PROCESS DESIGN-MAJOR EQUIPMENT

Distillation Tower – 2.

This tower has a feed, binary mixture of methanol and water.

<u>Assumptions</u> :

1. Feed is the saturated liquid entering at b.p of methanol.
2. All assumptions for McCabe – Thiele method hold good here.
3. No heat loss from column.

From the material balance of this tower, we obtain,

D, Distillate (methanol) = 130.189 kmoles/hr

W, Residue (water) = 8.171 kmoles/hr

Since feed is saturated liquid, slope of q-line is ∞.Using equilibrium data for methanol from Perry.

$X_D/ (R_m + 1) = 0.655$; $R_m = 0.5226$

Assume reflux ratio 1.5 times the minimum, then R = 0.7839; $X_D/ (R +1) = 0.559$

The plot gives →

No. of ideal stages = 17

No. of ideal stages in tower = 16

No. of enriching section stages = 11

No. of stripping section stages = 6

Feed enters at 11^{th} tray.

L = R.D = 102.055 kmoles /hr

G = L + D = 232.244 kmoles /hr

L = L + qF = 240.415 kmoles /hr

G = G = 232.244 kmoles /hr

Table 3 :

	Enriching section		Stripping section	
	Top	**Bottom**	**Top**	**Bottom**
Liq. Kmoles/hr	102.055	102.055	240.415	240.415
Vap. Kmoles/hr	232.244	232.244	232.244	232.244
$(\overline{M})_{liq}$ kg/kmol	31.962	31.146	31.146	18.1404
$(M)_{vap}$ kg/kmol	31.962	31.538	31.538	18.1404
X	0.9973	0.939	0.939	0.01
Y	0.9973	0.967	0.967	0.01
Tliq	64.512	64.981	64.981	92.501
Tvap	64.571	67.201	67.201	98.418
Liq kg/hr	3261.88	3178.6	7487.9	4361.13
Vap kg/hr	7422.98	7324.5	7324.5	4212.9
P_L kg/m^3	453.56	484.58	484.58	978.25
P_v kg/m^3	1.1536	1.1295	1.1295	0.5928
$(L/G\ (P_G/P_L)^{0.5}$	0.02216	0.02095	0.04936	0.02548

Surface tension for mixture is evaluated as follows (Perry)

$$\sigma_{mix}^{1/4} = \psi_w \sigma_w^{1/4} + \psi_o \sigma_o^{1/4}$$

σ_w, surface tension of pure water = 71.4 dynes/cm

σ_o, surface tension of pure methanol = 22.6 dyn/cm

ψ_w is defined by relation,

$$\log \frac{(\psi_w)^q}{1-\psi_w} = \log\left(\frac{(X_w V_w)^q}{X_o V_o}(X_w V_w + X_o V_o)^{1-q}\right) + 0.441\ \frac{q}{T}\left(\frac{\sigma_o V_o^{2/3}}{q} - \sigma_w V_w^{2/3}\right)$$

V_w, Molar volume of water = 18.09 cm^3 /mol

V_o, molar volume of methanol = 40.98 cm^3/mol

For methanol, q = 1

$X_o = 0.9675$; $X_w = 0.03285$

Solving, $\Psi_w = 7.5 \times 10^{-3}$; $\Psi_o = 0.9925$

Then σ_{mix} = 22.827 dyn/cm

ENRICHING SECTION

Plate hydraulics

Tray spacing ts = 18" = 500 mm

Hole diameter d_h = 5.0 mm

Hole pitch l_p = 15 mm Δ

Tray thickness t_T = 3 mm

Total Hole Area / Perforated area, Ah/Ap = 0.1

From table 3 it is seen –

$(L/G)(\rho_G/\rho_L)^{0.5}$ = 0.02216, is maximum at top.

Using Perry : For t_s = 18", Csb, flood = 0.295 ft/s

$$Unf = (C_{sb}, \text{flood}) \left(\frac{\sigma}{20}\right)^{0.2} \left(\frac{\rho_L - \rho_v}{\rho_r}\right)^{0.5}$$

$$= (0.295) \left(\frac{22.827}{20}\right)^{0.2} \left(\frac{484.58 - 1.1295}{1.1295}\right)^{0.5}$$

= 6.267 ft/s = 1.91 m/s

U_n = 0.8 Unf = 1.52 m/s

Vol flow rate of vapour at top $= \frac{7324.5}{3600 \times 1.1295} = 1.801\ m^3/s$

