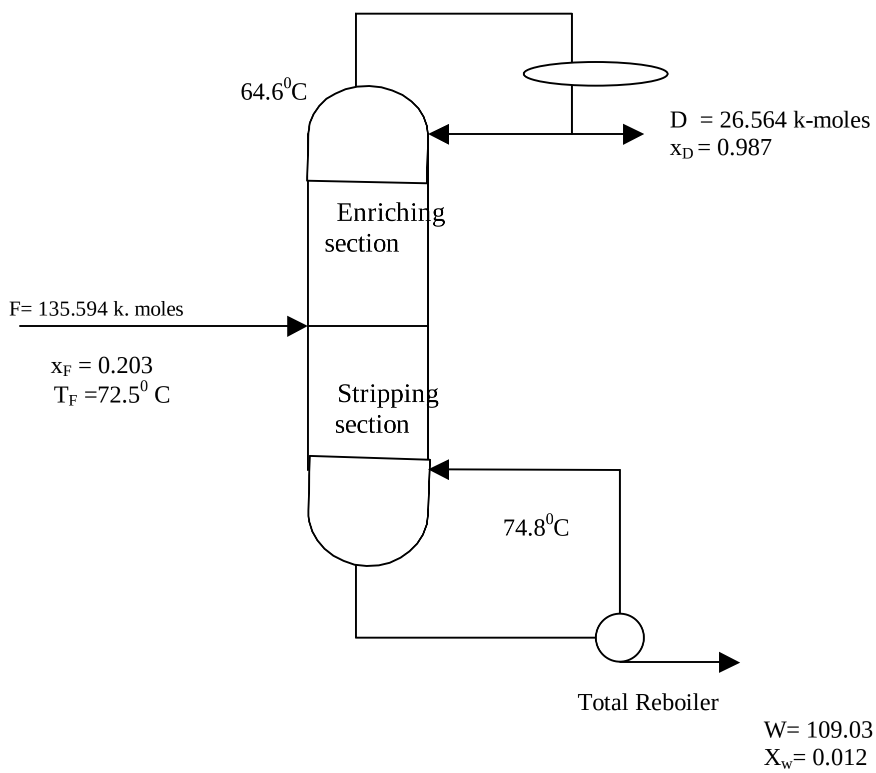
CHAPTER -6

MAJOR EQUIPMENT

DISTILLATION COLUMN:



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 iso-butyraldehyde in liquid

x_D = mole fraction of iso-butyraldehyde in distillate

x_W = mole fraction of iso-butyraldehyde in residue

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

$\bar{L}$ = molar flow rate of liquid in stripping section, kmol/hr

$\bar{G}$ = molar flow rate of vapor in stripping section, kmol/hr

$\bar{M}$ = average molecular weight of feed, kg/kmol
q = Thermal condition of feed

Feed = Saturated liquid at boiling point .

$\bar{M}$ = 72.11

$$\frac{x_D}{R_m+1} = 0.077$$

$$R_m+1 = \frac{x_D}{0.077} = \frac{0.987}{0.077} = 12.82$$

R_m = 12.82 – 1.00 = <u>11.82</u>

R= 1.5 R_m =<u>17.73</u> k-moles

$$\frac{x_D}{R+1} = \frac{0.987}{17.73+1} = 0.053$$

Number of trays from graph =32

L = RD = 17.73 (26.564) = <u>470.98</u> K-moles

G =L+D = 470.98+26.564 = <u>497.544</u> K-moles

q=1 (Feed is saturated liquid)

$\bar{L}$ = L+qf = 470.98+ 1(135.594) = <u>606.574</u> K-moles

$\bar{G}$ = G+(q –1) F = 497.544 +0 = <u>497.544</u> K-moles

PLATE HYDRAULICS :

(A) ENRICHING SECTION:

(1) Tray spacing (t_s) =18” = 457.2mm

(2) Hole diameter (d_h) =5mm

(3) Pitch (l_p) =3d_h = 3x 5 =15mm

$\triangle^{lar}$ pitch

(4) Tray thickness (t_T) =0.6 d_h = 3mm

(5) $\frac{A_h}{A_p}$ = $\frac{\text{Area of hole}}{\text{Area of pitch}}$ = 0.10

(6) Plate diameter (D_c) :

$(L/G)(\rho_g/\rho_L)^{0.5} = 0.056$ (maximum at top)

∴ Flooding check at top

(Ref :1, p: 18-7, fig :18-10)

$C_{sb,flood}$ = 0.28 ft/s

$C_{sb,flood}$ = capacity parameter (ft/s)

U_{nf} = Gas velocity through net area at flood (ft/s or m/s)

Properties :

	Enriching section			Stripping section
	Top	Bottom	Top	Bottom
Liquid (k-moles/hr)	470.98	470.98	606.574	606.574
Liquid (kg/hr)	33962.37	33962.37	43740.05	43740.05
Vapor (k-moles/hr)	497.544	497.544	497.544	497.544
Vapor (kg/hr)	35877.9	35877.9	35877.9	35877.9
x	0.987	0.203	0.203	0.012
y	0.987	0.259	0.259	0.012
T_{liquid} (^{o} C)	64.6	72.5	72.5	74.8
T_{vapor}(^{o} C)	64.7	73	73	74.9
ρ_{vapor}(kg/m^3)	2.602	2.539	2.539	2.526
ρ_{liquid} (kg/m^3)	740.26	744.93	744.93	744.7
$(L/G)(\rho_g/\rho_L)^{0.5}$	0.056	0.055	0.0711	0.0710
σ_{liq} (dyn/cm)	16.1	17.8	17.8	18.0
μ_{vapor}	8.39 x10^{-3}	8.04 x10^{-3}	8.04 x10^{-3}	8.01 x10^{-3}
μ_{liq}	0.349	0.298	0.298	0.29
D_{vapor}	0.142	0.148	0.148	0.149
D_{liquid} (m^2/s)	4.92 x10^{-9}	4.60 x10^{-9}	4.60 x10^{-9}	4.93 x10^{-9}

Average conditions and Properties:

	Enriching section	Stripping section
Liquid (k-moles/hr) (kg/hr)	470.98 33962.37	606.574 43740.05
Vapor (k-moles/hr) (kg/hr)	497.544 35877.9	497.544 35877.9
$\overline{T}_{liq}$ (^{O}c)	68.55	73.65
$\overline{T}_{vapor}$ (^{O}c)	68.85	73.95
$\overline{\rho}_{liq}$ (kg/m^3)	742.60	744.82
$\overline{\rho}_{vapor}$ (kg/m^3)	2.571	2.533

$$C_{sb,\,flood} = U_{nf} \left[\frac{20}{\sigma}\right]^{0.2} \left[\frac{\rho_g}{\rho_L - \rho_g}\right]^{0.5}$$ (Ref; 1, pg: 18-7)

