MAJOR EQUIPMENT DESIGN

DISTILLATION COLUMN

(ACETIC ACID PURIFIER)

Process Design

Mol. Wt. of acetic acid = 60.05

Mol. Wt. of water = 18.00

	X_{D1}	X_{D2}	X_w	X_F
Wt.fration of acetic acid(%)	0.58	0.996	0.998	0.98
Mole fraction of water(%)	0.70	0.013	0.0066	0.064

From graph, $\frac{x_{D1}}{R_m+1} = 0.07$

$\therefore R_m = 9.0$

Let, $R = 1.4 * R_m = 12.6$

Now, $\frac{x_{D1}}{R+1} = 0.055$

From slope, *L/G* for enriching section = 0.93 (from slope)

*Avg.mol.Wt***.** of the top stream $D_1 = 0.707*18 + (1-0.707)*60$

$= 30.3$ kg/kmole

Now, for 3600 kg of D_2, D_1 required is 174.52 kgs

$\therefore$ for 150 tpd of D_2, D_1 required = 302.98 kg/hr

$\therefore$ D_1 in kmol = 302.98/avg.mol.wt.= 9.999 kmol/hr

We know that, $R = L/D_1$ and $(L+D_1) = G$

$\therefore D_1(R+1)= G$

$\therefore G = 135.9864$ kmol/hr

and $L = 125.9874$kmol/hr

As, side stream is also included, distillation tower is divided into 3 sections.

For enriching section, L and G are calculated as above.

So, for 2nd sub-section,

L' and G' are calculated as L' = L + q∗F = 262.5 kmol/hr

where F = 7824.62/avg.mol.wt. = 136.52 kmol/hr

and G' = G+(q-1)∗F = G = 135.9864 kmol/hr

∴ L'/G' = 1.93

Now, for 3rd section, G" = G'-D_2 = 135.9864–104.167

= 31.8194 kmol/h

and L" = L'

∴ L"/G" = 262.5/31.8194 = 8.25

∴ From graph, No.of ideal stages = 17

No. of ideal stages in the tower = 17-1 = 16

No. of ideal stages in the enriching section = 7

No. of ideal stages in the stripping section = 9

	ENRICHING SECT		STRIPPING SECT	
	Top	Bottom	Top	Bottom
Temp. liq, °C	102.4	114.8	114.8	117.7
Temp. vap, °C	103.7	115.1	115.1	118.1
Liq. Flowrate,kmol/hr	125.987	125.987	262.5	262.5
Vap. Flowrate,kmol/hr	135.986	136.986	136.986	136.986
Vap density,kg/m3	0.9814	1.795	1.795	1.863
Liq density,kg/m3	957.15	943.27	943.27	938.41
Avg. mol.wt. (vap.)	30.3	55.59	55.59	59.7228
Avg. mol wt. (liq.)	30.3	57.312	57.312	59.7228
Mole fraction, x	0.707	0.064	0.064	0.0066
Mole fraction, y	0.707	0.105	0.105	0.0066
Liq.(L),kg/hr	3817.41	7220.58	15044.4	15677.2
Gas (G),kg/hr	4120.38	7559.48	7559.48	8121.48
$L/G * (\rho_G/\rho_L)^{0.5}$	0.0296	0.0416	0.0868	0.0860

Mix. Viscosity $(\mu_m)_{liq}$,cp	0.3403	0.3403	0.3820	0.3820
Mix. Viscosity$(\mu_m)_{vap}$, cp	0.01548	Same	0.01067	same
Mix. Surfacetension(σ_{mix}),mN/m	18.29	18.29	16.744	16.744
Liq. Diffusivity (D_l), m^2/s	$3.946*10^{-9}$	Same	3.4362e-9	Same
Vap. Diffusivity (D_v), m^2/s	$0.25*10^{-4}$	Same	$0.26*10^{-4}$	Samr

a) ENRICHING SECTION

Tray spacing

t_s = 600 mm

Hole diameter

d_h = 10 mm.

Tray thickness

$T_t = 0.6d_h$ = 6 mm.

Plate diameter

$(\rho_1)_{bottom}$ = 943.27 kg/m^3.

$(\rho_g)_{bottom}$ = 1.795 kg/m^3.

$(\rho_1)_{top}$ = 957.15 kg/m^3.

$(\rho_g)_{top}$ = 0.9814 kg/m^3.

$\mathbf{(L/G)*(\rho_g/\rho_l)^{0.5}}$ = 0.0416 (max. at bottom)

Ref:2; fig. 14-25

For t_s = 600 mm and c_{sb} = 0.1112 m/s.

$\mathbf{u_{nf} = c_{sb} * (\sigma/20)^{0.2} *[(\rho_1 - \rho_g)/ \rho_g]^{0.5}}$

u_{nf} = 2.5015 m/s

where σ = 18.29 mN/m.

$u_n = 0.75\, u_{nf}$ = 1.8761 m/s.

Net area for gas flow

$$A_n = A_c - A_d = \frac{\text{Volumetric gas flow rate}}{u_n} = 0.6235\ m^2.$$

Weir length, L_w = $\mathbf{0.80*D_c}$

$\mathbf{A_c}$ = 0.785 $\mathbf{D_c^2}$

A_d = 0.1118 D_c^2

Substituting and evaluating,

D_c = 0.96 m.

L_w = 0.76 m.

A_c = 0.7234 m^2.

A_d = 0.103 m^2.

Active area

$A_a = A_c - 2A_d$ = 0.5174 m^2.

A_{cz} = 2 (L_w x 0.2) = 0.076 m^2.

α = 75.45° and **θ** = 104.55°

A_{wz} = 0.02586 m^2.

$A_p = A_a - A_{cz} - A_{wz}$

= 0.41554 m^2.

Total hole area

(A_h/A_p) = 0.1

A_h = 0.041554 m^2.

No. of holes = 529

Weir height

h_w = 50 mm.

Check for weeping

h_d = head loss due to dry force.

$$= k_1 + k_2 \frac{\rho_g}{\rho_1} v_h^2 \text{ where } V_h = Q_v/A_h \text{ where } Q_v = \text{vol.vaporflow}$$

$k_1 = 0$

$k_2 = 50.8/C_v^2$

$$A_h/A_a = 0.1 \quad : \quad T_t/d_h = 0.6$$

From pg. 18-9 fig. 18-14 ,ref :1

C_v = 0.735

k_2 = 94.034

h_d(bottom)= 75.91 mm where $\mathbf{V_h}$ = 28.06 m/s

h_d(top) = 141.79 mm where $\mathbf{V_h}$ = 28.15 m/s

h_{ow} = Height of liquid crest formed

$$\mathbf{h_{ow} = 664} \left|\frac{q}{L_w}\right|^{2/3} * \mathbf{F_w} \text{ where } q = 1.1078*10^{-03} \text{ m}^3\text{/s}$$

F_w = 1.02 (Ref:1; fig.18-16,pg 18-11)

h_{ow} = 8.706 mm

$\mathbf{h_\sigma = (409\sigma)/\ \rho_1 d_h}$ = 8.706 mm

$h_d + h_\sigma$ = 76.6915 mm

$h_w + h_{ow}$ = 58.706 mm

A_h/A_a = 0.0803

From Ref:1; fig. 18-11 pg. 18-7,

$h_d + h_\sigma$ > graphical value(14 mm)

∴ weeping does not occur**.**

Down comer flooding

Down comer back up :-

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

$$\mathbf{h_{ow} = 664} \left|\frac{q}{L_w}\right|^{2/3} * \mathbf{F_w} \text{ where } q = 2.126*10^{-03} \text{ m}^3\text{/s.}$$

F_w = 1.025 (from Perry, fig.18-16,pg 18-11)

