/4[2.99-0.05]^2*(82.82/360)]$
$= 2[1.6149 – 1.5606]$
$= 0.1085m^2$

$A_p=A_c – 2A_d – A_{cz}- A_{wz}$
$= 7.046 – 2* 0.7889 – 0.2247 – 0.1085$
$= 5.135\ m^2$

8. Hole area A_h:

We have , $A_h/A_p = 0.1$
$A_h = 0.1* A_p$
$= 0.1*5.135$
$= 0.5135m^2$

9. Number of holes :

$N_h = 0.5135 / \pi/4(5*10^{-3})2$
$= 26,165$

10. Weir height H_w:

let us take h_w = 50mm

11. Check for weeping:

From Perry's handbook 6th edition pg-18-9 equation 18-6

Pressure across the disperser,

$H_d = K_1 +K_2\ \rho_g/\rho_l\ U_h^2$ mm liquid

For sieve plate $K_1 = 0$

$K_2 = 50.8 / C_v^2$

$$\frac{\text{Hole area}}{\text{Active area}} = \frac{A_h}{A_a} = \frac{0.5135}{5.4682} = 0.0939$$

$$\frac{\text{Tray thickness}}{\text{Hole dia}} = \frac{t_T}{d_h} = \frac{3mm}{5mm} = 0.6$$

From figure 18-14 Cv(Discharge coefficient) = 0.73

$K_2 = 50.8/ (0.73)^2 = 95.32$

U_h = linear velocity of gas through the holes
= volumetric flow rate of vapour / A_h
= 7.2516 / 0.5135
= 14.12 m/sec

$h_d = 0 + 95.32(3.826/745) \times 14.12^2$
= 97.38 mm liquid

Height of liquid creast over weir ,

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

q = vol. flow rate of liquid ,m^3/sec [weeping check is done at the point where gas velocity is low]
= 34369/(746.3x3600)
=0.0127 m^3/sec

q'= volumetric flow rate of liquid in GPM
=0.0127 /(6.309×10^{-5})
202.76 GPM

L_w = 2.247m = 2.247/0.3048 =7.372 ft

$q'/(Lw)^{2.5} = 202.76/(7.372)^{2.5} = 1.37$

$L_w/D_c = 2.247/2.996 = 0.75$

Corresponding to this two values Fw=1.02

$h_{ow} = 1.02 \times 664 \times (0.0127/2.247)^{2/3}$
= 21.48 mm liquid

Head loss due to bubble for mation,
$h_\sigma = 409(\sigma/\rho_L d_L)$
= 409(37.3/ 746.3x 5)
= 4.08mm liq

$h_d + h_\sigma$ = 97.38+4.08= 101.47 mm liq
hw + how = 50 +21.48 = 71.48 mm

Ah/Aa = 0.0939, $h_w + h_{ow}$ = 71.48 mm
From fig 18-11, $h_d + h\sigma$ = 17mm
Since the value $h_d + h\sigma$ is well above the value obtained from graph no weeping will occur.

12. Check for downcommer flooding:

The downcommer backup is given by,

$h_{dl} = h_t + h_w + h_{ow} + h_{ad} + h_{hg}$

a. Hydraulic gradient across plate , h_{hg}

For stable operation $h_d > 2.5h_{hg}$

For sieve plates h_{hg} is generally small or neiglible

Let us take h_{hg} =0 mmliq

b. Total pressure drop across the plate ht:

$h_t = h_d + h_l'$

hl'=pressure drop through the aereated liquid = β hds

whereβ =aeration factor to be found from Perry's fig 18-15

$F_{ga} = U_a(\rho_g)^{1/2}$

$U_a = 99880/(3600x3.826x5.468)$

= 1.326m/sec

$\rho_g = 3.826 kg/m^3$

$F_{ga} = U_a(\rho_g)^{1/2}$

$= 1.326 \text{ x } (3.826)^{1/2} (m/sec)\ (kg/m^3)^{1/2}$

$= 2.5939/1.2199\ (ft/sec)(lb/ft^3)^{1/2}$

$= 2.1263\ (ft/sec)(lb/ft^3)^{1/2}$

from figure,β=0.6

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

= 50+21.48 + 0

= 71.48mm liq

h_l' = 0.6 * 71.48 = 42.88mm liq

ht = 97.38 +42.88

= 140.27mm liq

c loss under downcommer area head:

$h_{da} = 165.2(q'/A_{da})^2$

let us choose c' = 1inch =25.4mm

$h_{ap} = h_{ds} - c'$

= 71.48 – 25.4

= 46.08 mmliq

$A_{da} = L_w \, x h_{ap}$
$= 2.247 \; x 46.08 x 10^{-3}$
$= 0.1035 m^2$

$h_{da} = 165.2(0.0127/0.1035)^2$
$= 2.4873 mm$
$h_{dc} = 140.27 + 50 + 21.48 + 2.4873 + 0$
$= 214.23 mm$

taking $ø_{dc} = .5$

$h'_{dc} = h_{dc}/ø_{dc}$
$= 214.23/0.5$
$= 428.46$ mm

we have ts= 500 mm
hence , $h'_{dc} < ts$
therefore no downcommer flooding will occur.

STRIPPING SECTION

Plate Calculations:

5. Plate spacing $t_s = 500 mm$
6. Hole diameter $d_h = 5 mm$
7. Hole pitch $L_p = 3d_h = 15 mm$
8. Tray thickness $t_T = 0.6d_h = 3 mm$

5. $\dfrac{\text{Total hole area}}{\text{Perforated area}} = (A_h / A_p)$

$= 0.1$ for triangular pitch

6. Plate diameter
From above table , $L/G \, (\rho_g / \rho_L)^{0.5} = 0.083$ (maximum at bottom)

From Perry's handbook 6th edition for ts = 18 inches
Csb flood = 0.28

We have,

$$Unf = Csb(flooding) \, (\sigma/20)^{0.2} \, ((\rho_L - \rho_G)/ \rho_G)^{0.5}$$

$$= 0.28(33.41/20)^{0.2} \quad ((600-4.072) / 4.072)^{0.5}$$

$$= 3.75 ft/sec$$

Let us take Un= 0.8 Unf (% flooding = 80%)
= 0.8 * 3.75ft/sec
= 0.9144 m/sec

Volume rate of vapour = 132787.78/(3600*4.072)

$= 9.058\ m^3/sec$

Net area for gas flow, An = volumetric flow rate of vapor/Un

= 9.058/0.9144

$= 9.906\ m^2$

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

L_w = Weir Length

D_c = Column Diameter

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

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

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

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

$= (0.212 - 0.1239)\ D_c^2$

$= \underline{0.0879\ D_c^2}$

Area for gas flow , $A_n = A_c - A_d$

$= 0.785\ Dc^2 - 0.0879\ Dc^2$

$= 0.6971Dc^2$

$9.906 = 0.6971Dc^2$

Dc =3.769m

$A_c = \pi/4\ D_C^2$

$= 0.785 \times 3.769^2$

$= 11.15m^2$

$A_d = 0.7889m^2$

Active area, $A_a = A_c - 2A_d$

$= 11.15 - 2(1.248) = 8.654m^2$

7. Perforated area Ap:

Lw/Dc = 0.75

where Lw is the wier length

Lw = 0.75*3.769 = 2.827m

θc = 97.2 °

α =180 - θc = 180 – 97.2 = 82.8°

Periphery waste = 50mm = $50*10^{-3}$

Area of the calming zone $A_{cz} = 2[\ Lw *50*10^{-3}]$

= 2[2.827*50*10-3]