Net area, An = 1.801 / 1.52 = 1.1786 m^2

Assume Lw/Dc = 0.75 Lw → Weir length

D_c → Plate diameter

$\theta_c = 2 \sin^{-1} (L_w/D_c) = 97.2°$

$A_c = 0.785\ Dc^2$

$$\text{Downcomer area, } A_d = 0.785\ D_c^2 \times \frac{\theta_c}{360} - \frac{0.75}{4} D_c^2 \cos \frac{97.2}{2}$$

$$= 0.08795\ D_c^2$$

$A_n = A_c - A_d$

$1.1786 = 0.69705 \ D_c^2$

$D_c = 1.3$ m

$L_w = 0.975$ m $\approx$ 1m

Then $L_w/D_c = 0.77$

$A_c = 1.3266$ m^2

$A_d = 0.1486$ m^2

Active area, $A_a = A_c - 2\,Ad = 1.029$ m^2

Perforated area, $A_p = A_a - A_{cz} - A_{2z} = 0.8039$ m^2

Calming zone, $A_{cz} = 0.134 \ A_c = 0.1459$ m^2

Waste peripheral zone, $A_{wz} = 0.06\ A_c = 0.07959$ m^2

Then $A_h = 0.08039$ m^2

No. of holes, $n_h = 0.08039 / \frac{\pi}{4} (0.005)^2 = 4094.23$

Weir height, $h_2 = 50$ mm (assumption)

Weeping check :

Head loss through holes, $h_d = k_1 + k_2 \dfrac{P_G}{P_L} U_h^2$

$k_1 = 0$; $k_2 = 50.8 / C_v^2$

For $A_h / A_a = 0.07812$ and $t_t / d_L = 0.6$,

$C_v = 0.74$; $K_2 = 92.77$ (Sieve trays)

Vol. flow of vap at top = 1.7874 m^3/s

U_h (at top) = 1.7874 / 0.08039 = 22.34 m/s

U_h (at bottom) = 1.801 / 0.08039 = 22.4 m/s

Then h_d (at top) = $92.768 \times (1.1536 / 453.56) \times 22.34^2$

= 146.79 mm clear liquid

h_d (at bot.) = 108.49 mm (min)

$h_\sigma = 409\ (\sigma/d_L\rho_L) = 4.117$ mm clear liq

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

$q = 18.22 \times 10^{-4}\ m^3/s; \quad q^1 = 28.882$ GPM

$q^1 / L_w^{2.5} = 28.882 / (3.2802)^{2.5} = 1.4814$

$L_w / D_c = 0.77$

→ For these values, $F_w = 1.005$

$h_{ow} = 1.005 \times 664\ (18.22 \times 10^{-4} / 1.0)^{2/3} = 9.955$ mm

Now, $(h_d + h_\sigma)$ (min) = 112.60 mm

$(h_w + h_{ow}) = 59.955$

These are design values

For $A_n / A_a = 0.07812$, $(h_d + h_\sigma) = 17$ mm

which is less than design value.

Hence no weeping.

h_{ow} → Segmental weir hit

h_σ → Head loss due to bubble formation

h_{ds} → Dynamic seal

h_{hg} → Hydraulic gradient

h_t → Total pressure drop across plate

D.C. Flooding Check

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

q (max. at top) = $19.97 \times 10^{-4}\ m^3/s$ = 31.667 GPM

For $q^1 / L_w^{2.5} = 1.624$ and $L_w/D_c = 0.77$, $F_w = 1.01$

$h_{ow} = 10.64$ mm (max. at top)

$h_{ds} = 60.64$ mm

U_a (bot.) = 1.75 m/s = 5.7414 ft/s

U_a (top) = 1.737 m/s = 5.699 ft/s

$F_g\ a = U_a \rho_g^{1/2} = 1.86$

$\beta = 0.59$; $\phi_t = 0.2$

$h_e^1 = \beta . h_{ds} = 35.78$ mm

$h_f = h_e^1 / \phi_t = 178.9$ mm

$h_{ad} = 165.2 \ (q/A_{da})^2$ A_{da} - Min. flow area under down comer.

C → 13 to 38 mm

Let C = 1 – in = 25 mm

$L_{ap} = h_{ds} - C = 35.64$ mm

$A_{da} = L_w \times h_{ap} = 0.03564 \ m^2$

had = 0.5187 mm

$h_t = h_d$ (top) + h_e^1 = 146.79 + 35.78 = 165.75 mm

D.C. Back-up

$h_{dc} = h_t + h_w + h_{ow} + h_{hg}$ + had = 24.36 mm

Taking $\phi_{dc} = 0.5$; $h^1{}_{dc}$ S = 243.6 / 0.5 = 487 mm

$h_{dc} < t_s$. NO FLOODING.

STRIPPING SECTION

t_s = 500 mm

d_h = 5.0 mm

l_p = 15 mm Δ pitch

t_T = 3 mm

$A_h / A_p = 0.1$

$(L/G) \ (f_G / P_L)^{0.5}$ = 0.04936 (max. at top)

C_{sb} , flood = 0.28 ft/s

Surface tension is calculated to be 38.289 dyne / cm = σ_{mix}

U_{nf} = 6.596 ft/s

U_n = 0.8 U_{nf} = 5.277 ft/s

= 1.6084 m/s

Vol. flow rate of vapour at top (max) = 1.8013 m^2 /s

A_n = 1.1199 m^2

Assuming a $L_w / D_c = 0.75$; $\theta_c = 97.2°C$.

D_c is found to be 1.267 m. We assume D_c = 1.3 m for simplification of design and to bring down tower cost.