$\mathbf{h_{ow}}$ = 13.471 mm

h_{hg} = hydraulic gradient

h_t = total pressure drop across plate

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

a) Hydraulic gradient,h_{hg}

Let, $\mathbf{h_{hg}}$ **=** 0.01 mm

Again,

$\mathbf{h_t = h_d + h_l'}$

and $\mathbf{h_1'} = \beta\mathbf{*h_{ds}}$ where β = aeration factor

Now, $\mathbf{F_{ga}} = \mathbf{U_a(\rho_g)^{0.5}} = 2.481$

Where $\mathbf{U_a}$ = gas vel. through active area **=** 4.84 m/s

and $\rho_g = 1.795$ kg/m^3

From Ref-1;fig.18-15,pg:18-10

For $\mathbf{F_{ga}} = 2.481$; $\beta = 0.56$ and $\phi_t = 0.18$

$\mathbf{h_{ds} = h_w + h_{ow} + h_{hg}/2} = 63.475$ mm

$\mathbf{h_1'} = \beta\mathbf{*h_{ds}} = 35.546$ mm

$\mathbf{h_t = h_d + h_l'} = 177.336$ where $h_d = 141.79$ mm

$\mathbf{h_f = h_1' / \phi_t} = 197.47$

Now,

$$\mathbf{h_{hg}} = \frac{1000 f u_f^2 L_f}{g r_h}$$

again f is a function of Reynold's number.

Where,

$$\mathbf{N_{Reh.}} = \frac{r_h u_f \rho_1}{\mu_1} \quad \text{(from ref-1,eq.18-22)}$$

$\mathbf{r_h} = \mathbf{(h_f D_f)/(2h_f+1000D_f)}$ where, $\mathbf{D_f = (D_c+L_w)/2} = 0.86$ m

$\mathbf{r_h} = 0.1353$

$$\therefore \mathbf{u_f} = \frac{1000q}{h_1 D_f} = 0.0695 \text{ m/s}$$

$\mathbf{N_{reh.}} = 26064$ where $\mu_l = 0.3403*10^{-3}$ poise

From ref-1, fig 18-19

f = 0.095

$\mathbf{L_f} = \mathbf{D_c \, Cos(\theta_c/2)} = 0.587$ m

$\mathbf{h_{hg}} = 0.2029$ mm

$\therefore$ $\mathbf{h_{hg}}$ assumed is valid as h_{hg} (calculated) **<** h_{hg} (assumed)

b) Loss under downcomer,h_{da}

h_{da} = 165.2 $\left|\frac{q}{A_{da}}\right| * \left|\frac{q}{A_{da}}\right|$

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

c = 25.4 mm

h_{ap} = 38.075 mm

A_{da} = **$L_w h_{ap}$** = 0.02893 **m^2**

h_{da} = 0.8921 mm

h_{dc} = 241.7091 mm of clear liq

$h'_{dc} = h_{dc}/\varphi_t$ = 483.418 mm. where **φ_t**= 0.5

$h'_{dc} < t_s$ = 600 mm ; $\therefore$ hence no flooding occur.

<u>i)Column efficiency :</u>

<u>a)Point Efficiency :</u>

<u>*Gas phase transfer unit*</u>

$$N_g = \frac{0.776 + 0.00457h_w - 0.238U_a\rho_g^{0.5} + 0.0712W}{N_{Scg}^{0.5}}$$

U_a = 2.26 m/s.

W = q/D_f = 2.4720 $*10^{-03}$ m^3/(s.m)

Now, **N_{Scg} =** $\frac{\mu_g}{D_g\rho_g}$ = 0.3449

where μ_g = 0.01548 cp

ρ_g = 1.795 kg/m^3

D_g = $0.25*10^{-4}$ m^2/s

$\therefore$ **N_g** = 0.9253

<u>*Liquid phase transfer unit*</u>

N_1 = **$k_1 a\theta_1$**

k_1a = $\left(3.875\times10^{8}D_1\right)^{0.5}\left(0.40Ua\rho_g^{0.5}+0.17\right)$ eq.18-40(a),Ref-1

k_1a = 0.8 s^{-1} where **D_l** = diffusivity = 3.9465∗10^{-9} m^2/s

<u>Liquid Residence time</u>

θ_1 = **h_l*A_a/1000q** where h_l = h_l'= 35.546 mm

= 8.6507 sec q = 2.126∗10^{-3} m^3/s

A_a = 0.5174 m^2

∴ **N_1** = 14.7745

$$N_{og} = \frac{1}{\frac{1}{N_g}+\frac{\lambda}{N_l}}$$ (eq.18-34,Ref :1)

λ = **mG_m/L_m** = 1.4166 where **λ = (λ_{top} + λ_{bot})/2**

m = slope of equilibrium curve at top and bottom

N_{og} = 0.8499

$$E_{og} = 1 - e^{-N_{og}}$$

E_{og} = 0.5725

<u>b)Murphee stage efficiency :</u>

$$N_{Pe} = \frac{z_l^2}{D_e\theta_l}$$ where **N_{pe}** = pecklet no.(eq. 18-44,Ref :1)

z_1 = **D_c Cos (θ_c/2)** = 0.587 m

θ_1 = 8.6507 sec

D_e = **6.675 * $10^{-3}Ua^{1.44}$ + 0.992 * $10^{-4}h_1$ – 0.00512**

= 0.01925 ∗10^{-3} m^2/s

∴ **N_{Pe}** = 2.069

λ**E_{og}** = 0.81107

For **N_{Pe}** = 2.069 and λ**E_{og}** = 0.81107;

$$\frac{E_{mv}}{E_{og}}$$ = 1.2 (from fig. 18-29;ref:3)

∴ **E_{mv}** = 0.687

c)Overall column efficiency :

$$E_{oc} = \frac{\log\{1 + E_a(\lambda - 1)\}}{\log \lambda}$$

$$E_a = \frac{E_{mv}}{1 + E_{mv}\left|\frac{\psi}{1-\psi}\right|}$$

For 75% flooding and $\frac{L}{G}\left|\frac{\rho_g}{\rho_l}\right|^{0.5}$ = 0.0416

Fractional entrainment**,** ψ = 0.065 (fig.18-22;Ref:1)

$\mathbf{E_a}$ = 0.655

$\mathbf{E_{oc}}$ = 0.6934

$\mathbf{N_T}$ = No. of theoretical trays in enriching section $\mathbf{N_T}$ = 7

$$\text{Again, by definition } \mathbf{E_{oc}} = \frac{\text{Ideal no. of trays } (\mathbf{N_T})}{\text{Actual no. of trays } (\mathbf{N_A})}$$

∴ $\mathbf{N_A}$ = 7/0.6934 = 10 trays

∴ Tower Height, $H_{(E.S)} = t_s * N_A$ = 6 m

b) Stripping Section

Tray spacing

t_s = 600 mm

Hole diameter

d_h = 10 mm

Tray thickness

$T_t = 0.6d_h$ = 6 mm

Plate diameter

$(\rho_1)_{bottom}$ = 938.41 kg/m^3.

$(\rho_g)_{bottom}$ = 1.863 kg/m^3.

$(\rho_1)_{top}$ = 943.27 kg/m^3.

$(\rho_g)_{top}$ = 1.795 kg/m^3.

$(L/G)*(\rho_g/\rho_l)^{0.5}$ = 0.086 (max. at bottom)

From ref-2, edition fig. 14-25

For t_s = 600 mm and c_{sb} = 0.457 m/s.

$u_{nf} = c_{sb} * (\sigma/20)^{0.2} * [(\rho_1 - \rho_g)/\rho_g]^{0.5}$

u_{nf} = 0.9888 m/s.

where σ = 16.744 mN/m.

$u_n = 0.75\ u_{nf}$ = 0.791 m/s.