σ = liquid surface tension
ρ_g = gas density
ρ_L = liquid density

$$\therefore U_{nf} = 0.28 \left[\frac{16.1}{20}\right]^{0.2} \left[\frac{740.26 - 2.602}{2.602}\right]^{0.5} = 4.514 \text{ ft/s} = \underline{1.376 \text{m/s}}$$

Consider , 80% flooding

$U_n = 0.8\ U_{nf}$ = $\underline{1.101 \text{ m/s}}$
U_n = Gas velocity

Volumetric flow rate of vapor $= \dfrac{35877.9}{3600 \times 2.602} = \underline{3.83\ m^3/s}$

Net Area (A_n) $= \dfrac{\text{Volumetric flow rate of vapor}}{U_n} = \dfrac{3.83}{1.101} = \underline{3.479 m^2}$

Let $\dfrac{L_w}{D_c} = 0.70$

L_w = Weir Length

D_c = Column Diameter

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

$\sin(\theta_C/2) = (L_W/2)/(D_C/2) = 0.7$

$\theta c = \underline{88.86^0}$

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

$= (0.1939 – 0.1250)\ D_c^2$

$= \underline{0.0689\ D_c^2}$

$A_n = A_c – A_{d.}$

$0.785Dc^2 – 0.0689\ Dc^2 = 3.479$

$D_c = 2.204$ m.

$D_c \cong 2.2$m

$L_w = 0.7\ D_c = 1.54$m.

$L_w \cong \underline{1.6m}$

$\therefore A_d = 0.0689(2.2)^2 = 0.3335\ m^2$

$A_c = \dfrac{\pi(2.2)^2}{4} = \underline{3.801\ m^2}$

$A_n = A_c - A_d = 3.801-0.3335 = 3.4675\ m^2$

Active area (A_a) $= A_c – 2A_d = 3.801 – 2(0.3335) = \underline{3.134\ m^2}$

$$\frac{L_w}{D_c} = \frac{1.6}{2.2} = 0.727$$

$\therefore \theta c = 93.27^{\circ}$

$L_w = 0.727(2.2) \cong 1.6\text{m}$

$A_{cz} = 2\{60\text{mm}\} \times L_w = 2 \times 60 \times 10^{-3} \times 1.6 = 0.192\ \text{m}^2$

$$\frac{A_{cz}}{A_c} = \frac{0.192}{3.801} = 0.051$$

$A_{cz} = \underline{5.1\%\ A_c}$

$\alpha = \pi - \theta_c = 180 - 93.27 = \underline{86.73^{\circ}}$

A_{wz} is the waste zones area.

$$A_{wz} = 2\left[\frac{\pi}{4} D_c^2 \frac{\alpha}{360} - \frac{\pi}{4}(D_c - 0.06)^2 \frac{\alpha}{360}\right]$$

$$= 2\{0.916 - 0.867\} = \underline{0.098\ \text{m}^2}$$

$$\frac{A_{wz}}{A_c} = \frac{0.098}{3.801} = 0.026$$

$A_{wz} = \underline{2.6\%\ A_c}$

A_p = Area of perforation.

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

$= 3.134 - 0.192 - 0.098.$

$= \underline{2.844\ \text{m}^2}$

(8)A_h = Area of holes.

$A_h = 0.1\ A_p = \underline{0.2844\ \text{m}^2}$

n_h = number of holes.= $n_h = \frac{4 \times 0.2844}{\pi(5 \times 10^{-3})^2} = \underline{14484}$

(9) h_w = 40mm

h_w = weir height

(10) Weeping check : (Sieve Tray)

(a) (Ref:1, p:18-9, eq:18-6)

$$h_d = K_1 + K_2(\rho_g/\rho_L)U_h^2$$

K_1 = 0 (for sieve tray)

U_h = Linear gas velocity through holes.

h_d = pressure drop across dry hole (mm liquid)

$K_2 = \frac{50.8}{Cv^2}$ (Ref :1, pg :18-9).

C_v = Discharge co-efficient. (Ref :1, fig: 18-14, pg :18-9)

For $\frac{A_h}{A_a} = 0.091$

$\frac{t_T}{d_h} = 0.6$

$C_v = 0.74.$

$$\therefore K_2 = \frac{50.8}{0.74^2} = 92.77$$

$$(U_h)_{top} = \frac{35877.9}{2.602 \times 0.2844 \times 3600} = 13.47 \text{ m/s} \quad \text{(minimum)}$$

$$(U_h)_{bottom} = \frac{35877.9}{3600 \times 2.539 \times 0.2844} = 13.80 \text{ (m/s)} \quad \text{(maximum)}$$

$$(h_d)_{top} = 92.77 \left[\frac{2.602}{740.26}\right] (13.47)^2 = 59.17 \text{ mm of clear liquid .}$$

$$(h_d)_{bottom} = 92.77 \left[\frac{2.5397}{744.93}\right] (13.80)^2 = 60.22 \text{ mm of clear liquid.}$$

(b) $h_\sigma = 409\left(\frac{\sigma}{\rho_L d_h}\right)$ (Ref: 1, pg:18-7, eq:18-2 (a)

h_σ = head loss due to the bubble formation

$h_\sigma = 409\left(\frac{16.1}{740.26 \times 5}\right)$ =1.78 mm of clear liquid

(c) $h_{ow} = F_w\ 664\left(\frac{q}{L_w}\right)^{2/3}$ (Ref: 1, pg: 18-10, eq:18-12 (a)).

h_{ow} = height of crest over weir

F_w = weir constriction correction factor.

$q = \frac{L_t}{\rho_L}$

q = liquid flow per serration (m^3/s)

$q = \frac{33962.37}{740.26 \times 3600} = 12.74 \times 10^{-3}\ m^3/s$

$\frac{q^1}{(L_w)^{2.5}} = \frac{201.92}{(5.256)^{2.5}} = 3.2$ (Ref:1, pg:18-11, fig:18-16)

$\frac{L_w}{D_c} = 0.727$

$F_w = 1.02$

$\therefore\ h_{ow} = 1.02\ (664)\left\{\frac{12.74 \times 10^{-3}}{1.6}\right\}^{2/3}$ = 27mm of clear liquid

$h_d + h_\sigma = 59.17+1.78 = 60.95mm$

$h_w + h_{ow} = 40+27 = 67mm$

For $\frac{A_h}{A_a} = 0.091$

$h_{w} + h_{ow} = 67$ mm

(Ref :1, pg:18-7, fig:18-11)

$h_{d} + h_{\sigma} = 15mm < 60.95$ mm

∴ There is no weeping

(11) Flooding check

since The maximum flow rate is at the bottom, flooding checked at the bottom.

$$h_{ds} = h_w + h_{ow} + \frac{h_{hg}}{2} \quad \text{(For sieve trays)}$$

h_{hg} = liquid gradient across plate (mm liquid)

$(h_{ow})_{bottom}$ = 26.9 mm

h_{ds} = Calculated height of clear liquid over the dispersers.

$$h_{ds} = 40+26.9+\frac{0}{2} = 66.9 \text{ mm}$$

U_a = linear gas velocity through active area.

$$U_a = \frac{35877.9}{3600 \times 2.539 \times 3.134} = 3.886 \text{ ft/s}$$

$\rho_g = 2.539 \text{ kg/m}^3 = 0.1587 \text{ lb/ft}^3$

$F_{ga} = U_a (\rho_g)^{1/2} = 3.886 (01587)^{1/2} = 1.55$

(Ref:1, pg:18-10, fig:18-15)

Aeration factor (ß) =0.61

Relative froth density (ϕ_t) =0.22

h_l^1 = pressure drop through aerated liquid
h_f = actual height of froth.