= 0.2287m2

Area of the periphery waste ,

$A_{wz} = 2[\pi/4*(3.769)^2(82.8/360)- \pi/4[3.769-0.05]^2*(82.82/360)]$

$= 0.1352m^2$

$A_p=A_c – 2A_d – A_{cz}- A_{wz}$

= 11.15 – 2* 1.248 – 0.2287 – 0.1352

$= 8.2901\ m^2$

8. Hole area A_h:

We have , $A_h/A_p = 0.1$

$A_h = 0.1* A_p$

= 0.1*8.2901

$= 0.829m^2$

9. Number of holes :

$N_h = 0.829 / \pi/4(5*10^{-3})2$

= 42,242

10. Weir height H_w:

let us take h_w = 50mm

11. Check for weeping:

From Perry's handbook 6th edition pg-18-9 equation 18-6

Pressure across the disperser,

$H_d = K_1 +K_2\ \rho_g/\rho_l\ U_h^2$ mm liquid

For sieve plate $K_1 = 0$

$K_2 = 50.8 / C_v^2$

$$\frac{\text{Hole area}}{\text{Active area}} = \frac{A_h}{A_a} = \frac{0.829}{8.654} = 0.0958$$

$$\frac{\text{Tray thickness}}{\text{Hole dia}} = \frac{t_T}{d_h} = \frac{3mm}{5mm} = 0.6$$

From figure 18-14 Cv(Discharge coefficient) = 0.74

$K_2 = 50.8/ (0.74)^2 = 92.74$

U_h = linear velocity of gas through the holes
= volumetric flow rate of vapour / A_h
= 9.058 / 0.829
= 10.92 m/sec

$h_d = 0 + 92.74(4.072/600) \times 10.92^2$
= 75.14 mm liquid

Height of liquid creast over weir ,

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

q = vol. flow rate of liquid ,m^3/sec [weeping check is done at the point where gas velocity is low]
= 101851.2/(745x3600)
=0.0379 m^3/sec

q'= volumetric flow rate of liquid in GPM
=$0.0379/(6.309 \times 10^{-5})$
= 601.93 GPM

L_w = 2.827m = 2.827/0.3048 =9.2749 ft

$q'/(Lw)^{2.5} = 601.93/(9.2749)^{2.5} = 2.297$

L_w/D_c=2.827/3.769=0.75

Corresponding to this two values Fw=1.02

$h_{ow} = 1.02 \times 664 \times (0.0379/2.827)^{2/3}$
= 38.22 mm liquid

Head loss due to bubble formation,
$h_\sigma = 409(\sigma/\rho_L d_h)$
= 409(33.4/ 745x 5)
= 3.66mm liq

$h_d + h_\sigma$ = 75.14+3.66= 78.81 mm liq
hw + how = 50 +38.22 = 88.22 mm

Ah/Aa = 0.1, $h_w + h_{ow}$ = 88.22 mm
From fig 18-11, $h_d + h\sigma$ = 18mm

Since the value h_d+hσ is well above the value obtained from graph no weeping will occur.

12 Check for downcommer flooding:
The downcommer backup is given by,
$h_{dl} = h_t + h_w + h_{ow} + h_{ad} + h_{hg}$

c. Hydraulic gradient across plate , h_{hg}
   For stable operation $h_d > 2.5h_{hg}$
   For sieve plates h_{hg} is generally small or neiglible
   Let us take h_{hg} =0 mmliq

d. Total pressure drop across the plate ht:
   $h_t = h_d + h_l'$
   hl'=pressure drop through the aereated liquid = β hds
   whereβ =aeration factor to be found from Perry's fig 18-15

$F_{ga} = U_a(\rho_g)^{1/2}$

U_a = 132787.78/(3600x4.072x8.654)
= 1.046m/sec

ρ_g = 4.072kg/m^3

$F_{ga} = U_a(\rho_g)^{1/2}$
= 1.046 x $(4.072)^{1/2}$(m/sec) $(kg/m^3)^{1/2}$

= 1.73 (ft/sec)$(lb/ft^3)^{1/2}$

from figure,β=0.6

$h_{ds} = h_w + h_{ow} + h_{hg}/2$
= 50+38.22 + 0
= 88.22mm liq

hl' = 0.6 *88.22 = 52.93mm liq
ht = 75.14 +52.93
= 128.07mm liq

c loss under downcomer area head:

$h_{da} = 165.2(q'/A_{da})^2$
let us choose c' = 1inch =25.4mm
$h_{ap} = h_{ds} - c'$
= 88.22 – 25.4
= 62.82 mm liquid

$A_{da} = L_w \; x h_{ap}$
$=2.827 \; x 62.82 x 10^{-3}$
$=0.1775 m^2$

$h_{da} = 165.2(0.0379/0.1775)^2$
$=7.53mm$
hdc = 128.07 + 50+38.22 +7.53+0
= 223.82mm

taking $ø_{dc}$= .5

$h'_{dc} = h_{dc}/ø_{dc}$
=223.82/0.5
= 447.64 mm

we have ts= 500 mm
hence ,$h'_{dc} < ts$
therefore no downcommer flooding will occur.

13. Column efficiency:

The efficiency calculations are based on the average conditions prevailing in each section.

Enriching Section:

Average molar liquid rate = 285.6 Kgmoles/hr
Average mass liquid rate = (34369.1+34969)/2
= 34657.55 Kg/hr
Average molar vapour rate = 822.47 Kgmoles/hr
Average mass vapour rate = (98976+99880.75)/2
= 99428.37 kg/hr
Average density of liquid = (746.3 +745)/2
= 745.65Kgs/m^3
Average density of vapour = (3.436+3.826)/2
= 3.631kgs/hm^3
Average temperature of liquid = (152+153)/2 = 152.5°C
Average temperature of vapour = (154+155)/2 = 154.5°C
Viscosity of cumene at 152.5ºC = 0.16cp
Viscosity of DIPB at 152.5ºC = 0.15cp
X_1=(0.996+0.948)/2 = 0.972
X_2 = 1- 0.98 = 0.028

$\mu_{av} = [x_1\mu_1^{1/3}+x_2\mu_2^{1/3}]^3$
$= [0.535+0.0106]^3$
=0.1626cp

Viscosity of cumene vapour at 154.5 C = 0.01cp
Viscosity of DIPB vapour at 154.5 C = 0.011cp
Average vapour composition , $y_1 = (0.996+0.97)/2 = 0.983$
$y_2 = [1-0.983] = 0.017$

$$\mu_m = \Sigma y_i \mu_i M_i^{1/2} / \Sigma y_i M_i^{1/2}$$

$$= \frac{(0.983x0.01x120^{1/2} + 0.017x0.011x162^{1/2})}{(0.983x120^{1/2} + 0.017x162^{1/2})} = 0.01 \text{ cp}$$

Liquid phase diffusivities:

Wilke-chang equation

$$D_L = \frac{7.4x10^{-8}(\Phi M_B)^{0.5}\, T}{\eta_B V_A^{0.6}}$$

where,
M_B= Molecular weight of solvent B = 162
Φ = 1 for cumene
V_A& V_B are molar volume of solvent A & B
V_A = 16.5x 9 + 1.98x12 = 172.26
V_B=16.5x18 + 1.98x22 = 340.56

$$D_L = \frac{7.4x10^{-8}(1x162)^{0.5}x425.5}{0.16x(172.26)^{0.6}} = 1.14x\, 10^{-4} \text{ cm}^2/\text{sec}$$

Vapour phase diffusivity:
Fuller Etal equation,

$$D_g = \frac{10^{-3}xT^{1.75}(1/M_A+1/M_B)^{0.5}}{P[(\Sigma V_A)^{1/3} +(\Sigma V_B)^{1/3}]^2}$$

$$D_g = \frac{10^{-3}(273+154.5)^{1.75}(1/120 + 1/162)^{0.5}}{1x[(172.26)^{1/3} + (340.56)^{1/3}]^2}$$

$$= 0.0319 \text{cm}^2/\text{sec}$$

$N_{scg} = \mu_g/\rho_g\, D_g$
$= 0.01\, x10^{-3} / (3.631\, x0.0319\, x10^{-4})$
$= 0.863$

Stripping Section:

Average molar liquid rate = 275.34 Kgmoles/hr
Average mass liquid rate = (101851.2+134389.36)/2
= 118120.28 Kg/hr
Average molar vapour rate = 822.47 Kgmoles/hr
Average mass vapour rate = (99880.75+132787.78)/2
= 116334.26 Kgmoles/hr
Average temperature of liquid = (153+202)/2
= 117° C
Average temperature of vapour = (155+202)/2
= 178.5° C
Viscosity of liquid at 177.5 °C= 0.11cp
Viscosity of liquid at 177.5 C = 0.1cp

$\mu_l = [x_1\mu_1^{1/3} + x_2\,\mu_2^{1/3}]^3$

x_1=(0.948+0.013)/2 = 0.4805
x_2 = 1- 0.4805 = 0.5195

$\mu_l = [0.4805x0.11^{1/3} + 0.5195x0.1^{1/3}]^3$
= 0.1071 cp

Viscocity of vapour cumene at 178.5 C= 0.01cp
Viscosity of vapour DIPB at 178.5 C = 0.0115cp
Y_1=(0.97+0.013)/2 = 0.4915
Y2 = 1-0.4915 = 0.5085

$$\mu_v = \frac{\Sigma y_i \mu_i M_i^{1/2}}{\Sigma y_i M_i^{1/2}}$$

= (0.0553+0.072)/(5.531+6.261)
= 0.0108 cp

Liquid phase diffusivity:

Using wilky-chang equation

D_L= 1.672x10^{-4}cm^2/sec

Vapour phase diffusivity:

Dg = 0.0351 cm^2/sec

Nscg = $\mu_g / \rho_g x D_g$

= 0.779

Table of average conditions:

Condition	Enriching Section	Stripping Section
Liq flow rate Kgmoles/hr	285.6	832.39
Liq flow rate Kg/hr	34657.55	118120.28
ρ_L Kg/m3	745.65	672.5
T_L° C	152.5	177.5
μ_L cp	0.1626	0.1071
D_L cm^2/sec	1.14×10^{-4}	1.672×10^{-4}
Vap flow rate Kgmoles/hr	822.47	822.47
Vap flow rate Kg/hr	99428.37	116334.26
ρ_V Kg/m^3	3.631	3.95
Tv° C Dg cm^2/sec	154.5 0.0319×10^{-4}	178.5 0.0351
N_{scg}	0.863	0.779

A.**Enriching section Efficiency**:

$$Ng = \frac{0.776+0.0045h_w-0.238U_a\rho_g^{0.5}+0.0712W}{N_{scg}^{0.5}}$$

U_a=gas velocity theory
= 99428.37/(3600x3.631x5.4682)
=1.391 m/sec

q= 34657.55/(3600x745.65)
= 0.0129m^3/sec

D_f =(Dc+L_W)/ 2
= (2.996+2.247)/2
= 2.6215m

W = q/D_f
=0.0129/2.6215
= 4.92×10^{-3} m^2/sec

h_w=50mm

ρ_g = 3.631Kg/m^3

N_{scg} = 0.863

$$N_g = \frac{0.776+.0045x50-0.238x1.391(3.631)^{0.5}+0.0712x4.92x10^{-3}}{(0.863)^{0.5}}$$

$N_g = 0.3988$

$N_l = K_L a\ \theta_L$

$K_l xa = (3.875x10^8 D_L)^{0.5}(0.4U_a\rho_g^{0.5} + 0.17)$
$= (3.875x10^8 x1.14x10^{-8})^{0.5}[0.40x1.391x(3.631)^{0.5}+0.17]$
= 2.585/sec

$\theta_l = h_l\ A_a / 1000q$ [h_l=h_l']
= (42.88x5.4682)/(1000x0.0129)
=18.17

N_l = 2.585 x 18.17
= 46.986

$N_{og} = 1/(1/N_g + \lambda/N_r)$

Where, $\lambda = mG_m/L_m$
Gm/Lm = 822.47/285.6
= 2.88
m=slope of the equilibrium curve
mtop = 0.2857
mbottom = 0.2857

'm' value is same at the top and bottom as slope of equilibrium line is same at both the points

λ = 0.2857x2.88
= 0.8228

Nog = 1/ (1/0.3988+0.8228/46.98)
= 0.3960

$Eog = 1-e^{-Nog}$
=0.3270

B.**Murphy plate efficiency:**

$Npl = z_l^2/D_E\theta_l$

$Z_l = 2[(De/2) \cos(\theta_C/2)]$
= 2[(2.996/2) cos (97.18/2)]
=1.981

$D_E = 6.675x10\text{-}3U_a^{1.44} + 0.922x10^{-4}h_l\text{-}0.00562$
$=6.675x10^{-3}\ x(1.3981)^{1.44} + 0.922x10^{-4}x42.88 - 0.00562$
$= 9.069x10^{-3}m^2/sec$

$N_{pl} = (1.981)^2/(9.069x10^{-3}\ x18.17)$
$= 22.470$

$\lambda Eog = 0.8238x0.3270$
$= 0.269$

from fig 18.29(a) , $E_{mv}/E_{og} = 1.12$

e. Overall efficiency

$Eoc = N_t/N_A = \log[1+Ea(\lambda\text{-}1) / \log\lambda$

$E_a/E_{mv} = 1/\ 1+E_{mv}(\Psi/1\text{-}\Psi)$

Taking
$L/G(\rho g/\rho L)^{0.5} =0.02425$ (avg.value)

We get, $\Psi = 0.13$

$E_a/E_{mv} = 1/(1+0.3597(0.13/1\text{-}0.13)\ )$
$= 0.94289$

$Ea = 0.9489x0.3597$
$= 0.3413$

$Eoc = \log[1+0.3413(0.8228\text{-}1)]/\log(0.8228)$
$=0.3208$

$N_A = N_t/E_{oc}$
$= 3/0.3207$
$= 9.35 \approx 9$ trays
Height of enriching section is = 9x0.5
= 4.5 m