Net area for gas flow

$$A_n = A_c - A_d = \frac{\text{Volumetric gas flow rate}}{u_n} = 1.5308\ m^2.$$

Weir length L_W = **$0.80*D_c$**

A_c = 0.785 **D_c^2**

A_d = 0.1118 **D_c^2**

Substituting and evaluating,

D_c = 1.5 m

L_w = 1.2 m.

A_c = 1.76625 m^2

A_d = 0.2515 m^2

<u>Active area</u>

$A_a = A_c - 2A_d$ = 1.2632 m^2

$A_{cz} = 2 (L_w \times 0.2)$ = 0.12 m^2

α = 73.74° and **θ** = 106.26°

A_{wz} = 0.02866 m^2

$A_p = A_a - A_{cz} - A_{wz}$

= 1.1145 m^2

Total hole area

(A_h/A_p) = 0.1

A_h = 0.11145 m^2

No. of holes = 1419

Weir height

h_w = 50 mm

Check for weeping

h_d = head loss due to dry force.

$$h_d = k_1 + k_2 \frac{\rho_g}{\rho_1} v_h^2$$ where $V_h = Q_v/A_h$ where Q_v = vol.vaporflow

$k_1 = 0$

$k_2 = 50.8/C_v^2$

for ,

$$A_h/A_a = 0.1 \quad : \quad T_t/d_h = 0.6$$

(From pg. 18-9 fig. 18-14 ;ref:1)

C_v = 0.740

k_2 = 92.768

h_d(bottom)= 21.73 mm where V_h = 10.864 m/s

h_d(top) = 19.447 mm where V_h = 10.496 m/s

h_{ow} = Height of liquid crest formed

$$h_{ow} = 664 \left|\frac{q}{L_w}\right|^{2/3} * F_w$$ where q = $4.4304*10^{-03}$ m^3/s.

F_w = 1.02 (from ref-1, fig.18-16,pg 18-11)

h_{ow} = 16.178 mm

$h_\sigma = (409\sigma)/\rho_1 d_h$ = 0.726 mm.

$(h_d + h_\sigma)_{design}$ = 20.173 mm

$h_w + h_{ow}$ = 66.178 mm.

A_h/A_a = 0.0882

From ref-1, fig. 18-11 pg. 18-7,

$(h_d + h_\sigma)_{design} > (h_d + h_\sigma)$ graphical value(16 mm)

∴ weeping does not occur.

Down comer flooding

Down comer back up :-

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

$h_{ow} = 664 \left|\frac{q}{L_w}\right|^{2/3} * F_w$ where q = $4.6405*10^{-03}$ m^3/s.

F_w = 1.02 (ref-1, fig.18-16,pg 18-11)

h_{ow} = 16.68 mm

h_{hg} = hydraulic gradient

h_t = total pressure drop across plate

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

a) Hydraulic gradient,h_{hg}

Let, h_{hg} = 0.01 mm

Again,

$h_t = h_d + h_l'$

and $h_1' = \beta * h_{ds}$ where β = aeration factor

Now, $F_{ga} = U_a(\rho_g)^{0.5}$ = 1.0725

Where U_a = gas vel. through active area = 0.9586 m/s

and ρ_g = 1.863 kg/m^3

From ref-1,fig.18-15,pg:18-10

For F_{ga} = 1.0725; β = 0.64 and ϕ_t = 0.28

$h_{ds} = h_w + h_{ow} + h_{hg}/2$ = 66.685 mm

$h_1' = \beta * h_{ds}$ = 42.6784 mm

$h_t = h_d + h_l'$ = 64.4084 mm where h_d = 21.73 mm

$h_f = h_1' / \phi_t$ = 152.42 mm

Now,

$$h_{hg} = \frac{1000 f u_f^2 L_f}{g r_h}$$

Again f is a function of Reynold's number.

Where,

$\mathbf{N_{Reh.}} = \frac{r_h u_f \rho_1}{\mu_1}$ (ref-1,eq.18-22)

$\mathbf{r_h} = \mathbf{(h_f D_f)/(2h_f+1000D_f)}$ where, $\mathbf{D_f = (D_c+L_w)/2} = 1.35$ m

$\mathbf{r_h} = 0.1243$

$\therefore \mathbf{u_f} = \frac{1000q}{h_1 D_f} = 0.0805$ m/s

$\mathbf{N_{reh.}} = 24580$ where $\mu_l = 0.3820 * 10^{-3}$ poise

From ref-1, fig 18-19

f = 0.09

$\mathbf{L_f} = \mathbf{D_c\ Cos(\theta_c/2)} = 0.90$ m

$\mathbf{h_{hg}} = 0.4304$ mm

$\therefore$ $\mathbf{h_{hg}}$ assumed is valid as h_{hg} (calculated) $<$ h_{hg} (assumed)

b) Loss under downcomer, h_{da}

$$\mathbf{h_{da}} = 165.2 \left|\frac{q}{A_{da}}\right| * \left|\frac{q}{A_{da}}\right|$$

$\mathbf{h_{ap} = h_{ds} - c}$

$\mathbf{c} = 25.4$ mm

$\mathbf{h_{ap}} = 41.285$ mm

$\mathbf{A_{da}} = \mathbf{L_w h_{ap}} = 0.04954$ $\mathbf{m^2}$

$\mathbf{h_{da}} = 1.4495$ mm

$\mathbf{h_{dc}} = 132.045$ mm of clear liq

$\mathbf{h'_{dc} = h_{dc}/\ \varphi_t} = 483.418$ mm. where $\varphi_t = 0.5$

$h'_{dc} < t_s = 600$ mm **;** $\therefore$ hence no flooding occur.

i)Column efficiency :

a)Point Efficiency :

Gas phase transfer unit

$$N_g = \frac{0.776 + 0.00457h_w - 0.238U_a\rho_g^{0.5} + 0.0712W}{N_{Scg}^{0.5}}$$

U_a = 0.9586 m/s.

W = q/D_f = 3.437∗10^{-03} m^3/(s.m)

Now, $N_{Scg} = \frac{\mu_g}{D_g\rho_g}$ = 0.2202

where μ_g = 0.01067 cp

ρ_g = 1.863 kg/m^3

D_g = 0.26∗10^{-4} m^2/s

∴ N_g = 2.246

Liquid phase transfer unit

$N_1 = k_1a\theta_1$

$k_1a = \left(3.875\times10^8 D_1\right)^{0.5}\left(0.40Ua\rho_g^{0.5} + 0.17\right)$ eq.18-40(a),Ref:1

k_1a = 0.8 s^{-1} where D_l = diffusivity = 3.4362∗10^{-9} m^2/s

Liquid Residence time

$\theta_1 = h_l{*}A_a/1000q$ where $h_l = h_l'$= 42.6784 mm

θ_1 = 11.62 sec q = 4.6405∗10^{-3} m^3/s

A_a = 1.2632 m^2

∴ N_1 = 9.296

$$N_{og} = \frac{1}{\frac{1}{N_g} + \frac{\lambda}{N_l}}$$ (eq.18-34,Ref :1)

$\lambda = mG_m/L_m$ = 0.9889 where $\lambda = (\lambda_{top} + \lambda_{bot})/2$

m = slope of equilibrium curve at top and bottom

$\mathbf{N_{og}}$ = 1.8128

$$E_{og} = 1 - e^{-N_{og}}$$

$\mathbf{E_{og}}$ = 0.8368

b)Murphee stage efficiency :

$$N_{Pe} = \frac{z_1^2}{D_e \theta_1}$$ where $\mathbf{N_{pe}}$ = pecklet no.(eq. 18-44,Ref :1)

$\mathbf{z_1 = D_c \, Cos\,(\theta_c/2)}$ = 0.9 m

θ_1 = 11.62 sec

$\mathbf{D_e}$ = $\mathbf{6.675 * 10^{-3} Ua^{1.44} + 0.992 * 10^{-4} h_1 - 0.00512}$