L_w	$= 0.955 \approx 1m$	L_w / D_c	$= 0.77$
A_c	$= 1.3266\ m^2$	A_{cz}	$= 0.1459\ m^2$
A_d	$= 0.1486\ m^2$	A_h	$= 0.08039\ m^2$
n_h	$= 4094.23$	A_p	$= 0.8039\ m^2$
A_a	$= 1.029\ m^2$	A_{wz}	$= 0.07959\ m^2$

Weeping Check

$A_h / A_a = 0.07812$; $t_T / d_h = 0.6$

Then $C_v = 0.74$; $K_2 = 92.77$

Vol. flow of vapour at top = $1.8013\ m^3/s$

Vol. flow of vapour at bot. = $1.9741\ m^3/s$

$A_h = 0.08039\ m^2$

U_n (at top) = 22.4 m/s

U_h (at bot.) = 24.56 m/s

h_d (at top) = 108.499 mm clear liq. (max)

h_d (bottom) = 33.909 mm clear liq. (min)

h_σ = 3.2 mm liq.

q (bottom) = $12.3836 \times 10^{-4}\ m^3/s$; q^1 = 19.63 GPM

For $q^1 / L_w^{2.5} = 1.0069$ and $L_w / d_c = 0.77$, $F_w = 1/02$

h_{ow} = 7.793 mm clear liquid

$(h_d + h_\sigma)$ min = 37.109 mm; $h_w + h_{ow}$ = 57.793 mm

For $A_h / A_a = 0.07812$

$(h_d + h_\sigma)$ plot = 15.5 < design value

NO WEEPING

D.C. Flooding Check

q (max. at top) = $42.92 \times 10^{-4}\ m^3/s$

q^1 = 680.4 GPM

For $q^1 / (L_w)^{2.5}$ = 45.42 and $L_w / D_c = 0.77$

F_w = 1.75

h_{ow} = 20.57 mm liq

h_{ds} = $h_w + h_{ow}$ = 70.57 mm

U_a (top) = 1.7507 m/s

= 5.743 ft/s

F_{ga} = 1.104 → $\phi = 0.21$; $\beta = 0.61$

h_e^1 = 43.048 mm

h_f = 215.34 mm

c = 25 mm, h_{ap} = 45.57 mm

A_{da} = 0.04557 m^2

h_{da} = 1.4655 mm

h_t = 151. 547 mm

Actual D.C. Back-up

h_{dc} = 223.58 mm

h_{dc}^1 = h_{dc} / ϕ_{dc} ϕ_{dc} = 0.5

= 447.165 $< t_s$ NO FLOODING

Column Efficiency

a. Enriching Section

Calculation of EOG : h_w = 50 mm

Avg. vapour rate = 7373.74 kg/hr

Avg. density = 1.14155 kg/m^3

A_a = 1.029 m^2 ; U_a (top) = 1.737 m/s

D_f = $(D_c + L_w)/2$ = 1.15 m

Avg. liquid rate = 3220.24 kg/hr

Avg. liquid density = 469.07 kg/m^3

q = 19.97×10^{-4} m^3/sec

$w = q/D_f = 17.36 \times 10^{-4}\ m^3/sec.\ m$

$N_g = (0.776 + 0.00457\ h_w - 0.238\ U_{aP}g^{0.5} + 105\ w)\ (N_{scg})^{-0.5}$

$N_{scg} = (\mu_g/\rho_g D_g) = 0.578$, Schimdt No.

Gas viscosity and diffusivity in mixture are evaluated as follows :

$T_{vap} = 65.886°C$

$(\mu_g)_{CH3OH} = 0.015 \times 10^{-3}$ p. ; $(\mu_g)_{H2O} = 1200 \times 10^{-8}$ p.

$y_1 = 0.98215$ $y_2 = 0.01785$

$\rho_g = 1.153\ kg/m^3$

$$D_g = D_{AB} = \frac{10^{-3}\ T^{1.75}\ [1/\mu_A + 1/\mu_B]^{0.5}}{P\ [(\Sigma\ \gamma_i\ A)^{0.33} + (\Sigma\gamma_i B)^{0.33}]^{2+}}$$