Stripping Section Efficiency:

$$N_g = \frac{0.776+0.0045h_w\text{-}0.238U_a\rho_g^{0.5}+0.0712W}{N_{scg}^{0.5}}$$

U_a= 116334.26/(3600x3.95x8.654)

= 0.9453m/sec

$q = 118120.28/(3600x672.5)$
$= 0.0488$

$D_f = (Dc + L_w)/2$
$= 3.298$ m

$w = q/D_f$
$=0.0488/3.298$

hw=50mm

$\rho_g = 3.95$kg/m3

Nscg = 0.779

$Ng = [(0.776+0.0045x50-0.238x0.9453x(3.95)^{0.5}+0.0712x0.0148]/(0.779)^{0.5}$
$= 0.6287$

$N_l = K_L a\ \theta_L$

$K_l xa = (3.875x10^8 D_L)^{0.5}(0.4U_a \rho_g^{0.5} + 0.17)$
$= (3.875x10^8 x1.672x10^{-4})^{0.5}\ (0.4x0.9453x(93.95)^{0.5}+0.17)$
$=2.345\ sec^{-1}$

$\theta_l = h_l\ A_a / 1000q$ $[h_l=h_l']$
$= (52.93x8.654)/(1000x0.0488)$
$=9.386$

$N_l = 2.345 \times 9.386$
$= 22.01$

$N_{og} = 1/(1/N_g + \lambda/N_t)$

Where, $\lambda = mG_m/L_m$
Gm/Lm = 822.47/832.39
= 0.9880
m=slope of the equilibrium curve

$m_{top} = 0.2857$
$m_{bottom} = 4.37$

$\lambda_{top}= 0.2857x0.9880$
$= 0.2822$
$\lambda_{bottom} = 4.37x0.9880$
$=4.3175$

$\lambda = (\lambda_{top} + \lambda_{bottom})/2$
$= 2.29$

$N_{og} = 1/ (1/0.6287+2.29/22.01)$
$= 0.5901$

$E_{og} = 1-e^{-Nog}$
$=0.4457$

B.**Murphy plate efficiency:**

$N_{pl} = z_l^2/D_E\theta_l$

$Z_l = 2[(Dc/2) \cos(\theta_C/2)]$
$= 2[(3.769/2) \cos (97.2/2)]$
$=2.493$

$D_E = 6.675x10^{-3}U_a^{1.44} + 0.922x10^{-4}h_l-0.00562$
$=6.675x10^{-3} x(0.9453)^{1.44} + 0.922x10^{-4}x52.93 – 0.00562$
$= 5.41x10^{-3}m^2/sec$

$N_{pl} = (2.493)^2/(5.41x10^{-3} x9.386)$
$= 122.39$

$\lambda Eog = 2.29x0.4457$
$= 1.02$

from fig 18.29(a) , $E_{mv}/E_{og} = 1.7$

f. Overall efficiency

$Eoc = N_t/N_A = \log[1+Ea(\lambda-1)] / \log\lambda$

$E_a/E_{mv} = 1/ 1+E_{mv}(\Psi/1-\Psi)$

Taking
$L/G(\rho g/\rho L)^{0.5} =0.02425$ (avg.value)

We get, $\Psi = 0.037$

$E_a/E_{mv} = 1/(1+0.7577(0.037/1-0.037))$
$= 0.6920$

$Ea = 0.692x0.7577$
$= 0.5243$

Eoc = log[1+0.5243(2.29-1)]/log(2.29)
=0.6225

$N_A = N_t/E_{oc}$
= 6/0.6225
= 9.64 ≈ 10 trays

Height of stripping section is = 5x0.5
= 4.5 m

total height of tower = 4.5+5=9.5

6(B). MECHANICAL DESIGN

Specifications:-

Inside Dia :- 3.769m = 3769mm

Ht of top disengaging section = 40cm.

Working pressure = 1atm = 1.032 kg/cm^2

Design pressure = 1.032 x 1.1 = 1.135 kg/cm^2

Shell material = Carbon steel(Sp. gr. = 7.7)

Permissible tensile stress = 950 kg/cm^2

Insulation material = asbestos

Density of insulation = 2700 kg/m^3

Tray spacing = 500 mm

Insulation thickness = 50 mm

Down comer & plate material = S.S

Sp.gr of SS = 7.8

SKIRT = 2m

Shell thickness:-

$$t_s = \frac{P.D_i}{2fj - p} + C$$

t_s = shell thickness
P= design pressure
D_i = ID of shell
f = allowable stress
J = joint efficiency (0.85)

C= corrosion allowance (2 mm)

$$t_s = \frac{1.135 \times 3769}{2 \times 0.85 \times 950 - 1.135} + 2$$

= 5 mm.

Taking min shell thickness of 6mm

∴Shell outside Do = 3769+2x6 = 3781mm

The column is provided with torispherical head on both ends.

For torrispherical head, crown radius

=> Ro = Do = 3781 mm

r_o = 6% Ro
= 0.06 x 3781
= 226 mm

Calculation of head thickness

$t = 0.885\, Pr_c /(fE - 0.1p) + C$ [eqn.13.12 Brownell & Young]

r_c = crown radium
E = joint eff^n
f = allowable stress
C = corrosion allowance

$$t = \frac{0.855 \times 1.135 \times 3781}{950 \times 0.85 - 0.1 \times 1.135} + 2$$

= 7.00 mm

take head thickness to be 8mm
Approximate blank diameter can be found out as;

$$\text{Diameter} = OD + \frac{OD}{24} + 2\,Sf + \frac{2}{3}\,icr$$

Sf= 800 mm

$$\text{Diameter} = 3781 + \frac{2412}{24} + 2 \times 800 + \frac{2}{3} \times 226$$

= 5683mm

$$\text{wt of head} = \frac{\pi d^2 t}{4} \times \rho$$

$$= \frac{\pi \times (5.683)^2 \times 0.006}{4} \times 7700$$

= 1172kg.

calculation of thickness with Hgt ;-

Carbon steel material
IS 2002 – 1962 Grade I

Tensile strength $R_{20} = 37$ kgf/cm^2

Yield stress = $0.55\ R_{20}$
= 20.35 kgf/cm^2

$f_{ap} = \frac{pdi}{4(ts-c)}$
$= \frac{1.135 \times 3769}{4 \times (6-2)}$
= 267 kg/cm^2

f_{ap} = tensile stress due to internal pr (kg/cm^2)

<u>stresses due to dead load (compressive)</u> -:

Σ w = (weight of the shell + attachment)
+ (weight of plate)+ (weight of liquid hold up)
+ (weight of the head)

w_1 = weight of shell = $\pi d_i t\ \rho s\ .\ X$
w_2 = weight of insulation = $\frac{\pi}{4} (d_{o\ ins}^2 - d_o^2)\rho_{ins}\ .\ X$

$w_h = w_t$ of head = 1172 kg.
$W_p = w_t$ of each plate = $(A_n - A_h) \times t_p\ .\ \rho_p + [h_w + (t_s - h_{ap})] \times t_p \times P_p + W_a$

$W_L = w_t$ of liquid = $(A_a * H_L + A_d * h_{dl})\rho_L$

$\Sigma w = w_1 + w_2 + w_h + (w_p + w_L) * \frac{X}{t_s}$

w_1 = weight of shell = $\pi (3.769) \times 6 \times 10^{-3} \times 7700\ (X)$
= 547 X

w_2 = weight of insulation = $\frac{\pi}{4} (3.881^2 - 3.781^2) \times 2700$
= 1662.24 X kg.

w_h = weight of head = 1172 kg.

w_p = weight of each plate.
= (9.902- 0.829) x 0.003 x 7800
+ [0.05 + (0.500 – 0.0628)] x 0.003 x 7800
+ w_a [$w_a \simeq 50$]

w_p = 250 kg.