= $4.5956 * 10^{-3}$ m^2/s

∴ $\mathbf{N_{Pe}}$ = 15.168

$\lambda \mathbf{E_{og}}$ = 0.8275

For $\mathbf{N_{Pe}}$ = 15.168 and $\lambda \mathbf{E_{og}}$ = 0.8275;

$$\frac{E_{mv}}{E_{og}} = 1.45$$ (from fig. 18-29;ref:1)

∴ $\mathbf{E_{mv}}$ = 1.2133

c) Overall column efficiency :

$$\mathbf{E_{oc}} = \frac{\log\{1 + E_a(\lambda - 1)\}}{\log \lambda}$$

$$\mathbf{E_a} = \frac{E_{mv}}{1 + E_{mv}\left|\frac{\psi}{1-\psi}\right|}$$

For 75% flooding and $\frac{L}{G}\left|\frac{\rho_g}{\rho_l}\right|^{0.5}$ = 0.086

Fractional entrainment, ψ = 0.027 (fig.18-22;Ref:1)

$\mathbf{E_a}$ = 1.173

$\mathbf{E_{oc}}$ = 1.174

$\mathbf{N_T}$ = No. of theoretical trays in enriching section $\mathbf{N_T}$ = 9

$$\text{Again, by definition } \mathbf{E_{oc}} = \frac{\text{Ideal no. of trays } \mathbf{(N_T)}}{\text{Actual no. of trays } \mathbf{(N_A)}}$$

∴ $\mathbf{N_A}$ = 9/1.0 = 9 trays

∴ Tower Height, $H_{(E.S)} = t_s * N_A$ = 5.4 m

∴ Total tower height (**Z**) = $(E\text{-}S)_{ht.} + (S\text{-}S)_{ht.}$

= 6.0 + 5.4

= 11.4 m

Mechanical Design of Distillation Column

(a) Shell :

Diameter = 1.5 m

Operating pressure = 1atm = $1.0329\ kg/cm^2$

Design pressure = 1.1 * operating pressure = 1.1 * 1.0329

= $1.1362\ kg/cm^2$

Operating temperature = 118.1°C

Design Temperature = 1.1 *118.1 = 129.91°C

Shell material	Stainless steel (04 Cr19Ni09)
Shell	Double welded bolt joints stress relieved
Skirt height	2 m
Tray spacing	600 mm
Top Disengaging Space	600 mm
Bottom separator space	1 m
Allowable stress for shell material	1420 Kg/cm^2
Insulation material	Asbestos

Insulation thickness	50.8 mm
Density of Insulation	270 Kg/m^3

(b) Head: Torospherical dished head.

Material	Stainless Steel (04 Cr19Ni09)
Allowable tensile stress	1420 kg/cm^2

(c) Skirt support

Height	2m
Material	Stainless steel (04 Cr19Ni09)

(d) Nozzles (Number of Nozzles =5)

(e) Trays – Sieve type

Number of trays	16
Spacing	600 mm
Hole diameter	10 mm
Thickness	6 mm
Weir height	50 mm
Material for trays down comers weirs	Stainless steel.

(1) Calculations of shell thickness :

Considering the vessel as an internal pressure vessel.

$$t_s = \frac{PD_i}{2fJ-P} + C$$ (Ref: 4, p:13, eq:3.1)

t_s = Thickness of shell (mm)

P = Design pressure (kg/cm^2) = 1.1362 kg/cm^2

D_i = Diameter of the shell (mm) = 1500 mm

f = Allowable /permissible tensile stress (kg/cm^2) = 1420 kg/cm^2

C = Corrosion allowance (mm) = 3 mm

J = Joint Efficiency.

Considering double welded butt joints with backing strip

J = 85% = 0.85

$$t_s = \frac{1.1362 \times 1500}{2(1420 \times 0.85) - 1.1362} + 3 = \underline{3.7063 \text{ mm}}$$

Taking the thickness of the shell as $\underline{t_s = 6 \text{ mm}}$

(2) Head shallow dished & torospherical head.

$$t_h = \frac{P R_c W}{2fJ}$$ (Ref: 3, Pg: 238)

R_c = Crown radius = outer diameter of the shell = 1.512 = $\underline{1512 \text{ mm}}$

R_k= knuckle radius = $\underline{0.06 R_c}$

W= Stress intensification factor

$$W = \frac{1}{4}\left[3 + \sqrt{\frac{R_c}{R_k}}\right] = \frac{1}{4}\left[3 + \sqrt{\frac{R_c}{0.06 R_c}}\right] = 1.7706$$

$$t_h = \frac{1.1362 \times 1500 \times 1.7706}{2 \times 1420 \times 0.85} = \underline{1.26 \text{ mm}}$$

Thickness of head is t_h = $\underline{6\text{mm}}$ = 0.236 inches

Weight of head:

$$\text{Diameter} = OD + \frac{OD}{24} + 2S_f + \frac{2}{3} i_{cr}$$ (Ref: 6, pg:88, eq: 5-12)

OD = outside diameter of shell = 1512mm = 59.055(inches)

i_{cr} = inside cover radius = 1.25 inches } (Ref: 6, table 5.7, pg:88)

S_f = straight flange length = 1.0 inches

$$\text{Diameter} = 59 + \frac{59}{24} + 2\ (1.0) + \frac{2}{3}(1.25)$$

Diameter (d) = 64.3489 inches

$$\text{Weight of head} = \frac{\pi}{4}(1.6344)^2 (6 \times 10^{-3}) \times 7800$$

$$= \underline{98.8\ \text{kg}}$$ (Ref:3, pg: 325)

(3) Calculation of stresses:

(i) Axial tensile stress due to pressure (Ref : 3, pg :293)

$$f_{ap} = \frac{P_{di}}{4(t_s - c)} = \frac{1.1362 \times 1500}{4\ (6-3)} = \underline{142.025\ \text{Kg/cm}^2}$$

This is same throughout the column height

(ii) Circumferential stress :

$$2\ f_{ap} = 2 \times 142.025 = \underline{284.05\ \text{Kg/cm}^2}$$

(iii) Compressive stress due to dead loads:

(a) Compressive stress due to weight of shell up to a distance x metre.

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

$$f_{ds} = \frac{(\pi/4)\ (D^2o - Di^2)\rho_S\ x}{(\pi/4)\ (Do^2 - Di^2)}$$

Di & Do - Internal & external diameters of shell

ρ_S - density of shell.

Also,

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

D_m = Mean diameter of the shell (cm)

t_s = thickness of the shell (cm)

C = Corrosion allowance (cm)

$f_{ds} = \rho_S\ (x)$

ρ_S = 7850 kg/m^3

$= 0.00785 \quad kg/cm^3$

$f_{ds} = 0.7850(x) \quad kg/cm^2$

(b) Compressive stress due to weight of insulation at height (x) m

$$f_{d(ins)} = \frac{\pi D_{ins} t_{ins} \rho_{ins} (x)}{\pi D_m (t_s - c)} \qquad \text{(Ref: 3, pg: 293)}$$

D_{ins} = Diameter of insulation

t_{ins} = Thickness of insulation

ρ_{ins} = Density of insulation

D_m = Mean diameter of shell

$$= \frac{[\, Dc + (\, Dc+2\, t_s\,)]}{2}$$

<u>Assume</u> : asbestos is the insulation material.