$\Sigma\ \gamma_i A = 29.9$

$\Sigma\ \gamma_i B = 9.44$

$D_{AB} = 29.38 \times 10^{-6}\ m^2/s$

$N_g = 0.977$

$N_L = K_L.\ a.\ \theta_L$

$K_L\ a = (3.875 \times 10^8 \times D_l)^{0.5}\ (0.4\ U_a P_g^{0.5} + 0.17)$

Liquid diffusivity Calculation

$D_l = (7.4 \times 10^{-8}\ (\theta\ M_B)^{0.5}\ T)\ (n_B\ \gamma_A)^{-6}$

$\phi_{CH3OH} = 1.9$

$M_B = 32.04$

$T = 337.5$ K

$n_B = 0.34$ cp

$\gamma_A = 14.8\ cm^3$ / gmol, molar volume of water

$D_e = D_{AB} = 113.7 \times 10^{-10}\ m^2/s$

$K_L\ .\ a = 1.259\ (sec)^{-1}$

$\theta_L = h_L\ .\ A_a / (1000\ q)$

$h_L = h_L^1 = 35.78$ mm

$A_a = 1.029\ m^2$

$q \quad = 19.95 \times 10^{-4}\ m^3 / sec$

$\theta_L \quad = 18.43\ sec$

$\therefore N_L = 23.2115$

$m_{top} \quad = 0.241$

$m_{bot} \quad = 0.35$

$G_m / L_m \ \ 2.27$

$\left.\begin{array}{l} \lambda_t = 0.547 \\ \lambda_b = 0.7945 \end{array}\right\} \quad \lambda = 0.7877$

$N_{og} \quad = [\ (1/N_g) + (\lambda / N_L)\ ]^{-1} \quad = 0.9436$

$EOG = 1 - e^{-NOG} \quad = \underline{0.6115}$

Murphee Plate Efficiency, E_{MV}

$Z_L \quad = D_c Cos\ (\theta_c/2) \quad = 0.8597\ m$

$\theta_L \quad = 18.43\ sec$

$D_E \quad = 6.675 \times 10^{-3} \times U_a^{1.44} + 0.92 \times 10^{-4}\ x\ h_L - 0.00562$

$\quad = 0.01246\ m^2/s$

N_{Pe}, Peclet No. $= Ze^2 / DE\ \theta_L = 3.218$

For λ EOG = 0.4816 and $N_{Pe} = 3218$,

$E_{mv} / EOG = 1.1$

$\therefore E_{mv} = 0.67265$

Overall Column Efficiency, EOC

$E_{OC} \quad = N_{th} / N_{act}$

$E_{OC} \quad = \log\ (1 + Ea\ (\lambda - 1)) / \log \lambda$

$E_a / E_{mv} = 1/\ [\ 1+E_{mv}\ (\ \psi / 1\text{-}4)\ ]$

For 80% flooding and $(L/G)\ (P_G / P_L)^{0.5} = 0.0215$,

$\psi \quad = 0.14$

$E_a \quad = 0.6063$

E_{oc} = 0.5773

N_{act} = N_{th} / E_{oc} = 19.05 = 19 trays

$\therefore$ Tower height = $t_s \times N_{act}$

= 9.5 m

Stripping Section

Cal. of EOG : h_w = 50 mm

Avg. vapour rate = 5768.7 kg/hr

Avg. density = 0.7964 kg / m^3

U_a = 1.7507 m/s

D_f = 1.15 m

Avg. liquid rate = 5924.15 kg/hr

Avg. density = 731.415 kg/m^3

q = 27.6518×10^{-4} m^3/s

w = 24.045×10^{-5} m^3/sec m

N_{sg} = 0.429

Properties of gas mixtures after evaluation are as follows :

Mg = 1.29×10^{-5} P_{as}

P_g = 0.9358 kg/m^3

D_g = 32.14×10^{-6} m^2/s

$\therefore$ N_g = 0.9563

Liquid diffusivity, D_e = 39.6×10^{-10} m^2/s

θ_L = 16.03 sec

$\therefore$ N_L = 16.832

mtop = 0.35

m_{bot} = 4.44

G_m / L_m = 0.978

λ_t = 0.342
λ_b = 4.32 } λ = 2.3425
N_{og} = 0.844

EOG = 0.5701

<u>EMV</u> :

Z_L = 0.8597

D_E = 0.0133 m^2/s

N_{Pe} = 3.47

For λ EOG = 1.335 and N_{Pe} = 3.47

E_{mv} / EOG = 1.5

$\therefore$ E_{mv} = 0.855

<u>EOC</u> :

For 80% flooding and (L/G) $(P_G / P_L)^{0.5}$ = 0.04936, ψ = 0.07

E_a = 0.8033

E_{oc} = 0.859

N_A = 6.98 = 7 trays

Tower height = <u>3.5 m</u>

8. PROCESS DESIGN -MINOR EQUIPMENT

Total condensor (horizontal)

Methanol vapours leaving top of the distillation tower are condensed using cooling water on tube side. From energy balance and mass balance, we have –

mass m_1 of methanol vapors = 1.1586 kg/s

mass m_2 of cooling water = 32.069 kg/s.

Log Mean Temperature difference is found to be 31.4775°C

Assume overall h.t. coeff. Ud = 500 W/m^2k

H.T. area A = Q/U (LMTD)

Q from heat balance, = 2010.72 kJ/s

Choosing 3/4 – in O.D. 16 BWG tubes with O.D. = 19.05 mm

I.D. = 15.748 mm

a = 0.05987 m^2/m length

And with shell length L = 16 ft = 4.88 m,

No. of tubes N_t = 127.75 / (4.88 – 0.05) (0.05987)

= 441.77 tubes

Let us choose TEMA L or M-type with 480 tubes of 3/4 –in O.D. on 1 - in Δ pitch

1 –4 passes

Shell dia = 27" - 686 mm

Corrected H.T. area = 138.768 m^2

Corrected U_{od} = 460.43 $W/m^2 . K$

Shell side mean temp. = 64.571°C

Tube side mean temp. = 32.5°C

Assuming a condensing film transfer co-efficient of 1500 W/m^2K,

$(64.571 – T_w)$ A (1500) = (64.571 – 32.5) A (460.4)

T_w = 54.726°C, Wall temp.