$h_l^1 = \beta\, h_{ds} = 0.61\,(66.9) = 40.81mm$

$$h_f = \frac{h_l^1}{\phi_t} = \frac{40.81}{0.22} = 185.5mm$$

$$h_{da} = 165.2 \left(\frac{q_b}{A_{da}} \right)^2$$ (Ref:1, Pg: 18-10, eq:18-14)

h_{da} = head loss under the down –comer

A_{da} = minimum area of flow under the down comes apron.

$h_{ap} = h_{ds} - c = 66.9-25 = 41.9mm$

$A_{da} = L_w \times h_{ap} = 1.6 \times 41.9 \times 10^{-3} = \underline{0.0670 m^2}$

$$q_b = \frac{L_b}{\rho_L} = \frac{33962.37}{744.93 \times 3600} = \underline{12.664 \times 10^{-3}\ m^3/s}$$

$$h_{da} = 165.2 \left(\frac{12.664 \times 10^{-3}}{0.067} \right)^2 = \underline{5.9mm}$$

h_t = total head loss across the plate

$h_t = h_d + h_l^1 = 60.22+40.81 = \underline{101.03mm}$

$h_{dc} = h_t + h_w + h_{ow} + h_{hg} + h_{da}$ (Ref :1, eg:18-3, pg:18-7)

$= 101.03+40+27+0+5.9$
$= \underline{173.93mm}$

Taking (ϕ_{dc}) average = 0.50 ; ϕ_{dc} = relative froth density

h_{dc}^1 = actual back-up

$$h^1_{dc} = \frac{173.93}{0.5} = 347.86mm < 457.2\ mm$$

∴ Flooding check is satisfied

i.e. There is no flooding.

(III) Column efficiency : (Average Conditions)

(a) $N_g = \dfrac{0.776+0.00457h_w - 0.238\, U_a\, \rho_g^{0.5} + 105\, w}{(N_{sc,g})^{0.5}}$ (Ref :1, pg:18-15, eq:18-36)

N_g = gas phase transfer unit

$N_{sc,g} = \dfrac{\mu_g}{\rho_g D_g} = \dfrac{8.22 \times 10^{-3} \times 10^{-3}}{2.571 \times 0.142 \times 10^{-4}} = 0.2252$

$N_{sc,g}$ = gas phase schmidz number

$U_a = \dfrac{35877.9}{3600 \times 2.571 \times 3.134} = 1.237$ m/s

$D_f = \dfrac{L_w + D_c}{2} = \dfrac{1.6+2.2}{2} = 1.9$m

D_f = width of flow path on plate

W = liquid flow rate (m^3/sm)

$W = \dfrac{q}{D_f}$

$q = \dfrac{33962.37}{742.6 \times 3600} = 12.704 \times 10^{-3}$ m^3/s

$W = \dfrac{12.704 \times 10^{-3}}{1.9} = 6.686 \times 10^{-3}$ m^3/m-s

$N_g = \dfrac{0.776+0.00457(40) - 0.238\,(1.237)\,(2.571)^{0.5} + 105\,(6.686 \times 10^{-3})}{(0.2252)^{0.5}}$

$N_g = 2.51$

(b) $N_L = K_{L\,a}\, \theta_L$ (Ref:1, pg: 18-15, eq:18-36 (a))

N_L = liquid phase transfer units
$K_{L\,a}$ = liquid phase transfer coefficient (m/s)
Q_L =Residence time of liquid in froth or spray zone.

$(D_L)_{average} = 4.76 \times 10^{-9}$

$K_{L a}$ =$(D_L)^{½}$ $(0.40\ U_a\ \rho_g{}^{½} +0.17)$ (Ref:1, pg:18-16, eg:18-40(a))

$K_{L a}$ = $(3.875 \times 10^8 \times 4.76 \times 10^{-9})^{½}$ $(0.40 \times 1.237 (2.57)^{½} +0.17)$

$K_{L a}$ = 1.308 m/s

$\theta_L = \dfrac{h_L A_a}{1000 q_b}$ (Ref:1, pg:18-16, eq:18-39)

h_l = liquid hold-up on plate

$\theta_L = \dfrac{40.81 \times 3.134}{1000(12.704 \times 10^{-3})} = \underline{10.07\ s}$

$N_L = 1.308 \times 10.07 = \underline{13.172}$

m_{top} =0.49

m_{bottom} = 1.15

$\dfrac{G_m}{L_m}$ = 1.056

$\lambda_t = m_{top}\left(\dfrac{G_m}{L_m}\right) = 0.517$

$\lambda_b = m_{bottom}\left(\dfrac{G_m}{L_m}\right) = 1.214$

$\overline{\lambda}_{avg}$ = 0.866

λ = stripping factor

$$N_{og} = \dfrac{1}{\dfrac{1}{N_g} + \dfrac{\lambda}{N_L}}$$ (Ref: 1, pg:18-15, eq:18-34)

$$= \dfrac{1}{\dfrac{1}{2.51} + \dfrac{0.866}{13.172}} = 2.154$$

$E_{OG}= 1- e^{-(N_{og})}$ (Ref:1, pg: 18-15, eq:18-33)

$E_{OG}= 1- e^{-(2.154)} = \underline{0.884}$

(B) Murphee plate efficiency : E_{mv}

$\therefore \theta_L$ = Residence time of liquid = 10s

which is large.