$\rho_{ins} = 270\ kg/cm^3 = 0.00027\ kg/cm^3$

$t_{ins} = 50.8\ mm \quad = 5.08cm$

$D_{ins} = Dc + 2\, t_s + 2t_{ins}$

$D_{ins} = 1500 + 2(6) + 2(50.8) = \underline{1613.6\ mm} = \underline{161.36cm}$

$$D_m = \frac{1500 + (1512)}{2} = \underline{1506mm} = \underline{150.6cm}$$

$$f_d(ins) = \frac{\pi\, (150.6)\, 5.08 \times 0.00027\, (x)}{\pi\, (150.6)\, (0.6 - 0.3)}$$

$= 0.48986\, (x) \quad kg/cm^2$

(c) Compressive stress due to liquid & tray in the column up to height (x) m.

Liquid & tray weight fox height (x)

$$F_{liq} = \left[\frac{(x - \text{top disengaging space})}{\text{Tray spacing}}\right] + 1 \quad \frac{\pi Di^2}{4} \times \rho_{liquid} \qquad \text{(Ref: 3, pg :294)}$$

$$= \left[\frac{x - 0.6}{0.6}\right] + 1 \quad \frac{\pi\, (1.5)^2}{4} \times 957.15$$

$F_{liq} = \underline{2819.095\ (x)\ \ kg.}$

$f_d(liq) = \dfrac{F_{liq}}{\pi D_m(t_s - c)}$ (Ref :3, pg:294)

$= \dfrac{2819.095\ (x)}{\pi(150.6)(0.6-0.3)} = \underline{1.986\ (x)\ \ kg/cm^2}$

(d) Tensile stress due to wind loads in self supporting vessel

$f_{wx} = \dfrac{M_w}{z}$ (Ref :3; pg; 295)

M_w = bending moment due to wind load

$= \dfrac{\text{wind load x distance}}{2}$

$= \dfrac{0.7\ P_w\ D_m\ x^2}{2}$ (Ref: 3; pg: 295)

z=modulus for the area of shell = $\dfrac{\pi}{4} D_m^2 (t_s - c)$ (Ref : 3, pg: 295)

$z = \dfrac{\pi}{4} \underline{(2.306)^2}\ \underline{(0.006 - 0.002)} = \underline{0.00534}$

$f_{wx} = \dfrac{0.7\ P_w D_m\ x^2}{2\ \dfrac{\pi}{4} D_m^2 (t_s - c)} = \dfrac{1.4\ Pw\ \ x^2}{\pi D_m (t_s - c)}$

P_w = wind pressure

P_w = 26.625 lb/ft^2 (Ref: 6, pg:159, table :9.1)

= $\underline{130.0\ kg/m^2}$

$M_w = \dfrac{(0.7 \times 130 \times 1.506)\ (x^2)}{2} = 68.523\ x^2$

$f_{wx} = \dfrac{68.523x^2}{0.00534} = 8056x^2\ \ kg/m^2\ . = 0.8056\ x^2\ kg/cm^2$

Stresses due to seismic load are neglected.

Calculations of resultant longitudinal stress (upwind side)

Tensile:

$f_{t,max} = f_{wx} + f_{ap} - f_{ds}$ (Ref: 3, pg:293)

f_{wx} = Stress due to wind load.

f_{ap} = Axial tensile stress due to pressure

f_{ds} = Stress due to dead loads.

$f_{t,max} = 0.8056x^2 + 142.025 - 0.785x$

$f_{t,max} = fJ$

f = allowable stress = 1420 kg/cm^2

J= Joint factor = 0.85

$\therefore f_{t,max} = 1420\,(0.85) = \underline{1207 \text{ kg/cm}^2}$

$0.8056\,x^2 - 0.785x + 142.025 = 1207$

$0.8056\,x^2 - 0.785x - 1064.975 = 0$

Solving by trial and error,

x = $\underline{36.85\text{m}}$

Calculation of resultant longitudinal stress (downwind side) (compressive) :

$f_{c,max} = f_{wx} - f_{ap} + f_{ds}$

$f_{c,max} = 0.8056x^2 - 142.025 + 0.785x$

x = $\underline{40.44\text{m}}$

$(f_{c,max})_x = 1207.19$ Kg/cm^2 ($\therefore$Compressive)

$\therefore f_{c,max} = 0.105\,E \left(\frac{t}{D_o}\right)$ (Ref: 5, pg: 159)

E= Elastic modulus = 2.0389×10^6 kg/cm^2

t = Shell thickness = 6mm.

D_o = 1512 mm

$$f_{c,max} = 0.105 \times 2\times10^6 \left(\frac{6}{1512}\right) = \underline{426.46 \text{ kg/cm}^2}$$

Consider, $426.46 = 0.8056\, x^2 - 142.025 + 0.785\, x$

$0.8056\, x^2 + 0.785x - 568.485 = 0$

Solving by trial and error,

$x = \underline{26.09m}$

Since calculated height is greater than the actual tower height. So we conclude that the design is safe and thus design calculations are acceptable.

∴ A thickness of 6mm is sufficient throughout the length of the shell.

Design of skirt support :

Total height of column including skirt height (H) = 11.4 + 2 + 0.375

= 13.775m

Minimum weight of vessel (W_{min}) = $\pi(D_i+t_s)t_s$ (H-skirt height)ρ_s + 2 (2670)

(Ref: 5 ; pg:167)

D_i = diameter of shell = 1.5 m

t_s = 0.006 m

ρ_s = Density of material

$W_{min} = \pi\,(1.5 + 0.006)\, 0.006\, (13.775-2)\, 7850 + 2(98.8)$

= 2821.55kg.

Maximum weight of column (W_{max}) = $W_S + W_i + W_l + W_a$ (Ref: 5, pg: 167)

W_s = weight of shell during test = 2540.39 kgs

W_i = weight of insulation $= \frac{\pi}{4}\,(d^2_{ins} - d^2_o)\, H\, \rho_{ins}$

$= \frac{\pi}{4}\{ 1.6136^2 - 1.512^2\}\, 13.775(270)$

= 927.62 kgs

W_e = weight of water during test = $\frac{\pi}{4} Di^2\, (H-4)\, \rho_{water}$

$= \frac{\pi}{4}(2.3)\,(13.775-2)\, 1000$

= 21270.54kgs

Wa = weight of attachments = 443.175 kgs

W_{max} = 2540.39+ 927.62 + 21270.54 + 443.175 = <u>25181.72kgs</u>

Period of vibration at minimum dead weight

$$T_{min} = 6.35 \times 10^{-5} \left(\frac{H}{D}\right)^{3/2} \left(\frac{W_{min}}{t_s}\right)^{1/2}$$

$$= 6.35 \times 10^{-5} \left\{\frac{11.40}{1.5}\right\}^{3/2} \left\{\frac{2821.55}{0.006}\right\}^{1/2}$$

$$= \underline{0.9123\ s}$$

∴ K_2 = a coefficient to determine wind load =2 (Ref: 5, pg:147)

Period of vibration at maximum dead weight

$$T_{max} = 6.35 \times 10^{-5} \left(\frac{H}{D}\right)^{3/2} \left(\frac{W_{max}}{t_s}\right)^{1/2}$$

$$= 6.35 \times 10^{-5} \left(\frac{11.4}{1.5}\right)^{3/2} \left\{\frac{25181.72}{0.006}\right\}^{1/2}$$

$$= \underline{2.725\ s}$$

∴ k_2 =2

Total load due to wind acting on the bottom & upper part of vessel

$P_W = k_1\ k_2\ P_w\ HD$ (Ref: 5, pg: 168)

K_1 = coefficient depending upon safe factor

= 0.70 (for cylindrical surface)

P_W = wind load

p_w = wind pressure = 1000 N/m^2 = 100 kg/m^2

For minimum weight condition D = D_i = <u>1.5 m</u>

For maximum weight condition D =D_{ms} = <u>1.6136 m</u>

∴ $(P_W)_{min}$ = 0.7 x 2 x 100 x 13.775 x 1.5

<u>= 2892.75 kg</u>

$(P_{W})_{max}$ = 0.7 x 2 x 100 x 13.775 x 1.6136

= 3111.825 kg

Minimum & maximum wind moments

$$(M_W)_{min} = (P_W)_{min} \times \frac{H}{2} = 2892.75 \times \frac{13.75}{2} = 19923.81 \text{ kg-m}$$

$$(M_W)_{max} = (P_W)_{min} \times \frac{H}{2} = 8499.2 \times \frac{24.66}{2} = 21432.69 \text{ kg.m}$$