T_f = (64.571 + 54.726) / 2) = 59.6485°C, film temp.

<u>Tube side velocity</u> :

Flow area at $= \pi/4 \times [15.748 \times 10^{-3}]^2 \times \frac{480}{4}$

$= 0.02379$ m

$V_t = 32.069 / (994 \times 0.02379) = 1.35$ m/s

Let N_v be avg. number of tubes in vertical row.

$\rho_L = 746$ kg/ m^3 ; $\mu = 0.59$ cp; K = 0.163 W/mk.

Tubes in central row $= D_b / P_T$

$D_b = D_o \, [Nt / K_1]^{1/n}$

$= 586$ mm

$K_1 = 0.249$ and $n_1 = 2.207 \rightarrow$ Table 12.4 of Coulson and Richardson

Then tubes in central row = 23

(P_T = 25. mm) and $N_v = (2/3) \times (23) = \underline{16}$

<u>Film transfer coefficients</u> :

$$h_o = 0.95 \, K_L \left(\frac{\rho_L (\rho_L - \rho_v)}{\mu_{L.} \, \Gamma_h} \right)^{1/3} [N_v^{-1/6}]$$

$\Gamma_h \rightarrow$ the tube loading, condensate flow per unit length of the tube.

$\Gamma_h = 1.157 / (4.88 \times 48) = 4.93 \times 10^{-6}$ kg/ms

$\rho_v = 1.87$ kg/m^3

$h_o = \underline{1296 \text{ W/m}^2\text{K}}$

<u>Tube side</u> : T = 32.5°C

P = 994 kg / m^3

μ = 0.724 cp

K = 0.62 w/mk

$(N_{Re}) = D_i VP / \mu = 2.9228$

$(N_{Po}) = \mu C_p / K = 4.87$

$N_{Nu} = 0.023 (N_{Re})^{0.8} (N_{Pr})^{0.4} = 161.949$

$h_i D_o / K = 161.949$

$1/Uod = 1/1295.5 + 19.05 / (15.746 \times 6375) + 19.03 \times 10^{-3} \times \ln (19.05 / 15.748) \times 1 / (2 \times 45) + 5 \times 10^{-4}$

Dirt factor is assumed.

$U_{od} = 597.65 \quad W/m^2K > U_{ad}$ assumed

Pressure drop : Bell's method, using Perry Tube side – cooling water.

$(N_{Re}) = 29228$

$(N_{Pr}) = 4.87$

$h_i = 6375\ W/m^2K$

$\Delta P_L = 2fLV_t^2 \rho_t / D_1$

$f = 0.079 (N_{Re})^{-0.25} = 0.006$

$\therefore \Delta P_L = 6739.85\ N/m^2$

$\Delta P_E = 2.5 [P_t V_t^2 / 2] = 2264.45\ N/m^2$

$\Delta P_{total} = N_p [\Delta P_L + \Delta P_E] = 36.012\ KN/m^2$

Shell Side : Methanol vapours

ρ_{vap} (64.571 °C) $\rightarrow$ 1.93 kg/m^3

$\mu_{vap} \rightarrow 0.0135$ cp

Let N_b, No. of baffle = 5

L_s, baffle spacing = $L / (N_b + 1) = 0.81$

$S_m = [(P^1 = Do) Ls] (Ds/P^1)$

$= 0.1136\ m^2$

$V_s = m/\rho s_m = 7.24$ m/s

$N_{Re} = 91703$

Let us consider 30% baffle cut,

$L_c = 0.3 \times 0.686 = 0.205$ m

P_P, pitch parallel to flow $= (\sqrt{3} / 2) \times 25.4 = 22$m

N_c, No. of tube rows crossed in each cross – flow region,

$= D_s \ (1 - 2 (l_c/D_s) / P_P = 12.47$

ΔP in cross flow section

$\Delta P_c \ = [\ b.\ f_K\ .\ W^2 \times N_c / \rho_t.\ Sm^2\ ]\ [\mu_w / \mu_b]^{0.14}$