$\therefore E_{mv} \cong E_{OG}$

$\therefore E_{mv} = 0.884$

(C) Overall column efficiency : E_{oc}

$$E_{oc} = \frac{\log\{1+Ea(\lambda - 1)\}}{\log(\lambda)}$$ (Ref:1, pg:18-17, eq:18-46)

E_a = Murphee vapor efficiency

$$\frac{E_a}{E_{mv}} = \frac{1}{1+E_{mv}\left(\frac{\psi}{1-\psi}\right)}$$ (Ref:1, pg:18-13, eq:18-37)

ψ = fractional entrainment

$$\text{For}\quad \frac{L}{G}\left(\frac{\rho_g}{\rho_L}\right)^{0.5} = \frac{33962.37}{35877.9}\left(\frac{2.571}{742.6}\right)^{0.5} = 0.0557$$

For 80% flood

From (Ref:1, fig:18-22, pg:18-44)

$$\psi = 0.06$$

$$E_a = 0.884\left\{\frac{1}{1+0.884\left(\frac{0.06}{1-0.06}\right)}\right\} = 0.837$$

$$Eoc = \log\left\{\frac{1+0.837(0.866-1)}{\log(0.866)}\right\} = 0.827$$

N_A = Actual tryas;

N_T= theoretical trays.

$$N_A = \frac{N_T}{Eoc} = \frac{19}{0.827} = 22.97 \simeq 23$$

Height of enriching section = 23 x 0.457 = 10.51m

(B) Stripping Section :

(1) Tray spacing (t_s) = 18" = 457.2mm

(2) Hole diameter (d_n) = 5mm

(3) Pitch (l_p) =15mm
△ lar pitch

(4) Tray thickness (t_r) =3mm

(5) $\frac{A_h}{A_p} = 0.10$

(6) Plate Diameter (D_c) :

$(L/G)(\rho_g/\rho_L)^{0.5} = 0.0711$ (maximum of top)

$C_{sb\ flood}$ =0.27 ft/s
U_{nf} = 1.375 m/s
Consider , 80% flooding .
U_n =1.1 m/s

Volumetric flow rate of vapor =3.925 m^3/s
Net area (A_n) =3.568 m^2

Column diameter (D_c) =2.3 m
L_w =1.6m
A_d=0.3645 m^2
A_c=4.155 m^2
A_n=3.7905 m^2
A_a=3.426 m^2

$\frac{L_w}{D_c} = 0.696$

θ_c = 88.21^0
L_w = 1.6m
A_{cz} = 0.192 m^2 (4.62% of A_c)
A_{wz} = 0.026 m^2 (2.6% of A_c)
α = 91.79^0
A_p = 3.126 m^2
A_h = 0.3126 m^2
n_h = 15921

(9) h_w =40mm

(10) Weeping check (Top) :

(a) $(h_d)_{top}$ = 49.88mm of clear liquid
$(h_d)_{bottom}$ = 50.12 mm of clear liquid

(b) h_σ = 1.96 mm of clear liquid

(c) h_{ow} =32.47 mm of clear liquid

$h_w + h_{ow}$ = 72.47mm
$h_d + h_\sigma$ = 51.84mm

From graph, $h_d + h_\sigma$ = 18mm < 51.84 mm

∴ There is no weeping.

11) Flooding check (Bottom)

h_{ow} = 32.48mm
h_{ds} = 72.48mm ; β =0.60 ; ϕ_t = 0.23
h_l^1 = 43.49mm
h_f = 189.1mm
h_{ap} = 47.48mm
A_{da} = 0.076 m^2
h_{da} = 7.62mm
h_t = 93.61mm
h_{dc} = 173.71mm
h_{dc}^1 = 347.42mm < 457.2 mm

∴ There is no flooding

(III) Column Efficiency:

(a) N_g =3.04

(b) θ_L = 9.14s.

N_L = 11.2
N_{og}=2.36
E_{oG}=0.906

(B) Murphee plate efficiency :

E_{mv} = 0.906

(C) Overall column efficiency :

E_a = 0.873

E_{oc} = 0.876

N_A =14

Height of stripping section = 14 x 0.457 = 6.4m

Total height of the column = Enriching section + stripping section

= 10.51 +6.4

= 16.91m

Summary of the Distillation Column

Enriching section

Tray spacing = 457.2 mm

Column diameter = 2.2m

Weir length = 1.6m

Weir height = 40mm

Hole diameter = 5mm

Hole pitch = 15mm, triangular

Tray thickness = 3mm

Number of holes = 14484

Flooding % = 80

Stripping section

Tray spacing = 457.2 mm

Column diameter = 2.3m

Weir length = 1.6 m

Weir height = 40 mm

Hole diameter = 5mm

Hole pitch = 15mm, triangular

Tray thickness = 3mm

Number of holes = 15921

Flooding % = 80

Mechanical Design of Distillation Column

(a) Shell :

Diameter = 2.3m

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

Design pressure = 1.1 x operating pressure = 1.1 x 1.0329
= 1.1362 kg/cm^2

Operating temperature = (73.95^0c)

Design Temperature = 1.1 x 73.95 = 81.35^0c

Shell material	Carbon steel
Shell	Double welded bolt joints stress relieved
Skirt height	4m
Tray spacing	457.2mm
Top Disengaging Space	1 m
Bottom separator space	2.75 m
Allowable stress for shell material	950 Kg/cm^2
Insulation material	Asbestos
Insulation thickness	75 mm
Density of Insulation	575 Kg/m^3

(b) Head: Torospherical dished head.

Material	Carbon Steel
Allowable tensile stress	950 kg/cm^2

(c) Skirt support

Height	4m
Material	Carbon steel

(d) Nozzles (Number of Nozzles =4)

(e) Trays – Sieve type

Number of trays	31
Spacing	457.2mm
Hole diameter	5mm
Thickness	3mm
Weir height	40mm
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) = 2300mm

f = Allowable /permissible tensile stress (kg/cm^2) = 950kg/cm^2

C = Corrosion allowance (mm) = 2mm

J = Joint Efficiency.

Considering double welded butt joints with backing strip

J = 85% = 0.85

$$t_s = \frac{1.1362 \times 2300}{2(950 \times 0.85) - 1.1362} + 2 = \underline{3.62\ mm}$$

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

(2) Head shallow dished & torospherical head.

$$t_h = \frac{PR_cW}{2fJ} \qquad \text{(Ref: 3, Pg: 238)}$$

R_c = Crown radius = outer diameter of the shell = 2300+ 2(6) = $\underline{2312mm}$
R_k= knuckle radius = $\underline{0.06\ R_c}$

W= Stress intensification factor

$$W = \frac{1}{4}\left[3 + \sqrt{\frac{R_c}{R_k}}\right] = \frac{1}{4}\left[3 + \sqrt{\frac{R_c}{0.06\ R_c}}\right] = 1.77$$

$$t_h = \frac{1.1362 \times 2312 \times 1.77}{2 \times 950 \times 0.85} = \underline{2.88mm}$$

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

Weight of head:

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

OD = outside diameter of shell = 2312mm = 91(inches)

i_{cr} = inside cover radius = 0.75 inches
S_f = straight flange length = 1.5 inches
(Ref: 6, table 5.7, pg:88)

$$\text{Diameter} = 91 + \frac{91}{24} + 2\ (1.5) + \frac{2}{3}(0.75)$$

Diameter (d) = 98.3 inches

Weight of head $= \frac{\pi}{4} (2.4968)^2 (5.994 \times 10^{-3}) \times 7700$

$= \underline{225.98 kg}$

weight of head $\simeq$ 2670 (Ref:3, pg: 325)

(3) <u>Calculation of stresses</u>:

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

$$f_{ap} = \frac{P_{di}}{4(t_s-c)} = \frac{1.1362 \times 2300}{4\,(6-2)} = \underline{163.33\ Kg/cm^2}$$

This is same throughout the column height

(ii) Circumferential stress :

$$2\, f_{ap} = 2 \times 163.33 = \underline{326.66\ Kg/cm^2}$$

(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,

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

D_m = Mean diameter of the shell (cm)
t_s = thickness of the shell (cm)
C = Corrosion allowance (cm)

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

$\rho_S = 7700 \quad kg/m^3$
$\quad = 0.0077 \quad kg/cm^3$

$f_{ds} = 0.77x \quad kg/cm^2$

(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

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

Assume : asbestos is the insulation material.