As the thickness of the skirt is expected to be small, assume $D_i \simeq D_o$ = 1.5 m

$$f_{zwm}(min) = \frac{4 M_{W(min)}}{\pi D^2 t} = \frac{4 \times 19923.81}{3.14 \times 1.5^2 \times t} = \frac{11274.57}{t} \text{ kg/m}^2$$

f_{ZWM} = stress due to wind moment at the base of the skirt.

$$f_{zwm}(max) = \frac{4 M_{W(max)}}{\pi D^2 t} = \frac{4 \times 21432.69}{3.14 \times 1.5^2 \times t} = \frac{12128.42}{t} \text{ kg/m}^2$$

Minimum and Maximum dead load stresses.

$$f_{ZW}(min) = \frac{W_{min}}{\pi D t} = \frac{2821.55}{\pi(1.5)t} = \frac{598.75}{t} \text{ kg/m}^2$$

$$f_{ZW}(max) = \frac{W_{max}}{\pi D t} = \frac{25181.72}{\pi(1.5)t} = \frac{5343.72}{t} \text{ kg/m}^2$$

Maximum tensile stress without any eccentric load is computed as follows :

(tensile) $f_z = f_{Zwm}(min) = f_{Zw}(min)$

$f_Z = f J$

$$142 \times 10^5 \times 0.85 = \frac{(11274.57 - 598.75)}{t}$$

t= 0.8844×10^{-3} m = 0.884 mm

Maximum Compressive load :

Compressive : $f_Z = f_{Zwm}(max) + f_{Zw}(max)$

$$f_Z = 0.125 \frac{E\ t}{D_o}$$

t = 0.01mm

As per IS:2825-1969, minimum corroded skirt thickness is 7mm, providing 1mm corrosion allowance, a standard 8mm thick plate can be used for skirt.

Design of skirt-bearing plate:

Maximum compressive stress between bearing plate & foundation :

$$fc = \frac{Wmax}{A} + \frac{Mw(max)}{Z}$$

$A=\pi\ (Do-l)l$

L=Outer radius of bearing plate-Outer radius of skirt

$z=\pi\ R_m^2 l$

$R_m= (Do-l)/2$

$A=\pi\ (1.512 - l)l$

$R_m=(1.512-l)/2$

$Z = (\pi(1.512-l)^2 l)/4$

$fc = 25181.72/\pi(1.512-l)l + (21432.69 \times 4)/(\pi(1.512-l)^2 l$

Allowable compressive strength of concrete foundation varies from 5.5-9.5 MN/m^2

assume : $fc=5.5x10^5\ Kg/m^2$

i.e. $5.5 \times 10^5 = 25181.72/\pi(1.512-l)l + (21432.69 \times 4)/(\pi(1.512-l)^2 l$

By trail and error lc =0.0325m

∴ 32.5 mm is the width of the bearing plate.

Thickness of bearing plate $t_{bp} = l\sqrt{3fc/f}$

f_c=maximum compressive load at l=0.0325m

$f_c=0.55\times10^6$ Kg/m^2

$t_{bp}=32.5(3\times0.55\times10^6/142\times10^5)^{0.5}$ = 11.07 mm

Bearing plate thickness of 12 mm is required. As the plate thickness required is smaller than 20mm, gussets are not required to reinforce the plate.

Minimum stress between the bearing plate & the concrete foundation.

$f_{min} = (wmin /A)-(M_{w(min)})/z$ = - 39871.3089 Kg/m^2

$\therefore$ f_{min} is -ve, the vessel must be anchored to the concrete foundation by means of anchor bolts to present overturning owing to the bending moment induced by the wind load.

Approximate value of load on the bolts is given by,

P_{bolt} n = f_{min} x A (Ref:5 pg:166)

P_{bolt} = load on one – anchor bolt.

n= number of anchor bolts.

A=Area of contact between bearing plate & foundation.

$= \pi(D_o-t_{bp})t_{bp}$

P_{bolt} x n=+ (70469.11) 3.14 (1.512-0.0325) (0.0325)

=10639.63 Kg

If hot rolled Carbon Steel is selected for bolts

f = 57.3 MN/m (Ref:5 Pg:108)

= 58.409×10^5 Kg/m^2

$(a_r\ n)\ f = n\ P_{bolt}$ (Ref:5, pg:171)

$$a_r\ n = \frac{10639.63}{58.409\times10^5} = 1.8215\times10^{-03}\ m^2 = 182.15\ mm^2$$

a_r = root area of bolts

For M12 x 1.5 bolts,

$a_r = 0.63 \times 10^{-4}\ m^2$ (Ref:5, pg:122)

$$n = \frac{1.8215 \times 10^{-3}}{0.63 \times 10^{-4}}$$

n = 28.91

i.e The number of bolts required is 32, as always used in multiple of fours.

MINOR EQUIPMENT DESIGN - CONDENSER

Process Design

(I) Preliminary Calculations:

(a) Heat Balance:

Mass flow rate of vapor (m) = 6250 kg/hr

= 1.736 kg/s

Vapor Feed Inlet Temperature (T_s) = 117.87°C

Condensate outlet temperature = 117.87°C

∴Average Temperature = 117.87°C

Latent heat of vaporisation (λ) = 394.5 KJ/kg

$Q_h = m * \lambda$ where Q_h = heat transfer by the hot fluid

$Q_h = 1.76 * 394.5 = 684.852$ KJ/s

$Q_c = m_c * C_p * \Delta T$ = heat transfer by the cold fluid.

Assume : $Q_h = Q_c$

Inlet temperature of water, $t_1 = 25\ ^0C$.

Let the water be treated water.

∴ Outlet temperature of water, t_2 (maximum) = 45^0C

∴ $\Delta t = t_2 - t_1 = 45 - 25 = 20^0C$

Cp = 4.817 KJ/kg°k

$m_c = 7.898$ kg/s

(b) LMTD Calculations:

assume : counter current

$$LMTD = \frac{(T_s - t_2) - (T_s - t_1)}{\ln \frac{(T_s - t_2)}{(T_s - t_1)}}$$

$T_s = 64.6°C$; $t_1 = 25°C$; $t_2 = 40°C$

$\therefore$ **LMTD = 81.54°C**

(C) Routing of fluids :

Vapors - Shell side

Liquid - Tube side

(D) Heat Transfer Area:

(i) $q_h = q_C = U * A * (\Delta T)_{LMTD,corrected}$

U = Overall heat transfer coefficient ($W/m^{2\circ}k$)

Assume : $U = 567.83\ W/m^{2\circ}k$

$\therefore A_{(assumed)} = 14.79\ m^2$

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

Outer diameter of pipe (D_o) **= 1.25" = 0.03175 m**

Inner diameter of pipe (D_i) **= 1.01" = 0.02566 m**

Let, length of tube (L) = 16 ft. = 4.877m

Now, $A_{(assumed)} = N_t * \pi * Do * L$ **where** N_t **= Number of tubes**

$\therefore N_t = 31$ **tubes**

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

Choose TEMA : P or S,1.25" OD tubes in 29/16" Δ^{lar} **pitch**

1 - 1	Horizontal Condenser

$\therefore$ **N_p = 1**

$\therefore$ **N_{tubes} (Corrected) = 33**

Shell Diameter (D_s)= 0.305 m

$\therefore$ **$A_{corrected}$ = 16.063 m^2**

$\therefore$ **$U_{corrected}$ = 522.87 W/m^2K**

(II) Film Transfer Coefficient:

a) Shell Side - Distillate

T_{wall} = 0.5$*$[Ts +(t_1 + t_2)/2] **= 349.93°k**

T_{film} = (T_s + T_w)/2 **= 370.4°k**

Properties are evaluated at T_{film} :

T_{film} at 97.4°C, ρ = density = 1049.28 kg/m^3

μ_l = viscosity = 0.48 cp

C_p = specific heat = 2.323 kJ/kg°k

k = thermal conductivity =0.1713 W/m°k

Reynold's number $(N_{Re})_s$ **=** $$\frac{4 \times \text{Mass flow rate of condensate}}{\mu \times N_t^{2/3} \times \text{Length of tube}}$$

$(N_{Re})_s$ **= 288.14**

For Horizontal condenser :

$$(Nu)_s = \frac{1.51\{(D_o)^3(\rho)^2 g\}^{1/3}(Re)^{-1/3}}{\mu^2} = 261.72$$

Also,

$$(Nu)_s = \frac{h_o (D_o)}{k}$$

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

k = Thermal conductivity of liquid.