$b \ = 2 \times 10^{-3} \quad f_K \quad = 0.1$

$\Delta P_c \ = 0.469$ KPa

$(\Delta P)_t \ = 2\Delta P_{\#} + (N_b - 1) + N_b\ \Delta\ P_w$

ΔP in end zones, $\Delta P_E = \Delta P_c\ [\ 1 + N_{cw} / N_c\ ]$

New number of effective tubes, $= 0.8\ L_c/P_P$

$= 7.45 = 8$

$\Delta P_E \ =$ <u>0.796 KPa</u>

Window Zone : $\Delta P_w = b_w^2\ (2 + 0.6\ N_{cw}) / S_m.\ S_w.\ P.$

$B = 5 \times 10^{-4}$

S_w, area of flow through window $= 150 - \text{inch}^2$

S_{wt}, area occupied by tubes $= (N_t/8)\ (1\text{-}F_c)\ \pi\ Do^2$

$L_s / D_s = 0.3,\ F_c = 0.55$

$S_{wt} \ = 0.009798\ m^2$

$\therefore\ \Delta P_w = 0.831\ KN/m^2$

$(\Delta P)_t \ = 2\Delta P_E + (N_b - 1)\ \Delta P_c + N_b.\ \Delta\ P_w$

$= \underline{8.923\ KN/m^2}$

9. MECHANICAL DESIGN

Major : <u>Distillation Tower – 2</u>,

Shell diameter = 1300 mm = 51.18” = 4.265[1]

Working pressure = 1 atm = 14.7 lb/sq- in gauge

Design pressure = 16.17 lb / sq- in gauge

Shell length = 13 m = 42.6504 - in

Shell material = SA – 283, Grade C

Shell, double welded butt joints stress relieved but not radiographed.

Tray spacing = 18” – in

Skirt height = 3 m

Corrosion allowance, C = 1/8 – in

Tray support rings = 2.5 – in $\times$ 2.5 – in 3/8 – in angles

Insulation = 3 – in on column

Accessories $\rightarrow$ one caged ladder

Overhead vapor line - 12 – in, outside dia

Making use of Brownell and Young, calculation of minimum shell thickness.

t_{sh} = P/(SXE – 0.4 P) +C

= 0.1605 – in

But min. shell thickness must be 8 mm = 5/16 – in

SA – 283, Grade C, has allowable stress.

f = 12m650 psi

E, Joint Efficiency

Selection of head – torispherical

Thickness + = 0.885 pr / (fE – 0.1 p) + C

= 0.16 - in

Min. thickness should be 15/16 – in

<u>Black Dia</u> = O.D. + O.D / 24 + 2 Sf + 2/3 icr

Sf $\rightarrow$ Standard st. flange = 3 – in

icr $\rightarrow$ Inside corner radius = 15/16"

then B.D. = 70.6 – in

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

= 346.89 lb

= 157 kg

Calculation of axial stress

Assume di = d_0 = 5.18 – in

Axial stress, $f_{ap} = Pd/4\,(t_s - c) = 1003.13$ psi

Calculation of dead weight

f dead wt. shell = 3.4x

f dead wt. insulation = $\rho_{ins} \times t_{ins} / 144\,(t_s - c)$

= 4.44x

insulation – asbestos, ρ_{ins} = 40 lb/cuft

Weight of top head = 346.89 lb

Weight of ladder = 25.00 lb per ft

Weight of 12 – in schedule 30 pipe (Appendix K)

= 43.8 lb per ft

Weight of pipe insulation = $\pi/4\ (1.5^2 - 1.0^2)\ 40$

= 39.3 lb per ft.

Adding up all these weights, W = 346.89 + 108.1x

f dead wt. attachments (not including trays) = $\sum W/\pi d\,(t_s - c)$

= 11.506 + 3.586 x

The wt. of trays plus liquid (below × = 4) is calculated as follows –

n = (x/2) – 1

f dead wt. (liq + trays) = $\dfrac{(x/2 - 1)\ 25\,(\pi D^2 / 4)}{12\,\pi D\,(t - c)}$

$= 5.925\,x - 11.85$

Adding all, fdw $= 17.351\,x - 0.344$

<u>Calculation of stress due to wind loads</u> :

Assume wind pressure $= 25$ psi

$f_{wx} = 15.89\ \text{deff.}\ x^2 / d_0^2\ (t_s - c)$

def = insulated tower + vapor line

$= (51.2 + 6) + (12+6) = 75.2$ – in

$f_{wx} = 2.43x^2$

Calculation of combined stresses under operating conditions

Upwind side : $f_t\ (max) = f_{wx} + f_{ap} - f_{dx}$

$f_{t\,(max)} = 2.43\,X^2 + 1003.13 - 17.351\,X$

i.e. $= (12650)\,(0.85)$

Solving, x = <u>67 ft</u>

<u>Downwind side</u> : $f_c\ (max) = f_{wx} - f_{ap} + f_{dx}$

$f_c\ (max) = 2.43\,X^2 + 17.351\,X - 1003.474$

From elastic stability,

$f_c = 1.5 \times 10^6\ (t/r)$

$= 10986.3$ psi $\leq 1/3$ (yield pressure = 40,000)

Solving x = 66.76 ft.