W_L = weight of liq
= [8.654 x 52.93 x 10^{-3} + 0.1775 x 0.2238] x 673
= 335 kg

$\Sigma w = 547\ X + 1662.24\ X + 1172 + (250 + 335) \frac{X}{0.5}$

= 3489 X + 1172

Stress due to dead load (compressive) at distance X:

$f_{dw} = \dfrac{\Sigma w}{\pi \, di \, (ts - 6)}$

$= \dfrac{3489 X + 1172}{\pi \times 376.9 \times (6 - 2) 10^{-1}}$

$= 7.366 X + 2.474 \text{ kg/cm}^2$

Stress due to wind load at a dist X:-

$f_{wx} = \dfrac{1.4 \, Pw \, x^2}{\pi \, do \, (ts - c)}$

The design is being due for a wind press of 150 kg/m^2

$\therefore P_w = 150 \text{ kg/m}^2$

$f_{wx} = \dfrac{1.4 \times 150 X^2}{\pi \times 378.1 \times (6 - 2) \times 10^{-1}}$

$= 0.4427 X^2 \text{ kg/cm}^2$

Resultant longitudinal stress in the upwind side:

$ft_{max} = f_{ax} + f_{ap} - f_{dw}$

$950 \times 0.5 = 0.4427 X^2 + 267 - (7.366 X + 2.474)$

$\Rightarrow 0.4427X^2 - 7.366 X - 210.4 = 0$

$X = \dfrac{7.366 \pm \sqrt{7.366^2 + 4 (0.4427)(210.4)}}{2 \times 0.4427}$

$= 31.65 \text{ m}$

Resultant longitudinal stresses:- at down wind sides:-

$- fc_{max} = -f_{wx} + f_{ap} - f_{dw}$

$fc_{max} = \dfrac{1}{3} \text{(yield stress)} = \dfrac{1}{3} \times 20.35$

$= 6.783 \text{ kg/cm}^2$

$-6.783 = - 0.4427X^2 + 267 - (7.366X + 2.474)$

$\Rightarrow 0.4427X^2 + 7.366X - 271.3 = 0$

$X = \dfrac{- 7.366 \pm \sqrt{7.366^2 + 4 \times (0.4427)(271.3)}}{2 \times 0.4427}$

$= 17.8 \text{ m}$

which suggests that the design is safe. Since the design is being made on the basis of higher diameter, so the design is assumed to be safe for the entire length of the tower.

Design of skirt support:-

Specifications:-

Top disengaging space = 1m
Bottom separator space = 2m
Skirt Hgt = 2m.

Total Height of column including skirt height-

$$H = 9.5 + 2.00 + 1.00 + 2.00$$
$$H = 14.5m$$

Wt. of shell $w_1 = \pi dit\, \rho s\, H = 7931.5$ kg.

Wt of insulation $w_2 = 1662.24 x 14.5$
$= 24102.5kg$

W_h = Wt. of Head = 1172 kg.

Wp = Wt. Of plate = 250kg.

W_L = wt. of liquid = 335 kg

$$\Sigma W = W_1 + W_2 + (W_P + W_L) \frac{H}{t_s} + W_h$$

$$= 7931.5 + 24102.5 + (250 + 335) \times \frac{14.5}{0.5} + 1172$$

$$= 51767 \text{ kg}$$

Wind Load

$$f_{wb} = \frac{(K P_1 H D_O). (H/2)}{\frac{\pi}{4} D_O^2 . t}$$

$$= \frac{2K P_1 H^2 D_O}{\pi D_O^2 t.}$$

$K = 0.7$, $P_1 = 128.5$ kg/m^2

$$f_{bw} = \frac{2 \times (0.7) (128.5 \times 14.5^2 \times 3.781)}{\pi \times (3.781)^2 \times t \times 10^4} \text{ kg/cm}^2$$

$$f_{bw} = \frac{0.1592}{t} \text{ kg/cm}^2$$

$$f_{ds} = \frac{w}{\pi D_m t.}$$

Dm = Di + t = 2400 + 6 = 3.775 m

$$f_{ds} = \frac{51767}{\pi \times 3.775 x\, t\, x 10^2} = \frac{43.65}{t}$$

Seismic load :

$$f_{sb} = \frac{8}{3}\ \frac{CWH}{\pi Do^2 t}$$

C= 0.08

$$f_{sb} = \frac{8}{3} \times \frac{0.08 \times 51767 \times 14.5}{\pi \times (3.781)^2 \times t \times 10^4}$$

$$= \frac{0.3565}{t}\ kg/cm^2$$

max possible tensile stress:-

$Jf = f_{db} - f_{sb}$

$$807.5 \geq \frac{43.65}{t} - \frac{0.3565}{t}$$

$$807.5 \geq \frac{43.29}{t}$$

$t \geq 0.0536$cm.

We can have t = 6mm

max permissible compressive stress:-

$Jf \geq f_{db} + f_{sb}$

$$807.5 \geq \frac{43.65}{t} + \frac{0.3565}{t}$$

$$807.5 \geq \frac{44.00}{t}$$

$$t \geq \frac{44.00}{807.5}$$

$t \geq 0.0545$ cm

choose skirt thickness = 6mm

Skirt bearing plate

$$fc = \frac{\sum W}{A} + \frac{M_s}{Z}$$

$$= \frac{51767 \times 4}{\pi (403^2 - 377^2)} + \frac{Msb}{2}$$

$$M_{sb} = \frac{2}{3} CWH.$$

$$Z = \frac{(D_{op}^4 - D_{os}^4) \times \pi}{D_{op} \times 32}$$

$$= \left(\frac{403^4 - 377^4}{\quad} \times \pi \right)$$

32 x 403

$$fc = \frac{51767 \times 4}{\pi(403^2 - 377^2)} + \frac{2}{3}\frac{0.08 \times 51767 \times 14.5}{\frac{\pi(403^4 - 377^4)}{32 \times 403}}$$

= 3.2496 + 0.0266
= 3.2762 kg/cm^2

This is much less than permissible compressive stress of concrete.

$M_{max} = fc \,.\, b.l^2/2$

$$f = \frac{6\ M\ max}{b\ t_B^2} = \frac{3\ fcl^2}{t_B^2} = \frac{3 \times 3.2762 \times 15^2}{t_B^2}\ \ kg/cm^2$$

f = 9.6 MN/m^2 = 9.5 x 10^2 N/ cm^2
= 96 kgf/cm^2

$$t_B = \sqrt{\frac{3x3.2762x15^2}{96}}$$

t_B = 4.799 cm = 48mm
bolting has to be used.