$\therefore h_o = \frac{180.6\ (0.121}{0.0191} = 1412.05\ W/m^2K$

b) Tube Side - Water

Properties are evaluated at 36°C

K = Thermal conductivity = 0.578 W/m°K

μ **= Viscosity = 0.75 cp.**

ρ **= Density = 993.68 kg/m^3**

c_p **= Heat capacity = 4.187 KJ/kg°K**

$$a_t = \frac{\pi * D_i^2 * N_t}{4 * N_p} = 0.01705\ m^2$$

$G_t = m_c/a_t = 7.898/0.01705 = 463.168\ kg/m^2s$

$(N_{Re})_t = (G_t * D_i/\mu) = 15840$

$(N_{Pr})_t = (\mu C_p/k) = 5.43$

$$Nu = \frac{hi\ (D_i)}{k} = 0.023*(Re)^{0.8} * (Pr)^{0.3} = 87.49$$

h_i **= inside heat transfer coefficient**

$h_i = 1971.57\ W/m^2K$

Fouling factor =(Dirt –coefficient) = 0.528$*10^{-3}$ W/m^2°k

Ref :1 , p :10-44, t:10-10]

$$\frac{1}{U_{0d}} = \frac{1}{h_o} + \frac{(D_o)}{(D_i)} * \frac{1}{h_i} + \text{Fouling factor}$$

U_{od} **= design overall heat–transfer coefficient**

$U_{0d} = 536.47\ W/m^{2\circ}K$

$U_{0d} > U_{assumed}$ **,this design is permissible.**

(III) PRESSURE DROP CALCULATION :

a)Shell side:(ΔP)$_s$ Kern's method

a_s = (I.D)*C'*B/P_T

where

I.D. = inner dia of shell = D_s

Baffle spacing (B) = D_s = 0.305 m

C' = clearance between tubes = 1.5625 – 1.25 = 0.03968 m

P_T = pitch = 0.03968 m

a_s = 0.0186 m^2

$D_e = 4\{(P_T/2 * 0.86 P_T) - (0.5\pi D_0^2/4)\}/(0.5*\pi D_o)$

= 0.02255 m

G_s = (m/a_s) **= Superficial velocity in shell**

= 93.333 kg/m^{2}s

$(N_{Re})_s = \frac{G_s D_e}{\mu_{vap}}$ **= 140310**

f = $1.87*(N_{Re})^{-0.2}$ = 0.1747

N_b+1 = L/B = 16

$(\Delta P)_s = 0.5*[4*f*(N_b + 1)D_s*G_s^2]/(2gD_e*\rho_{vapor})$

= 10.9875 kPa < 14 kPa which is well within permissible limit

b)TUBE SIDE : (ΔP)$_t$

N_{Re} = 15840

f = $0.079*(N_{Re})^{-1/4}$ **= 0.007041**

$(\Delta P)_{total} = (\Delta P)_L + (\Delta P)_e$

$(\Delta P)_L = 4(f*L*V_t^2*\rho_f*g)/(2gD_i) = 2(f*L*G_t^2)/(D_i\rho_f)$

where L = length

f = friction factor = 0.007041

D_i = inner dia of tube = 4.887 m

ρ_f = density of fluid in tube = 993.68 kg/m^3

$V_t*\rho_f = G_t$ = superficial velocity in tube

$(\Delta P)_L$ **= 578.39 Pa**

$(\Delta P)_e$ **= $2.5*G_t^2/(2*\rho_f)$ = 269.861 Pa**

$(\Delta P)_{total}$ = 578.39 + 269.861

= 848.251 Pa which is very less than permissible, therefore design is permitted.

Mechanical Design

(a) Shell Side:

Material stainless steel (304 Cr19 Ni09) (Corrosion allowance = 3mm)

Number of shells = 1

Number of passes = 1

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 = 117.87° C

Temperature of the outlet = 117.87°C

Permissible Strength for

Stainless steel = 140 N/mm^2 [Ref : 4, p: 118]

b) Tube side :

Number of tubes = 33

Outside diameter = 0.03175 m

Inside diameter = 0.02565 m

Length = 4.877 m

Pitch, $\triangle^{lar}$ = 0.03968 m

Feed = Water

Working Pressure = 1 atm = 0.101 N/ mm^2

Design Pressure = 0.11 N/mm^2

Inlet temperature = 25°C.

Outlet temperature = 45°C

Shell Side:

$t_s = \frac{PD_i}{2fJ-P}$ [Ref:4, pg:13, eq : 3-1]

t_s = Shell thickness

P = design pressure =0.11 N/ mm^2

Di = Inner diameter of shell = 0.305 m = 305 mm

f = Allowable stress value = 140 N/mm^2

J = Joint factor = 0.85

$t_s = \frac{0.11 * 305}{2*140(0.85)-0.11}$ = 0.141 mm

Minimum thickness = 6.3 mm (Including corrosion allowance)

∴ t_s = 8 mm

Head : (Torrispherical head)

$t_h = \frac{PR_CW}{2fJ}$ [Ref –3 ; pg: 238]

t_h = thickness of head

$W = ¼ \{3+ \sqrt{R_c/R_k}\}$

R_c = Crown radius = outer diameter of shell = 305 mm

R_k = knuckle radius = 0.06 R_C

∴W = ¼ {3+$(R_c/0.06R_c)^{1/2}$ } = 1.77

∴ $t_h = \frac{0.11 *305 *1.77}{2 *140* 0.85}$ = 0.249 mm

Minimum shell thickness should be = 10 mm (Ref .7)

∴ t_h = 10 mm

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 = 305 mm

Shell side thickness = 10mm (for head)

Outside diameter of shell = 305 + 10* 2 = 325 mm

<u>Determination of gasket width :</u>

$$\frac{d_o}{d_i} = \left[\frac{y - pm}{y - p(m+1)}\right]^{1/2}$$ (Ref :6 Pg:227)

y = Yield stress

m = gasket factor

Gasket material chosen is asbestos with a suitable binder for the operating conditions.

