

DISTILLATION TRAY TOWER DESIGN

(SIEVE PLATE)

$$F = 40.26 \text{ kmol/s} \quad ; \quad D = 35.58 \text{ kmol/s} \quad ; \quad W = 4.68 \text{ kmol/s}$$

From figure $X_D/(R_m + 1) = 0.71$; $R_m = 0.394$

Assuming $R = 1.5R_m = 1.5 \times 0.394 = 0.5915$

$$L = R \cdot D = 0.5915 \times 35.58 = 21.05 \text{ kmol/hr}$$

$$G = L + D = 21.05 + 35.58 = 56.63 \text{ kmol/hr}$$

$$L = L + qF = 21.05 \text{ kmol/hr} \quad \quad \quad (q = 0)$$

$$G = G + (q-1)F = 16.37 \text{ kmol/hr}$$

	L	G	X	Y
ENRICHING SECTION				
Top	21.05	56.63	0.99	0.99
Bottom	21.05	56.63	0.89	0.98
STRIPPING SECTION				
Top	21.05	16.37	0.89	0.98
Bottom	21.05	16.37	0.15	0.4

	L (kg/hr)	G (kg/hr)	L/G(ρ_g/ρ_l)^{0.5}
ENRICHING SECTION			
Top	2237.2	6018.64	0.0216
$\rho_g = 2.7 \text{ kg/m}^3$			
$\rho_l = 800 \text{ kg/m}^3$			
Bottom	2296.13	6177.2	0.0225

$$\rho_g = 2.9 \text{ kg/m}^3$$

$$\rho_l = 795 \text{ kg/m}^3$$

STRIPPING

SECTION

Top	2296.13	1785.64	0.078
-----	---------	---------	-------

$$\rho_g = 2.9 \text{ kg/m}^3$$

$$\rho_l = 795 \text{ kg/m}^3$$

Bottom	2732.29	2124.83	0.0797
--------	---------	---------	--------

$$\rho_g = 3.0 \text{ kg/m}^3$$

$$\rho_l = 780 \text{ kg/m}^3$$

Feed temperature = 111.5°C ; Top temperature = 113.2°C

Bottom temperature = 149.3°C

ENRICHING SECTION

Plate hydraulics

Let $t_s=500$ mm, $d_h=5.0$ mm, $l_p=15$ mm on triangular pitch

$t_T=3.0$ mm and $A_h/A_p=0.1$ (say)

$$(L_b/G_b)(\rho_g/\rho_l)^{0.5} = 0.0225 \text{ (max at bottom)}$$

for $t_s=18$ inch. $C_{sb, flood}=0.275$ ft/s

$$\begin{aligned} U_{nf} &= C_{sb, flood}(\sigma/20)^{0.2} \{(\rho_l - \rho_g)/\rho_g\}^{0.5} \\ &= 0.275(28.48/20)^{0.2} \{(795-2.9)/2.9\}^{0.5} \\ &= 4.88 \text{ ft/s} \end{aligned}$$

let $U_n = 0.8 U_{nf} = 3.9$ ft/s = 1.19 m/s

Vol flow rate of vapour = $6177.2/3600 \times 2.9 = 0.59$ m³/s (max at bottom)

$$A_n = \text{vol flow rate of vapour}/U_n = 0.59/1.19 = 0.496 \text{ m}^2$$

Let $L_w/D_c = 0.75$

$$\Theta_c = 2\text{Sin}^{-1}(L_w/D_c) = 97.2^\circ$$

$$A_c = 0.785 D_c^2$$

$$A_d = 0.785 D_c^2 (\theta_c/360) - 0.25 L_w / D_c \cos(\theta_c/2)$$

$$A_d = 0.0879 D_c^2$$

$$A_n = A_c - A_d$$

Substituting the values

$$0.496 = 0.785 D_c^2 - 0.0879 D_c^2$$

$$D_c = 0.8435 \text{ m}, \text{ take } D_c = 0.85 \text{ m}$$

$$\text{So } L_w = 0.75 \times 0.85 = 0.6375 \text{ m or } 0.64 \text{ m}$$

$$\theta_c = 2 \sin^{-1}(L_w/D_c) = 2 \sin^{-1}(0.64/0.85) = 97.7^\circ$$

$$A_c = 0.567 \text{ m}^2 ; A_d = 0.0635 \text{ m}^2$$

$$A_c - 2A_d = A_a$$

$$A_a = 0.449 \text{ m}^2$$

$$A_{cz} = 2(L_w \times 25 \times 10^{-3}) = 0.032 \text{ m}^2$$

$$A_{wz} = 2[0.785 D_c^2 (\alpha/360) - 0.785 (D_c - 0.025)^2 (\alpha/360)] = 0.015 \text{ m}^2$$

$$A_p = A_c - 2A_d - A_{cz} - A_{wz} = 0.449 - 0.032 - 0.015 = 0.402 \text{ m}^2$$