$\rho_{ins} = 575\ kg/cm^3 = 0.000575\ kg/cm^3$
$t_{ins} = 75mm \quad = 7.5cm$
$D_{ins} = Dc + 2\,t_s + 2t_{ins}$

$D_{ins} = 2300 + 2(6) + 2(75) = \underline{2462mm} = \underline{246.2cm}$

$$D_m = \frac{2300 + (2312)}{2} = \underline{2306mm} = \underline{230.6cm}$$

$$f_d(ins) = \frac{\pi\,(246.2)\ 7.5\ \times\ 0.000575\ x}{\pi\,(230.6)\,(0.6 - 0.2)}$$

$$= 1.151\ x \quad kg/cm^2$$

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

$$F_{liq} = \left[\frac{(x-1)}{(0.4572)} + 1\right] \frac{\pi Di^2}{4} \times \rho_{liquid}$$

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

$$= \left[\frac{x - 1}{0.4572} + 1\right] \frac{\pi (2.3)^2}{4} \times 743.71$$

$$= \left[\frac{x - 0.5428}{0.4572}\right] \frac{\pi (2.3)^2}{4} \times 743.71$$

$$= (x - 0.5428)\ 6758.39 \text{ kg.}$$

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

$$= \frac{(x - 0.5428)\ 6758.39}{\pi (230.6)(0.6 - 0.2)} = (23.32x - 12.66) \text{ kg/cm}^2$$

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

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

M_w = bending moment due to wind load

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

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

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

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

P_w = wind pressure

P_w = 45 lb/ft^2 (Ref: 6, pg:159, table :9.1)

= 219.42 kg/m^2

$$M_w = \left(\frac{0.7 \times 219.42 \times 2.306}{2}\right) x^2 = 177.09\ x^2$$

$$z = \frac{\pi (2.306)^2 (0.006 - 0.002)}{4} = \underline{0.0167}$$

$$f_{wx} = \frac{177.09\, x^2}{0.0167} = 10604.2\, x^2 \quad kg/m^2 \,. = 1.0604\, x^2\ kg/cm^2$$

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.

$f_{t,max} = 1.0604\, x^2 + 163.33 - 0.77x$

$f_{t,max} = fJ$
f = allowable stress = 950 kg/cm^2
J= Joint factor = 0.85

$\therefore f_{t,max} = 950\,(0.85) = \underline{807.5\ kg/cm^2}$

$1.0604\, x^2 - 0.77x + 163.33 = 807.5$
$1.0604\, x^2 - 0.77x - 644.17 = 0$
a =1.0604, b = -0.77, c = - 644.17

$$x = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a} = \frac{0.77 \pm \sqrt{0.77^2 + 4\,(1.0604)\, 644.17}}{2(1.0604)}$$

$$x = \frac{0.85 \pm 52.27}{2(1.0604)}$$

x = $\underline{25.01m}$

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

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

$f_{t,max} = 1.0604\, x^2 - 163.33 + 0.77x$

x = 16.91m

$(f_{t,max})_x = 152.91\ Kg/cm^2$ $(\therefore$ Compressive)

$\therefore\ f_{c,max} = 0.125\, E \left(\frac{t}{Do}\right)$ (Ref: 5, pg: 159)

E= Elastic modulus = $2x10^5\ MN/m^2 = 2x10^6\ kg/cm^2$
t = Shell thickness = 6mm.
D_o = 2312 mm

$f_{c,max} = 0.125 \times 2x10^6 \left(\frac{6}{2312}\right) = \underline{648.79\ kg/cm^2}$

Consider, $648.79 = 1.0604\, x^2 - 163.33 + 0.77\, x$
$1.0604\, x^2 + 0.77x - 812.12 = 0$

a= 1.0604, b = 0.77, c= - 812.12

$x = \frac{-0.77 \pm \sqrt{0.77^2 + 4\,(1.0604)\,(812.12)}}{2(1.0604)}$

x= 27.31m

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) = 16.91 + 4 + 2.75 + 1

= 24.66m

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 = 2.3m

t_s = 0.006m

ρ_s = Density of material

$W_{min} = \pi$ (2.3 + 0.006) 0.006 (24.66-4) 7700 + 2(2670)

= 12254.83kg.

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 = 10, 800 kgs.

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

$= \frac{\pi}{4}\{ 2.462^2 - 2.312^2\}$ 24.66 (575)

= 7975 kgs

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

$= \frac{\pi}{4}$ (2.3) (24.66-4) 1000

= 37320.55kgs

Wa = weight of attachments = 7100 kgs

W_{max} = 10,800 + 7975 + 37,320.55 + 7100 = 63195.55 kgs

Period of vibration at minimum dead weight

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

$$= 6.35 \times 10^{-5} \left\{\frac{24.66}{2.3}\right\}^{3/2} \left\{\frac{12254.83}{0.006}\right\}^{1/2}$$

= 3.186 s

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

Period of vibration at maximum dead weight

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

$$= 6.35 \times 10^{-5} \left(\frac{24.66}{2.3}\right)^{3/2} \left\{\frac{63195.55}{0.006}\right\}^{1/2}$$

$$= \underline{7.24\ s}$$

$\therefore$ 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 $D = D_i$ = 2.3 m
For maximum weight condition $D = D_{ms}$ = 2.462 m

$\therefore$ $(P_W)_{min}$ = 0.7 x 2 x 100 x 2.3 x 24.66

= 7940.52kg

$(P_W)_{max}$ = 0.7 x 2 x 100 x 2.462 x 24.66

= 8499.8kg

Minimum & maximum wind moments

$$(M_W)_{min} = (P_W)_{min} \times \frac{H}{2} = 7940.52 \times \frac{24.66}{2} = \underline{97906.6}\ \text{kg-m}$$

$$(M_W)_{max} = (P_W)_{min} \times \frac{H}{2} = 8499.2 \times \frac{24.66}{2} = \underline{10,4,802.53}\ \text{kg.m}$$

As the thickness of the skirt is expected to be small, assume $D_i \simeq D_o$ = 2m

$$f_{zwm}(min) = \frac{4\,M_{W(min)}}{\pi D^2 t} = \frac{4 \times 97906.6}{3.14 \times 2.3^2 \times t} = \frac{23564.94}{t} \quad kg/m^2$$