Thickness = 10 mm

m = 2.75

y = 2.60 * 9.81 = 25.5 N/mm^2

$$\frac{d_o}{d_i} = \left[\frac{25.5-0.11(2.75)}{25.5-0.11(2.75+1)}\right]^{1/2} = 1.0002$$

d_i = inside diameter of gasket = outside diameter of shell

= 325 + 5 mm

= 330 mm

d_o = outside diameter of the gasket

= 1.002 (330)

= 332 mm

Minimum gasket width = $\frac{0.332 - 0.330}{2}$ = 0.001 m = 1 mm

But minimum gasket width = 10 mm

∴ G = 0.33 + 2 (0.01) = 0.35 m

G = diameter at the location of gasket load reaction

<u>Calculation of minimum bolting area</u> :

Minimum bolting area(A_m) = $A_g = \frac{W_g}{S_g}$ [Ref: 4, pg :45]

S_g = Tensile strength of bolt material (MN/m^2)

W_g = load to seat gasket under bolting condition

Consider , 5% Cr-Mo steel, as design material for bolt

At 97.4°C,

$S_g = 138 * 10^6$ N/m^2 [Ref: 6, pg :108]

$W_g = \pi(G\ b\ y) = \pi(0.35 * 0.005 * 25.5 * 10^6 = 0.1401 * 10^6$ [Ref: 4, pg :45

$A_m = \frac{0.1404 * 10^6}{138 * 10^6}$ = $1.0159 * 10^{-3}\ m^2$

<u>Calculation for optimum bolt size :</u>

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

g_l = thickness of the hub at the back of the flange

g_o = thickness of the hub at the small end = 10 + 1 = 11 mm

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) [Ref: 6, pg :122]

C= 0.305 + 2 (1.415 (0.011) + 0.027) = 0.3901 m

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

Load due to design pressure (H) = $\frac{\pi}{4} G^2 P$ [Ref: 4, pg :44]

H = $\frac{\pi}{4}$ * $(0.342)^2$*(0.11*10^6) = 0.010104 *10^6 N

Load to keep the joint tight under operating conditions.

$H_p = \pi$ g (2b) m p [Ref: 4, pg :45]

b= Gasket width = 6mm = 0.006m

$H_p = \pi$ (0.342) (2 x 0.005) 2.75 *0.11 * 10^6 = 0.00325* 10^6 N

Total operating load (W_o) = H+H_p

= 0.013354* 10^6 N

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

W_g. = π g b y = 0.14019 *10^6 N [Ref: 4, pg :45]

W_g = 0.6037 x 10^6 N

$W_g > W_0$

∴ W_g is the controlling load

∴ Controlling load = 0.14019 *10^6 N

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

= 0.3901 + 0.018+ 0.02

= 0.3471 m

Check for gasket width :

A_b = minimum bolt area = 24 x 1.54 x 10^{-4} m^2

$\frac{A_b S_g}{\pi GN} = \frac{(24 \times 1.54 \times 10^{-4})138}{\pi * 0.342 * 0.01}$ = 47.4717 N/mm^2 [Ref: 6, pg :123]

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 : [Ref: 4, pg :113]

$W_{Q} = W_1 + W_2 + W_3$

$W_1 = \frac{\pi}{4} B^2 P$ = 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 = 0.325 m

$W_1 = \frac{\pi}{4} (0.325)^2 * 0.11 * 10^6 = 0.009125 * 10^6$ N

$W_2 = H - W_1 = (0.010104 - 0.009125) * 10^6 = 0.000979 * 10^6$ N

$W_3 = 0.00325 * 10^6$ N

$W_o = (0.009125 + 0.000979 + 0.00325) * 10^6$

$= \underline{0.013354 * 10^6}$ N

M_o = Total flange moment = $W_1 a_1 + W_2 a_2 + W_3 a_3$ [Ref: 4, pg :53]

$a_1 = \frac{C - B}{2}$; $a_2 = \frac{a_1 + a_3}{2}$; $a_3 = \frac{C - G}{2}$ [Ref: 4, pg :55]

C=0.3901 m; B=0.325 m; G=0.342 m

$a_1 = \frac{0.3901 - 0.325}{2} = 0.0325$ m

$a_3 = \frac{C - G}{2} = \frac{0.3901 - 0.342}{2} = 0.02405$ m

$a_2 = \frac{a_1 + a_3}{2} = \frac{0.0345 + 0.026}{2} = 0.02827$ m

$\therefore M_o = \underline{0.4024 * 10^3}$ J

(b) For bolting up condition :

M_g = Total bolting Moment = $W * a_3$ [Ref: 4, pg :56, eq: 4.6]

$W = \frac{(A_m + A_b)}{2} S_g$. [Ref: 4, pg :56, eq: 4.6]

$A_m = 1.0159 * 10^{-3}$ m^2

$A_b = 24 * 1.5\ 4 * 10^{-4} = 36.96 * 10^{-4}$ m^2

$S_g = 138 * 10^6$ N/ m^2

W= $0.2961*10^6$ N

$M_g = 0.2961* 10^6 * 0.02405 = \underline{0.007121 * 10^6 \text{ J}}$

$\therefore \quad \underline{M_g > M_o}$

$\therefore$ M_g is the moment under operating conditions

$\therefore$ M= M_g = $0.007121* 10^6$ J

Calculation of the flange thickness:

$$t^2 = \frac{MC_FY}{BS_{FO}}$$ [Ref: 6, eq:7.6.12]

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

B_s = Bolt spacing = $\frac{\pi C}{n} = \frac{\pi(0.3901)}{24}$ = 0.003639 m

n= number of bolts.

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

$S_{FO} = 100 * 10^6$ N (Ref : 6, pg : 24)

M = $0.0071 * 10^6$ J

B = 0.325 m

$K = \frac{A}{B} = \frac{\text{Flange diameter}}{\text{Inner Shell diameter}} = \frac{0.3471}{0.325} = 1.068$

Y = 31 (Ref : 6, pg : 115, fig:7.6).

$$t = \frac{(0.0071 * 10^6 *1 * 31 \}^{0.5}}{(0.325 *100 * 10^6)^{0.5}} = \underline{0.0824 \text{ m}}$$

d = 18 * 2 = 36 mm

$$C_F = \sqrt{\frac{0.05106}{2(36 \times 10^{-3}) + 0.0824}} = \underline{0.575}$$

$C_F = (0.7582)^2$

t = 0.0824*0.7582 = $\underline{0.0624 \text{ m}}$

Let t = 60mm = $\underline{0.06\text{m}}$

Tube sheet thickness : (Cylindrical Shell) .

$T_{1s} = G_c \sqrt{KP / f}$ (Ref :3, 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.

$t_{1s} = 0.342 \sqrt{(0.25 * 0.11 * 10^6) / (140 * 10^6)}$ = 0.00479 m

Channel and channel Cover

$t_h = G_c (KP0/f)^{0.5}$ (K = 0.3 for ring type gasket)

$= 0.342 (0.3 * 0.11*10^6/ 95*10^6)^{0.5}$

= 0.00479 m = 4.79 mm

Consider corrosion allowance = 4 mm

t_h = 0.004 + 0.00479 = 0.00879 m

Saddle support

Material: Stainless steel

Total length of shell: 4.877 m

Diameter of shell: 325 mm

Knuckle radius = 0.06 *0.325 = 0.0195 m = r_o

Total depth of head (H) = $(D_o r_o/2)^{0.5}$ = (0.32

Weight of the shell and its contents = 78.99 kg = W

R=D/2=0.1625 mm

Distance of saddle center line from shell end = A =0.5R = 0.1625 m

Longitudinal Bending Moment

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

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

= 78.99 (4.88 + 4 *.0562/3)/2

= 195.69 kg m

M_1 = 195.69*0.08125*0.02759

= 0.4388 kg-m

<u>Bending moment at center of the span</u>

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

M_2 =235.59 kg-m

<u>Stresses in shell at the saddle</u>

(a) At the topmost fibre of the cross section

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

$= 0.4308/(3.14 * 0.1625^2 * 0.008)$

= 0.066118 kg/cm^2

The stresses are well within the permissible values.

Stress in the shell at mid point

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

= 35.498 kg/cm^2

Axial stress in the shell due to internal pressure

f_p= PD/4t

$= 0.11 \times 10^6 *0.305 /(4 * 0.008)$

= 104.8 kg/cm^2

$f_2 + f_p$ = 140.298 kg/cm^2

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