If credit is taken for the stiffening effect of tray support rings, a higher allowable compressive stress will result. Therefore $t_t = t_s + (A_y / d_y)$

$t_y \rightarrow$ equivalent thickness of shell, inches

$A_y \rightarrow$ c.s.a of one circumferential stiffener, in

$t_x = t_s$ (since no longitudinal stiffeners are used)

The tray support rings are $2\frac{1}{2} \times 2\frac{1}{2} \times 3/8$ -in angles

$A_y = 1.73$ sq – in

$d_y = 18''$ (tray spacing)

t_y = 0.1875 + 1.73/18 = 0.2836 –in

But f_c = 1.5×10^6 $(ty\ tx)^{1/2}$ / r ≤ 1/3 y.p.

12,011.8 ≤ 1/3 (40000)

$2.43\ x^2 + 17.351\ x - 12.0131 = 0$

Solving, x = <u>66.83 ft.</u>

Stress conditions are satisfied for a tower height of 42.65 –in. We choose 6 courses of 8 –ft wide and 5/16 –in plate.

So the actual tower height = 6×8 = <u>48 ft.</u>

Design of Flanges

Design pressure = 16.17 psi

Flange material - ASTM – A – 201, grade B.

Bolting material - ASTM A – 193, grade B-7

Gasket material - Stainless steel

Shell outside dia = 51.18 –in

Shell thickness = 5/16 –in

Allowable stress of flange material = 15,000 psi

Allowable stress of bolting material = 20,000 psi

Calculation of gasket width

d_o/d_i = $(Y - pm / (y - p\ (m+1)))^{½}$

Y, min. design seating stress = 3700

m, gasket factor = 2.75

d_o/d_i = 1.002

Assume d_i of gasket to be 53 –in

Then do = 53.06 –in

Min. gasket width = (53.06 – 53)/2 = 0.028 –in

Therefore use a ½ -in gasket width

Then mean gasket diameter G = 53.5 in

Then d_o = 54 –in

Calculation of bolt loads

Load to seat gasket, $Wm_2 = H_y = b\pi GY$

$b_o = 0.5/2 = 0.25 = b$

$Wm_2 = Hy = 1{,}55{,}470$ lb

Load to keep joint under operation, $H_p = 2b\pi Gpm =$ <u>7474lb</u>

Load from internal pressure, $H = (\pi G^2/4)p = 36{,}350$ lb

Total operating load, $Wm_1 = H + H_p = 46{,}541.7$ lb

$Wm_2 > Wm_1$

Controlling load is 1,55,470 lb

Calculation of minimum bolting area

$Am_2 = Wm_2 / f_b$ $\quad\quad f_b = 20{,}000$ psi

$= \underline{7.7735}$ sq –in

By using shape constants,

K = A/B = O.D. of flange / shell dia = 1.24

A = 63.46 –in

Taking 5/4 –in bolt size whose root area = 0.202 sq –in, no. of bolts is

$$n = \frac{2y\,\pi G \times \text{gasket width}}{\text{Root area} \times f_b}$$

= 154 bolts

A_b, actual total c.s.a of bolt = (154) (0.202)

= 31.108 sq –in

Moment Computations

For bolting up condition (no internal pressure)

Design load is given by,

W = (Ab + Am) f /2 = 3, 8, 8815

The corresponding level arm is given by :

$h_G = (C – G) / 2 = 11.5$

C $\rightarrow$ O.D. of gasket + 2 $\times$ dia of bolt = 56.5 in

<u>Flange Moment</u> :

M_a = Wh_G = 5,83,225.5 lb

For operating condition,

$W = Wm_2$

For H_D ; H_D = $0.785\ B^2_p$

= 33,249.13 lb

The lever arm h_D = (C – B) / 2 = 2.66 in

Moment M_D = $H_D \times h_D$

= 88442.7 in – lb

H_G = $H_y - H$

= 1,19,120 lb

h_G = 1.5

Moment $M_G = H_G \times h_G$ = 1,78,680 in-lb

H_T is given by $H_T = H - H_D$ = 3100 lb

The corresponding lever arm, $h_T = (h_D + h_G) / 2$

= 2.08 –in

Moment $M_T = H_T \times h_T$

= 6448 in –lb

∴ The summation of moments for operating condition $M_o = M_D + M_G + M_T$

= 2,73,570.7 in-lb

Therefore the operating moment is controlling and M_{max} = 2,73,570.7 in-lb

<u>Calculation of flange thickness</u> :

$t = (y.\ M_{max} / f.B)^{½}$

For K = 1.24, from figure, y = 10

t = 1.63 -in = 41.5 mm

Stress due to seismic loads

Total dead wt. stress f_{dw} = 17.351 × - 0.344

X, Actual tower length = 48”

$\therefore$ f_{dw} = 832,504 psi

$\therefore$ The total wt. of dead loads is

= $f_{dw} \times$ c.s.a. of tower

$\sum W_x$ = 48 ft = $f_{dw} \times \pi \times d \times t_s$

= 41829.9 lb

W_{avg} = 41829.9 / 48 = 871/46 lb/ft

From table 9.3, C = 0.04

M_{sx} = $4CWX^2 [3H - X] / H^2$

= $4 \times 0.04 \times 4182.9 \times 48^2 [3 \times 60 - 48] / 60^2$

= 5,65406.4 in-lb

Corresponding stress is – f_{sx} = $M_{sx} / \pi r^2 (ts - c)$

= 1,466.524 psi

At X = 48.0 ft wind load stress is

F_{wx} = $2.43 X^2$ = 5,598 psi < f_{sx}

$\therefore$ Wind loads are controlling rather than seismic.