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

$$f_{zwm}(max) = \frac{4\,M_{W(max)}}{\pi D^2 t} = \frac{4 \times 104802.53}{3.14 \times 2.3^2 \times t} = \frac{25224.71}{t} \quad kg/m^2$$

Minimum and Maximum dead load stresses.

$$f_{ZW}(min) = \frac{W_{min}}{\pi Dt} = \frac{12254.83}{\pi(2.3)t} = \frac{1696}{t} \quad kg/m^2$$

$$f_{ZW}(max) = \frac{W_{max}}{\pi Dt} = \frac{63195.55}{\pi(2.3)t} = \frac{8745.99}{t} \quad kg/m^2$$

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

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

$f_Z = f\,J$

$$95 \times 10^5 \times 0.85 = \frac{(23564.94 - 1696)}{t}$$

$t = 2.71 \times 10^{-3} m = 2.71mm$

Maximum Compressive load :

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

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

t = 1.773mm

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=π (Do-l)l

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

$z=\pi R_m^2 l$

R_m= (Do-l)/z

A=π (2.3 - l)l

R_m=(2.3-l)/2

$$Z = \pi \left\{ \frac{2.3 - l}{2} \right\}^2 l$$

$$fc = \frac{63195.55}{\pi(2.3 - l)l} + \frac{104802.53}{\pi \left\{ \frac{2.3 - l}{2} \right\}^{2l}}$$

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

assume : $fc = 5.5 \times 10^5$ Kg/m^2

$$\text{i.e. } 5.5 \times 10^5 = \frac{63195.55}{\pi(2.3 - l)l} + \frac{419210.12}{\pi(2.3 - l)^2 l}$$

By trail and error lc =0.12m

∴ 120 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=0.12m
$f_c = 0.23 \times 10^6$ Kg/m^2

$$t_{bp}=120\sqrt{\frac{3(0.23\times10^{6})}{95\times10^{5}}}=32.34\text{ mm}\cong 33\text{mm}$$

Bearing plate thickness of 33 mm is required. As the plate thickness required is large than 20mm, gussets must be used to reinforce the plate.

Maximum bending moment is bearing plate with gussets for
l/b=1

$M(max)=My= - 0.119fc\ l^2 = -0.199 \times 0.23 \times 10^6\ (0.12)^2=-394.128$ KJ

$$tbp=\sqrt{\frac{6M(max)}{f}}=\sqrt{\frac{6(394.128)}{95\times10^{5}}}=0.01577\text{ m}\cong 16\text{mm}$$

i.e. If gussets are used at 120 mm spacing then bearing plate thickness of 16 mm will be sufficient .

Minimum stress between the bearing plate & the concrete foundation.

$$fmin=\frac{Wmin}{A}-\frac{Mw(min)}{Z}=\frac{12254.83}{\pi(2.3-0.12)0.12)}-\frac{97906.6}{\pi(2.3-0.12)^{2}0.12}$$

$$= -39871.3089\quad Kg/m^2$$

$\therefore$ 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,

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

P_{bolt} = load on one – anchor bolt.

n= number of anchor bolts.

A=Area of contact between bearing plate & foundation.

$P_{bolt} \times n=+ (39871.3089)\ 3.14\ (2.3-0.12)\ (0.12)$
=32751.25 Kg

If hot rolled Carbon Steel is selected for bolts

$f = 57.3\ MN/m^2$ (Ref:5 Pg:108)

$= 57.3 \times 10^5\ Kg/m^2$

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

$$a_r\ n = \frac{32751.25}{57.2 \times 10^5} = 5.716 \times 10^{-03}$$

a_r = root area of bolts

For M16 x 1.5 bolts,

$a_r = 1.33 \times 10^{-4}\ m^2$ (Ref:5, pg:122)

$$n = \frac{5.716 \times 10^{-3}}{1.33 \times 10^{-4}}$$

n = 43

i.e The number of bolts required is 43.

MINOR EQUIPMENT

CONDENSER

(I) Preliminary Calculations:

(a) Heat Balance:

Vapor flow rate $(\bar{G})$ = 497.544 K-moles/hr.
= 497.544 x 72.11 = 35877.9 kg/hr
= 9.9661 kg/s

Vapor Feed Inlet Temperature =64.6^{0}c.

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

Condensate outlet temperature = 64.6 ^{0}C

∴ Average Temperature = 64.6 ^{0}C

Latent heat of vaporisation (λ)=3.15e7 (0.987)+3.2e7 (0.013)

= 436.92 KJ/kg

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

q_h = heat transfer by the hot fluid .

q_h =9.9661 x 436.92 = 4354.39 KJ

q_C= mass flow rate of cold fluid x specific heat x $\triangle$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.

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

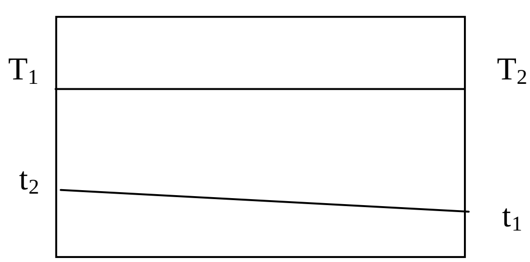
$\therefore$ $\triangle t$ = 40-25= $\underline{15\ ^0C}$

$\overline{Cp}$ = 4.285 KJ/kg K.

$$m_c = \frac{4354.39 \times 10^3}{4.285 \times 10^3 \times 15} = \underline{67.75} \text{ kg/s.}$$

(b) <u>LMTD Calculations:</u>

assume : counter current



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

$T_1 = 64.6\ ^0C$; $T_2 = 64.6\ ^0C$; $t_1 = 25\ ^0C$; $t_2 = 40\ ^0C$

$\therefore$ LMTD = $\underline{35.65\ ^0C}$

(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 = 250 W/m^2K

$$\therefore A_{assumed} = \frac{4354.39 \times 10^3}{250 \times 35.65} = 488.57\ m^2$$

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

Outer diameter of pipe (OD) = ¾" = 0.0191 m

Inner diameter of pipe (ID) =0.620" = 0.0157m

Let length of tube =16' = 4.877m

Let allowance = 0.05m

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

= π x 0.0191 x (4.877 – 0.05)

= $0.29\ m^2$

$$\therefore \text{Number of tubes } (N_{tubes}) = \frac{A_{assumed}}{a_{heat\text{-}transfer}} = \frac{488.57}{0.29}$$

= 1685

(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 - 6	Horizontal Condenser

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

Shell Diameter (D_c) = 1.219 m.