Assume W min = 45,000 kg.

$$f_c = \frac{45,000 \times 4}{\pi\,(403^2 - 377^2)} - \frac{2}{3} \times \frac{0.08 \times 51767 \times 14.5}{\frac{\pi \times (403^4 - 377^4)}{32 \times 377}}$$

= 20.8 – 3.09
= 17.7 kg/cm

$$j = \frac{Mwt}{Ms} = \frac{W\ min\ R}{Ms.}$$

$$Ms = \frac{2}{3}\ (8.08) \times 51767 \times 1450$$

= 4.043 x 10^6

Mwt = W min x R

= 45,000 x 270
= 12.15 x 10^6

$$j = \frac{12.15x\ 10^6}{4.043 \times 10^6}$$

= 3.05

j > 1.5 anchor bots are not required.

6(C). MINOR EQUIPMENT

CONDENSER (PROCESS DESIGN)

(I) Preliminary Calculations:

(a) Heat Balance:

Vapor flow rate (G) = (R+1)D
= 1.532 x 64525.5 kg/hr
= 98976 kg/hr
= 27.49 kg/s

`

Vapor Feed Inlet Temperature =152.4^{0}c.

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

Condensate outlet temperature = 152.4 ^{0}C

∴Average Temperature = 152.4 ^{0}C

Latent heat of vaporisation (λ) :

$\lambda = C_1 \times (1-T_r)^{(C2+C3 \times Tr + C4 \times Tr2)}$ [Perry, 7th edition ; 2nd chapter]

for cumene, Tc= 631.1K ; Pc = 3.25 x 10^6

Now Tr = T/ Tc = (152.4+273)/ 631 = 0.6735
C_1= 5.795 x 10^7 ; C_2 = 0.3956
C_3 = 0 ; C_4 = 0

$\lambda = 5.795 \times 10^7 + (1-0.6735)^{0.3956}$
= 5.795 x 10^7 J/Kmole
= 482.153 KJ/ kg

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

q_h = heat transfer by the hot fluid .

q_h = 27.49 x 482.153 = 13254.3 KW

q_C= mass flow rate of cold fluid x specific heat x t △

q_c = heat transfer by the cold fluid.

Assume : $q_h = q_c$.

Inlet temperature of water = 25 ^{0}C.

Let the water be untreated water.

∴ Outlet temperature of water (maximum) = $\underline{40\ ^0C}$

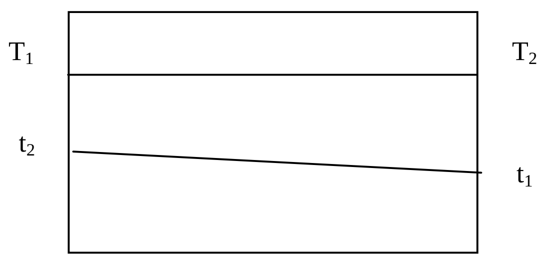
∴ Δt = 40-25= $\underline{15\ ^0C}$

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

$$m_c = \frac{13254.3}{4.187\times10^3\times15} = \underline{211}\ \text{kg/s.}$$

(b) LMTD Calculations:

assume : counter current



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

T1 = 152.4 ^{0}C; T_2 = 152.4 ^{0}C ; t_1 =25 ^{0}C ; t_2 =40 ^{0}C

∴ LMTD = 119.74 ^{0}C

(C) Routing of fluids :

Vapors - Shell side

Liquid - Tube side

(D) Heat Transfer Area:

(i) $q_h = q_C = UA\ (\Delta T_{LMTD,corrected}$.

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

Assume : U = 536 W/m^{2}K

$$\therefore A_{assumed} = \frac{13254\times10^3}{536 \times 119.74} = 206.5\ m^2$$

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

Outer diameter of pipe (OD) = ¾” = 0.01905 m

Inner diameter of pipe (ID) =0.620” = 0.01574 m

Let length of tube =16’ = 4.88m

Let allowance for tubesheet thickness = 0.05m

Heat transfer area of each tube ($a_{heat-transfer}$) $= \pi$ x OD x (Length – Allowance)

$= \pi$ x 0.01905 x (4.88 – 0.05)

$= 0.2889\ m^2$

$\therefore$ Number of tubes (N_{tubes}) = $\dfrac{A_{assumed}}{a_{heat-transfer}} = \dfrac{206.5}{0.2889}$

= 715

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

Choose TEMA : P or S. ¾” OD tubes in 1” $\triangle^{lar}$ pitch

1 – 2	Horizontal Condenser

Nearest tube count = 716

$\therefore N_{tubes}$ (Corrected) = 1740

Shell Diameter (D_c) =0.787 m.

$\therefore A_{corrected} = 206.8\ m^2$

$\therefore U_{corrected} = 536\ W/m^2K = U_{asssumed}$

(iv) Fluid velocity check :

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

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

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

4

$\therefore a_{tube} = \frac{\pi}{4} (0.01574)^2 \times \frac{716}{2} = 69.71\ m^2/pass$

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

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

$$\therefore v_p = \frac{211}{995.6 \times 69.71} = \underline{3.04\ m/s}$$

∴ fluid velocity check is satisfied

(II) Film Transfer Coefficient :

Properties are evaluated at ^{t}film :

$$^t\text{film} = \left[\frac{t_v + 1\{t_v + \frac{(t_1+t_2)}{2}\}}{2}\right] = \left[\frac{152.4 + \{152.4 + \frac{(25+40)}{2}\}]}{2}\right] = \underline{120\ ^0C}$$

a) Shell side:

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

$$= \frac{4}{0.000317} \times \frac{27.49}{(716)^{2/3} \times 4.88} = \underline{882}$$

For Horizontal condenser :

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

$$= 1.51 \left\{ \frac{0.01905^3 (862.3)^2 \times 9.81}{(0.3176 \times 10^{-3})^2} \right\}^{1/3} (882)^{-1/3} = \underline{321.6}$$

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

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

k = Thermal conductivity of liquid.

$h_o = Nu \times K/(OD) = \underline{839\ W/m^2K}$

b) <u>Tube side</u>:

$v_{pipe} = 3.04$ m/s

$$Re = \frac{v(ID)\rho}{\mu} = \frac{3.04 \times 0.01574 \times 995.6}{0.8 \times 10^{-3}} = \underline{59{,}625}$$

$$Pr = \frac{\mu C_p}{K} = \frac{0.8 \times 10^{-3} \times 4.1796 \times 10^{3}}{0.617} = \underline{5.39}$$

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

h_i = inside –heat transfer coefficient

$$h_i = \frac{0.023\ (59625)^{0.8}\ (5.39)^{0.3}}{0.01574} \times 0.617$$

$h_i = 11{,}751\ W/m^2K$

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

$$\frac{1}{U_0} = \frac{1}{h_o} + \frac{(OD)}{(ID)}\frac{1}{h_i} + \text{Fouling factor} + \frac{x\ \ (OD/D_{avg})}{Kw}$$

U_o = overall heat –transfer coefficient

$$\frac{1}{U_0} = \frac{1}{839} + \frac{0.01905}{0.01574} \times \frac{1}{11751} + 0.003/5.678 + \{(0.065 \times 0.0254)/55\} \times (0.01905/0.01739)$$