10. MECHANICAL DESIGN-MINOR EQUIPMENT

Horizontal condensor

using M.V. Joshi

Shell side : 1 –4 passes

Material – carbon steel

Corrosion allowance = 3mm

Working pressure = 0.1 N/mm^2

Design pressure = 0.11 N/mm^2

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

Tube side :

Working pressure = 0.5 N/mm^2

No. of tables – 688

d_o = 19.05 mm

d_i = 15.748 mm

Length, L = 4.88 m

Design pressure = 0.55 N/mm^2

Shell thickness → t_s = PD / (2fJ + P)

= 0.47 mm

Minimum thickness of shell must be 6.3 mm, with corrosion allowance, let t_s=8mm

Head thickness → Shallow dished and Torispherical head

t_h = PR_cW / 2 fJ

Rc, Crown radius

W, stress intensification factor

Rx, Knuckle radius = 0.06Rc

$W = ¼ [3 + (Rc/Rk)^{½}] = 1.77$

Rc = 1, Rk = 0.06

tn = (0.11 x 686 x 1.77)/(2x 95x1) = 0.858mm from IS 4503 – 1967

min head thickness = 10mm

Baffles :

No. of baffles = 5

Thickness = 6mm IS : 4503 – 1967

Tie Rods and spaces

From IS – 4503 – 1967, for shell dia = 686mm

Dia of rod = 12mm

No. of tie rods = 6

Flanges

Flange material, IS 2004 – 1962, Class R

Bolting steel → 5% G M_o steel

Gasket material – asbestos composition

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

Determination of gasket width

do/di = 1.002 with $y = 25.5\ MN/m^2$

$m = 2.75$

Assumed gasket width = 1.6mm

Let di of gasket = 7.4mm

Then do =0.7054m

Taking a gasket width of 0.01m = N

do = 0.724

mean gasket dia, G= di + N = 0.705m

Estimation of bolt loads

Load due to design pressure,$H = \pi G^2 P/4 = 0.043$ MN

Load to keep joint tight under operation, $Hp = \pi G (2b)mp = 0.0082$MN

Total operating load, $W_m = H + Hp = 0.0512$MN

Load to seat gasket under botten up condition $Wm_2 = \pi GB = 0.3456$MN

Wm_2 is controlling

Calculation of minimum bolting area,

$Am_2 = Wm_2 / S = 0.3456/138 = 2.5 \times 10^{-3} m^2$

Total flange moment

$M_o = W_1a_1 + W_2a_2 + W_2a_3$

$a_1 = (C-B)/_2 = 0.037M$

$a_3 = (C-G)/_2 = 0.0275M$

$a_2 = (A_1 + A_3)/_2 = 0.03225m$

M_o = 1.8054 x 10-3 MN

For bolting up condition

$Mg = Wa_3$

$W = (Am_2 + Ab)Sg /2$

$Ab = 44 (1.54 \times 10^{-4})$

$= 6.76x10^{-3} m^2$

W = 0.639MN

Mg = 0.0176MN

Mg > Mo; Mg is controlling

Mg = M

Calculation of flange thickness,

$t = (My/BS_{Fo})^{½}$

For K = 1.163; y = 15 → S_{Fo} = 100

Bolt circle dia, C = O.D gasket + 2 x bolt dia

C = 0.724 + 2 x 0.018

= 0.76m

No. of bolts = 44, bolt dia = 18mm

Calculation of flange O.D

A = C + bolt dia + 0.02

= 0.798m

Check of gasket width

$AbSg/\pi GN = 42.22 < 2y$

Hence, satisfied.

Flange moment computations

For operating conditions, $W_o = W_1 + W_2 + W_3$

$W_1 = \pi B^2 P/_4$

= 0.04066 B – shell dia

$W_2 =$ H-W1

= 0.00234 MN

Hp, gasket load = 0.0082MN

Then t = 0.062m

Standard flange thickness = 50mm

Tube sheet thickness

$t_{TS} = FG\ (0.25P/f)^{½}$ f = 95, F = 1

= 0.0268m

= 27mm.

With corrosion allowances, t_{TS} = 30mm

Nozzle : shell side

Select inlet x outlet dia = 100mm

Vent = 50mm

Drain = 50mm

Opening for relief valve = 75mm

Nozzle thickness tn = PD/ (2fJ – P)

J = 1, for seamless pipe

tn = 5.9836×10^{-2}mm

using a corrosion allowance of 3mm

tn = 4mm

Tube side

Inlet and outlet dia   = 100mm

Nozzle thickness tn = 3.6mm

With corrosion allowance, tn = 8mm

Support for the vessel – saddle

Material → low carbon steel