$\therefore A_{corrected}$ = 504.6 m^2

$\therefore U_{corrected}$ = 242.0 W/m^2K

(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 = $\dfrac{\pi (ID^2)}{4}$

$$\therefore a_{tube} = \frac{\pi}{4}(0.0157)^2 \times \frac{1750}{6} = 0.056 \ m^2/pass$$

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

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

$$\therefore v_p = \frac{67.75}{994.865 \times 0.056} = 1.22 \ m/s$$

∴ fluid velocity check is satisfied

(II) Film Transfer Coefficient :

Properties are evaluated at t_{film} :

$$t_{film} = \left[\frac{t_v + 1\{t_v + \frac{(t_1+t_2)}{2}\}}{2} \right] = \left[\frac{64.6 + \{64.6 + \frac{(25+40)}{2}\}}{2} \right] = \underline{56.58\ ^0C}$$

a) Shell side:

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

$$= \frac{4}{0.0004} \times \frac{9.9661}{(1740)^{2/3} \times 4.877} \qquad = \underline{141.3}$$

For Horizontal condenser :

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

$$= 1.51 \left\{ \frac{0.0191^3 (749.5)^2 \times 9.81}{(0.4 \times 10^{-3})^2} \right\}^{1/3} (141.3)^{-1/3} \qquad = \underline{180.6}$$

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

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

k = Thermal conductivity of liquid.

$$h_o = \frac{180.6\,(0.121)}{0.0191} \qquad = \underline{1141.3\ W/m^2K}$$

b) Tube side:

$$G_t = \frac{m_{pipe}}{a_{tube}}$$

G_t= Superficial mass velocity

$$G_t = \frac{67.75}{0.056} = 1210 \text{ kg/m}^2\text{s}$$

$$Re = \frac{(ID)\, G_t}{\mu} = \frac{0.0157 \times 1210}{0.8 \times 10^{-3}} = \underline{23, 746}$$

$$Pr = \frac{\mu C_p}{K} = \frac{0.8 \text{ X } 10^{-3} \times 4.1796 \times 10^{3}}{0.617} = \underline{5.42}$$

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

h_i = inside –heat transfer coefficient

$$h_i = \frac{0.023\,(23, 746)^{0.8}\,(5.42)^{0.3}}{0.0157} \times 0.617$$

h_i = 4751 W/m^{2}K

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

$$\frac{1}{U_0} = \frac{1}{h_o} + \frac{(OD)}{(ID)}\frac{1}{h_i} + \text{Fouling factor}$$

U_o = overall heat –transfer coefficient

$$\frac{1}{U_0} = \frac{1}{1143.3} + \frac{0.0191}{0.0157} \times \frac{1}{4751} + 0.003$$

$\underline{U_0 = 242.2 \text{ W/m}^2\text{K}}$

$U_0 > U_{assumed}$

(III) Pressure Drop Calculations :

a) Tube Side :

Re = 23746.

$f = 0.079\,(Re)^{-1/4} = 0.079\,(23746)^{-1/4} = 6.364 \times 10^{-3}$

f = friction factor

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

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

$$= \frac{4 \times 6.364 \times 10^{-3} \times 4.877 \times 1.22^2 \times 994 \times 9.81}{2 \times 9.81 \times 0.0157}$$

$= \underline{5.851\ KPa}$

Pressure Drop in the end zones $(\triangle P)_e = \frac{2.5\,\rho\,Vp^2}{2} = \frac{2.5 \times 994 \times 1.22^2}{2} = 1.85\ KPa$

Total pressure drop in pipe $(\triangle P)_{total} = [5.851 + 1.85]6 = \underline{46.21\ KPa} < 70\ KPa$

b) Shell side: Kern's method

Number of baffles =0

$\therefore$ Baffle spacing (B) = 4.877 m

$C^1 = 2.54 \times 10^{-2} - 0.0191 = \underline{0.0063}$

P_T = pitch = 25.4×10^{-2} m

$$a_{shell} = \frac{\text{shell diameter} \times C^1 \times B}{P_T} = \frac{1.219 \times 0.0063 \times 4.877}{25.4 \times 10^{-2}}$$

$$= \underline{1.475\ m^2}$$

$$De = \frac{4\left\{\frac{P_T}{2} \times 0.86 P_T - \frac{1}{2}\ \frac{\pi}{4}\ (OD)^2\right\}}{\left(\frac{\pi\ do}{2}\right)} = \frac{4\left\{\frac{(25.4 \times 10^{-3})^2}{2} \times 0.86 - \frac{\pi}{8}(0.0191)^2\right\}}{\frac{\pi\ (0.0191)}{2}}$$

$$= \underline{17.89mm.}$$

$$Gs = \text{Superficial velocity in shell} = \frac{m_{shell}}{a_{shell}} = \frac{9.9661}{1.475} = 6.76\ kg/m^2 s$$

$$(N_{Re})_s = \frac{G_s D_c}{\mu} = \frac{6.76 \times 17.89 \times 10^{-3}}{8.3896 \times 10^{-6}} = 14415$$

$$f = 1.87\ (14415)^{-0.2} = \underline{0.275}$$

$\therefore$ Shell side pressure drop

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

$$N_b = 0$$

$$\therefore \quad \triangle Ps = \left[\frac{4(0.275)\ (1)\ (1.219)\ (6.76)^2\ 9.81}{2 \times 9.81\ (17.89 \times 10^{-3}) \times 2.6}\right] \times 0.5$$

$$= 0.329\ KPa \quad < \quad 14\ Kpa$$

Mechanical Design

(a) Shell Side:

Material carbon steel (Corrosion allowance = 3mm)
Number of shells =1
Number of passes =6

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 = 64.6 ^{0}C
Temperature of the outlet =64.6 ^{0}C

Permissible Strength for
Carbon steel = 95 N/mm^2 [Ref : 4, p: 115]

b) Tube side :

Number of tubes =1740
Outside diameter =0.0191m
Inside diameter = 0.0157m
Length = 4.877m
Pitch, $\triangle^{lar}$ = 25.4 x 10^{-3} m
Feed =Water.
Working Pressure =1 atm = 0.101 N/ mm^2
Design Pressure =0.11 N/mm^2
Inlet temperature =25 ^{0}C.
Outlet temperature = 40 ^{0}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 = 1.219m =1219mm
f = Allowable stress value = 95 N/mm^2
J= Joint factor = 0.85

$$t_s = \frac{0.11 \times 1219}{2 \times 95\ (0.85) - 0.11} = 0.83\text{mm}$$

Minimum thickness = 6.3 mm (Including corrosion allowance)
$\therefore$ t_s = 8mm

Head : (Torrispherical head)

$t_h = \frac{PR_C W}{2fJ}$ [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 =1219mm
R_k = knuckle radius = 0.06 R_C

$\therefore W = ¼\{3+ \sqrt{R_c / 0.06 R_c}\}$ = 1.77

$\therefore t_h = \frac{0.11 \times 1219 \times 1.77}{2 \times 95 \times 0.85}$ = 1.47 mm

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

$\therefore t_h$ = 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 =1219mm
Shell side thickness =10mm

Outside diameter of shell =1219 + 10x 2 = 1239mm

Determination of gasket width :

$\frac{d_o}{d_i} = \left[\frac{y- pm}{y-p(m+1)} \right]^{½}$ (Ref :6 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

$$\frac{d_o}{d_i} = \left[\frac{25.5 - 0.11\,(2.75)}{25.5 - 0.11\,(2.75 + 1)}\right]^{1/2} = 1.0004$$

d_i = inside diameter of gasket = outside diameter of shell
= 1239 + 5mm
=1244 mm

d_o = outside diameter of the gasket
= 1.004 (1244)
= 1249 mm

$$\text{Minimum gasket width} = \frac{1.249 - 1.244}{2} = 0.0025m = 2.5\ mm$$

But minimum gasket width = 6mm
∴ G= 1.244 + 2 (0.006) = 1.256 m

G = diameter at the location of gasket load reaction

Calculation of minimum bolting area :

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

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

At 64.6^0C.