$\underline{U_0 = 539\ W/m^2K}$

$U_0 > U_{assumed}$

(III) <u>Pressure Drop Calculations</u> :

a) <u>Tube Side :</u>

Re =59625

$f = 0.079\ (Re)^{-1/4} = 0.079\ (59625)^{-1/4} = 0.0021$

f = friction factor

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

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

$$= \frac{4 \times 0.0021 \times 4.88 \times 3.04^2 \times 995.6 \times 9.81}{2 \times 9.81 \times 0.01574}$$

$$= \underline{11.981 \text{ KPa}}$$

Pressure Drop in the end zones $(\Delta P)_e = \frac{2.5\, \rho\, Vp^2}{2} = \frac{2.5 \times 995.6 \times 3.04^2}{2} = 11.5 \text{ KPa}$

Total pressure drop in pipe $(\Delta P)_{total} = [11.981 + 11.5]2 = \underline{46.96 \text{ KPa}} < 70 \text{ KPa}$

b) Shell side: Kern's method

Number of baffles =0

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

$C^1 = 2.54 \times 10^{-2} - 0.01905 = \underline{0.00635}$

P_T = pitch = 25.4×10^{-2} m

$$a_{shell} = \frac{\text{shell diameter} \times C^1 \times B}{P_T} = \frac{0.787 \times 0.00635 \times 4.88}{25.4 \times 10^{-3}}$$

$$= \underline{0.9601 \text{ m}^2}$$

$$De = \frac{4\left\{\frac{P_T}{2} \times 0.86\, P_T - \frac{1}{2}\frac{\pi}{4}(OD)^2\right\}}{\left(\frac{\pi\, do}{2}\right)} = \frac{4\left\{\frac{(25.4 \times 10^{-3})^2}{2} \times 0.86 - \frac{\pi}{8}(0.01905)^2\right\}}{\frac{\pi\,(0.01905)}{2}}$$

$= \underline{22.13\text{mm.}}$

$$Gs = \text{Superficial velocity in shell} = \frac{m_{shell}}{a_{shell}} = \frac{27.49}{0.9601} = 28.63 \text{ kg/m}^2\text{s}$$

$$(N_{Re})_s = \frac{G_s D_c}{\mu} = \frac{28.63 \times 22.13 \times 10^{-3}}{0.01 \times 10^{-3}} = 63{,}363$$

$f = 1.87\ (63363)^{-0.2} = \underline{0.1972}$

∴ Shell side pressure drop

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

$N_b = 0$

$$\therefore \quad \Delta Ps = \left[\frac{4(0.1972)\ (1)\ (0.787)\ (28.63)^2\ 9.81}{2 \times 9.81\ (22.13 \times 10^{-3}) \times 3.48} \right] \times 0.5$$

$= 1.049$ KPa < 14 Kpa

Hence pressure drop on shell side is permissible.

6(D). Mechanical Design

(a) Shell Side:

Material carbon steel (Corrosion allowance = 3mm)
Number of shells =1
Number of passes =2

Working pressure = 1 atm = 0.101 N/mm^2
Design pressure = 1.1 x 0.101 = 0.11 N/mm^2
Temperature of the inlet = 152.4 ^0C
Temperature of the outlet = 152.4^0C

Permissible Strength for
Carbon steel = 95 N/mm^2 [IS : 2000-1968 Grade-1, IS 2825 , Pg : 115]

b) Tube side :

Number of tubes =716
Outside diameter =0.01905m
Inside diameter = 0.01574m
Length = 4.88m
Pitch, $\Delta^{lar} = 25.4 \times 10^{-3}$ m
Feed =Water.
Working Pressure =1 atm = 0.101 N/ mm^2
Design Pressure =0.11 N/mm^2
Inlet temperature =25 ^0C.
Outlet temperature = 40 ^0C

Shell Side :

$t_s = \frac{PD_i}{2fJ-P}$ [IS 2825, pg:13, eq : 3-1]

t_s = Shell thickness
P = design pressure =0.11 N/ mm^2
Di = Inner diameter of shell = 787mm
f = Allowable stress value = 95 N/mm^2
J= Joint factor = 0.85

$t_s = \frac{0.11 \times 787}{2 \times 95 (0.85) - 0.11} = 0.536mm$

Minimum thickness of shell must be 6 mm & corrosion allowance =3 mm
∴ shell thickness, t_s = 10 mm
Head : (Torrispherical head)

$t_h = \frac{PR_CW}{2fJ}$ [Brownell & Young ; pg: 238]

t_h = thickness of head

$W = \frac{1}{4}\{3+ \sqrt{R_c / R_k}\}$

R_c = Crown radius = outer diameter of shell =787mm
R_k = knuckle radius = 0.06 R_C

∴ $W = \frac{1}{4}\{3+ \sqrt{R_c / 0.06 R_c}\} = 1.77$

∴ $t_h = \frac{0.11 \times 787 \times 1.77}{2 \times 95 \times 0.85} = 1.05$ mm

Minimum shell thickness should be = 10 mm [IS : 4503-1967]

∴ t_h = 10mm

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

Flanges :

Loose type except lap-joint flange.
Design pressure (p) =0.11 N/mm2
Flange material : IS:2004 –1962 class 2
Bolting steel : 5% Cr Mo steel.
Gasket material = Asbestos composition
Shell side diameter =787mm
Shell side thickness =10mm

Outside diameter of shell =787 + 10x 2 = 807mm

Determination of gasket width :

$\frac{d_o}{d_i} = \left[\frac{y - pm}{y - p(m+1)}\right]^{1/2}$ (Brownell & Young , Pg:227)

y= Yield stress
m= gasket factor

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

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

d_i = inside diameter of gasket = outside diameter of shell
= 807 + 5mm
=812 mm

d_o = outside diameter of the gasket
= 1.004 (812)
= 816 mm

Minimum gasket width = $\frac{0.816 - 0.812}{2}$ = 0.002m = 2 mm

But minimum gasket width = 6mm
∴ G= 0.812 + 2 (0.006) = 1.256 m

G = diameter at the location of gasket load reaction

Calculation of minimum bolting area :

Minimum bolting area (A_m) = A_g= $\frac{W_g}{S_g}$

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

At 152.4^{0}C.

S_g = 138 x 10^6 N/m^2 [B.C.Bhattacharya , pg :108]

$$A_m = \frac{0.3960 \times 10^6}{138 \times 10^6} = 2.87 \times 10^{-3}\ m^2$$

Calculation for optimum bolt size :

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

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

Selecting bolt size M18x2

R = Radial distance from bolt circle to the connection of hub & back of flange
R= 0.027
C= Bolt circle diameter = ID +2 (1.415 g_o + R) [B.C.B, pg :122]

C= 0.787 +2 (1.415 (0.0125)+0.027)=0.876 m

<u>Estimation of bolt loads :</u>

Load due to design pressure (H) = $\frac{\pi G^2 P}{4}$

$H = \frac{\pi}{4} (0.824)^2 \quad (0.11 \times 10^6) = \underline{0.0586 \times 10^6 \text{ N}}$

Load to keep the joint tight under operating conditions.