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

$$A_m = \frac{0.6037 \times 10^6}{138 \times 10^6} = 4.375 \times 10^{-3}\ m^2$$

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) [Ref: 6, pg :122]

C= 1.219 +2 (1.415 (0.0125)+0.027)=1.308m

Estimation of bolt loads :

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

$H = \frac{\pi}{4} (1.256)^2 (0.11 \times 10^6) = \underline{0.1363 \times 10^6 \text{ N}}$

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

$H_p = \pi (1.256)(2 \times 0.006)\, 2.75 \times 0.11 \times 10^6 = 0.0143 \times 10^6$ N

Total operating load (W_o) = H+H_p
= $\underline{0.1506 \times 10^6 \text{ N}}$

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

W_g. = π g b y [Ref: 4, pg :45]

$= \pi \times 1.256 \times 0.006 \times 25.5 \times 10^6$

$W_g = 0.6037 \times 10^6$ N

$W_g > W_0$

$\therefore W_g$ is the controlling load
$\therefore$ Controlling load = $\underline{0.6037 \times 10^6 \text{ N}}$

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

= 1.308 +0.018+ 0.02
= $\underline{1.346\text{m}}$

Check for gasket width :

A_b = minimum bolt area = $44 \times 1.54 \times 10^{-4}\ m^2$

$$\frac{A_b S_g}{\pi GN} = \frac{(44 \times 1.54 \times 10^{-4})138}{\pi \times 1.256 \times 0.012} = 19.75 \quad N/mm^2$$ [Ref: 6, pg :123]

$2y = 2 \times 25.5 = 51 \quad N/mm^2$

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

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 = $\underline{1.239\text{m}}$

$W_1 = \frac{\pi}{4} (1.239)^2 \times 0.11 \times 10^6 = 0.1326 \times 10^6$ N

$W_2 = H - W_1 = (0.1363 – 0.1326) \times 10^6 = 0.0037 \times 10^6$ N

$W_3 = 0.0143 \times 10^6$ N

$W_o = (0.1326 + 0.0037 + 0.0143) \times 10^6$

$= \underline{0.1506 \times 10^6}$ 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=1.308; B=1.239; G=1.256

$a_1 = \frac{1.308 - 1.239}{2} = 0.0345$

$a_3 = \frac{C - G}{2} = \frac{1.308 - 1.256}{2} = 0.026$

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

$M_o = [\, 0.1326 (0.0345) + 0.0037 (0.0303) + 0.0143 (0.026) \,] \times 10^6$

$= \underline{5.059 \times 10^3}$ J

(b) For bolting up condition :

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

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

$A_m = 4.375 \times 10^{-3}$

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

$S_g = 138 \times 10^6$

$W = \left(\frac{4.375 \times 10^{-3} + 67.76 \times 10^{-4}}{2}\right) \times 138 \times 10^6 = \underline{0.7694 \times 10^6}$

$M_g = 0.7694 \times 10^6 \times 0.026 = \underline{0.020 \times 10^6 \text{ J}}$

$\underline{M_g > M_o}$

$\therefore M_g$ is the moment under operating conditions

$M = M_g = 0.020 \times 10^6$ 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 = $\frac{\pi C}{n} = \pi\left(\frac{1.308}{44}\right) = 0.0934m$

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 (Ref : 6, pg : 24)

$M = 0.020 \times 10^6$ J

B = 1.239

$$K = \frac{A}{B} = \frac{\text{Flange diameter}}{\text{Inner Shell diameter}} = \frac{1.346}{1.239} = 1.086$$

Y = 24 (Ref : 6, pg : 115, fig:7.6).

$$t = \sqrt{\frac{0.020 \times 10^6 \times 1 \times 24}{1.239 \times 100 \times 10^6}} = \underline{0.0622\ m}$$

d = 18 x 2 = 36mm

$$C_F = \sqrt{\frac{0.0934}{2(36 \times 10^{-3}) + 0.0622}} = \underline{0.834}$$

$C_F = (0.913)^2$

t = 0.0622 x 0.913 = $\underline{0.057\ m}$

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

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.

$t_{1s} = 1.256 \sqrt{(0.25 \times 0.11 \times 10^6) / (95 \times 10^6)}$ = 0.0214 m

Channel and channel Cover

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

$= 1.256 \sqrt{(0.3 \times 0.11/ 95)}$

= 0.0234m =23.4mm

Consider corrosion allowance = 4 mm.

t_h=0.004 + 0.0234 = 0.0274 m.

Saddle support

Material: Low carbon steel

Total length of shell: 4.877 m

Diameter of shell: 1239 mm

Knuckle radius = 0.06 x 1.239 = 0.074 m = r_o

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

$= \sqrt{(1.239 \times 0.074 /2)}$

= 0.214 m

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

R=D/2=620 mm

Distance of saddle center line from shell end = A =0.5R=0.31 m.

Longitudinal Bending Moment

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

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

$= 12681.25\ (4.877 + 4 \times 0.214/3)/2$

$= 32732.42$ kg m

$M_1=32732.4 \times 0.31[1-(1-.31/4.877+(0.62^2-$
$0.214^2)/(2 \times 4.877 \times 0.31))/(1+4 \times 0.214/(3 \times 4.877))]$

$= 96.703$ kg-m

Bending moment at center of the span

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

$M_2 = 28629.58$ kg-m

Stresses in shell at the saddle

(a) At the topmost fibre of the cross section

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

$=96.703/(3.14 \times 0.62^2 \times 0.008)$

$= 1.0096$ kg/cm^2

The stresses are well within the permissible values.

Stress in the shell at mid point

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

$= 296.34$ kg/cm^2

Axial stress in the shell due to internal pressure

$f_p = PD/4t$

$= 0.11 \times 10^6 \times 1.219 /4 \times 0.008$

$= 419$ kg/cm^2

$f_2 + f_p = 715.34$ kg/cm^2

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