$H_p = \pi$ g (2b) m p

b= Gasket width = 6mm = <u>0.006m</u>

$H_p = \pi (0.824)(2 \times 0.006)\, 2.75 \times 0.11 \times 10^6 = 0.00939 \times 10^6$ N

Total operating load (W_o) = H+H_p
= (0.0586+0.00939)
= <u>0.06799 x 10^6 N</u>

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

W_g. = π g b y

= $\pi \times 0.824 \times 0.006 \times 25.5 \times 10^6$

$W_g = 0.3960 \times 10^6$ N

$W_g > W_0$

$\therefore$ W_g is the controlling load
$\therefore$ Controlling load = <u>0.3960 x 10^6 N</u>

Actual flange outside diameter (A) = C+ bolt diameter + 0.02

= 0.876 +0.018+ 0.02
= <u>0.914m</u>

<u>Check for gasket width :</u>

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

$\frac{A_b S_g}{\pi GN} = \frac{(44 \times 1.54 \times 10^{-4})138}{\pi \times 0.824 \times 0.012} = 30.10 \quad N/mm^2$

2y = 2 x 25.5 = 51 N/mm^2

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

i.e., bolting condition is satisfied.

Flange Moment calculations :

(a) For operating conditions :

$W_Q = W_1 + W_2 + W_3$

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

$W_2 = H - W_1$

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

B= outside shell diameter = 0.807m

$W_1 = \frac{\pi}{4} (0.807)^2 \times 0.11 \times 10^6 = 0.05626 \times 10^6$ N

$W_2 = H - W_1 = (0.0586 – 0.0562) \times 10^6 = 0.0026 \times 10^6$ N

$W_3 = 0.00939 \times 10^6$ N

$W_o = (0.05626 + 0.0026 + 0.00939) \times 10^6$

$= 0.068 \times 10^6$ N

M_o = Total flange moment = $W_1 a_1 + W_2 a_2 + W_3 a_3$ [IS : 2825-1969 ; pg :53]

$a_1 = \frac{C - B}{2}$; $a_2 = \frac{a_1 + a_3}{2}$; $a_3 = \frac{C - G}{2}$ [IS 2825-1969, pg :55]

C=0.876; B=0.807; G=0.824

$a_1 = \frac{0.876 - 0.807}{2} = 0.0345$

$a_3 = \frac{C - G}{2} = \frac{0.876 - 0.824}{2} = 0.026$

$a_2 = \frac{a_1 + a_3}{2} = \frac{0.0345 + 0.026}{2} = 0.0303$

$M_o = [0.05626 (0.0345) + 0.0026 (0.0303) + 0.00939 (0.026)] \times 10^6$

$= 2.264 \times 10^3$ J

(b) For bolting up condition :

M_g = Total bolting Moment = $W a_3$ [IS 2825-1969, pg :56, Eqn:4.56]

$$W = \frac{(A_m + A_b)}{2} S_g .$$

$A_m = 2.87 \times 10^{-3}$

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

$S_g = 138 \times 10^6$

$$W = \frac{(2.87 \times 10^{-3} + 67.76 \times 10^{-4})}{2} \times 138 \times 10^6 = \underline{0.665 \times 10^6}$$

$M_g = 0.665 \times 10^6 \times 0.026 = \underline{0.0173 \times 10^6\ J}$

$\underline{M_g > M_o}$

$\therefore$ M_g is the moment under operating conditions

$M = M_g = 0.0173 \times 10^6$ J

Calculation of the flange thickness:

$$t^2 = \frac{MC_FY}{BS_{FO}}$$ [B.C.B: , eq:7.6.12]

C_F= Bolt pitch correction factor = $\sqrt{B_s / (2d + t)}$ [IS 2825-1969: 4, pg:43]

B_s = Bolt spacing = $\frac{\pi C}{n} = \frac{\pi(0.876)}{44} = 0.0625$m

n= number of bolts.

Let $C_F = 1$

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

$S_{FO} = 100 \times 10^6$ N

$M = 0.0173 \times 10^6$ J

B = 1.239

$$K = \frac{A}{B} = \frac{\text{Flange diameter}}{\text{Inner Shell diameter}} = \frac{0.914}{0.807} = 1.132$$

Y = 15 (B.C.Bhattacharya, pg : 115, fig:7.6).

$$t = \sqrt{\frac{0.0173 \times 10^6 \times 1 \times 15}{0.807 \times 100 \times 10^6}} = \underline{0.0567\ m}$$

d = 18 mm

$$C_F = \sqrt{\frac{0.0625}{2(18 \times 10^{-3}) + 0.0622}} = \underline{0.675}$$

$C_F = (0.675)^2$

$t = 0.0567 \times 0.821 = \underline{0.049\ m}$

Let t = 50mm = 0.05m

Tube sheet thickness : (Cylindrical Shell) .

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

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

$t_{1s} = 0.824 \sqrt{(0.25 \times 0.11 \times 10^6) / (95 \times 10^6)} = 0.014$ m

Channel and channel Cover

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

$= 0.824 \sqrt{(0.3 \times 0.11/ 95)}$

= 0.015 m =15 mm

Consider corrosion allowance = 4 mm.

t_h=0.004 + 0.015 = 0.019 m.

Saddle support

Material: Low carbon steel

Total length of shell: 4.88 m

Diameter of shell: 807 mm

Knuckle radius = 0.06 x 0.807 = 0.048 m = r_o

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

= √(0.80

= 0.139

Weight of the shell and its contents = 12681.25 kg = W

R=D/2=807/2 mm

Distance of saddle center line from shell end = A =0.5R=0.202 m.

Weight of the vessel and condensate :

Density of steel = 7600 kg/m^3

Weight of steel vessel = $(\pi d_i^2/4) \times \rho_{water} \times L \times N_t + \pi d_s \times t \times \rho_{steel} \times L + \pi d_i t \times L \times \rho_{steel} \times N_t$

$= \pi(0.0157)^2/4 \times 994 \times 4.88 + \pi \times 0.787 \times 0.01 \times 4.88 \times 7600 + \pi \times 0.0157 \times 0.0016 \times 7600 \times 716 \times 4.88$

W = 3685 kg

Longitudinal Bending Moment

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

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

$= 3685\ (4.88 + 4 \times 0.139/3)/2$

$= 9333$ kg m

$M_1=9333 x 0.202[1-(1.202/4.88+(0.4035^2-0.139^2)/(2x4.88x0.31))/(1+4x0.139/(3x4.88))]$

$= 11.97$ kg-m

Bending moment at center of the span

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

$M_2 = 9804$ kg-m

Stresses in shell at the saddle

(a) At the topmost fibre of the cross section

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

$=11.97/(3.14 \times 0.4035^2 \times 0.01)$

$= 0.2340$ kg/cm^2

Stress in the shell at mid point

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

$= 191.685$ kg/cm^2

f_1 and f_2 are well within permissible limits

Axial stress in the shell due to internal pressure

$f_p = PD/4t$

$= 0.11 \times 10^6 \times 0.807 /4 \times 0.01$

$= 221.9$ kg/cm^2

$f_2 + f_p = (191.685 + 221.9)$ kg/cm^2

$= 413.585$ kg/cm^2

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