$$A_h = 0.1 \times 0.402 = 0.0402 \text{ m}^2$$

$$n_h = 0.0402 / 0.785 (5 \times 10^{-3})^2 = 2048.4 \text{ or } 2048$$

WEEP CHECK

$K_1 = 0$ because of sieve plate

$$A_h/A_a = 0.089 ; t_T/d_h = 0.6 \text{ therefore } C_v = 0.74$$

$$K_2 = 50.8/C_v^2 = 92.77$$

$$\text{Vol rate of vapour at the top} = 6018.64 / (3600 \times 2.7) = 0.619 \text{ m}^3/\text{s} \text{ (max)}$$

$$\text{Vol rate of vapour at the bottom} = 6177.2 / (3600 \times 2.9) = 0.592 \text{ m}^3/\text{s} \text{ (min)}$$

$$\text{Hole area} = 0.0402 \text{ m}^2$$

$$U_h \text{ at top} = 0.619 / 0.0402 = 15.4 \text{ m/s} \text{ (max)}$$

$$U_h \text{ at bottom} = 0.592 / 0.0402 = 14.73 \text{ m/s} \text{ (min)}$$

$$h_d \text{ at top} = K_2 (\rho_g / \rho_l) U_h^2 = 74.25 \text{ mm clear liq (max)}$$

$$h_d \text{ at bottom} = K_2 (\rho_g / \rho_l) U_h^2 = 73.42 \text{ mm clear liq (min)}$$

$$h_\sigma = 409 (\sigma / d_h \rho_l) = 2.91 \text{ mm clear liq}$$

$$h_{ow} = 664F_w(q/L_w)^{2/3} ; q=2237.2/(3600 \times 800) = 7.77 \times 10^{-4} \text{ m}^3/\text{s (min at top)}$$

$$q^1 = 12.31 \text{ gpm}$$

$$L_w = 0.64 \text{ m or } 2.1 \text{ ft} ;$$

$$q^1/L_w^{2.5} = 1.93 ; L_w/D_c = 0.753 \text{ therefore } F_w = 1.01$$

$$h_{ow} = 1.01 \times 664 \times (7.77 \times 10^{-4} / 0.64)^{2/3} = 7.63 \text{ mm of clear liq.}$$

$$h_w = 50 \text{ mm (assume)}$$

$$h_d + h_\sigma = 77.16$$

$$h_w + h_{ow} = 57.63$$

$$\text{for } A_h/A_a = 0.089 \text{ \& } h_w + h_{ow} = 57.63 \text{ therefore } h_d + h_\sigma = 16 \text{ mm}$$

D.C FLOODING

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

h_{hg} is neglected

$$q = 2296.13/(3600 \times 795) = 8.02 \times 10^{-4} \text{ m}^3/\text{s (max at bottom)}$$

$$q^1 = 12.71 \text{ gpm}$$

$$q^1/L_w^{2.5} = 1.989 \text{ \& } L_w/D_c = 0.753 \text{ therefore } F_w = 1.02$$

$$h_{ow} = 664F_w(q/L_w)^{2/3} = 7.87 \text{ mm of clear liq max at bottom}$$

$$h_{ds} = 50 + 7.87 + 0 = 57.87 \text{ mm}$$

$$U_a = 6177.2/(3600 \times 2.9 \times A_a) = 1.317 \text{ m/s or } 4.32 \text{ ft/s (max at bottom)}$$

$$\rho_g = 2.9 \text{ kg/m}^3 = 0.181 \text{ lb/ft}^3$$

$$F_{ga} = U_a(\rho_g)^{0.5} = 1.84$$

$$\beta = 0.63 ; \phi_t = 0.21$$

$$h_1^1 = \beta h_{ds} = 36.46 \text{ mm}$$

$$h_s = h_1^1 / \phi_t = 173.61 \text{ mm}$$

$$h_{da} = 165.2(q/A_{da})^2 ; \text{ take } C = 25 \text{ mm } h_{ap} = h_{ds} - C = 57.87 - 25 = 32.87$$

$$A_{da} = L_w h_{ap} = 0.021 \text{ m}^2$$

$$h_{da} = 0.241 \text{ mm}$$

$$h_t = h_{d(\text{top})} + h_1^1 = 74.25 + 36.46 = 110.71 \text{ mm}$$

$$h_{dc} = 110.71 + 50 + 7.87 + 0.241 + 0 = 168.82 \text{ mm}$$

take $\phi_{dc} = 0.5$ therefore $h_{dc}^1 = 168.82/0.5 = 337.64$ mm

hence $h_{dc}^1 < t_s$ therefore flooding will not take place.

EFFICIENCY CALCULATIONS

ENRICHING SECTION

CALCULATION OF E_{og} (point efficiency)

$$h_w = 50 \text{ mm}$$

$$\text{average vapor rate} = 6097.92 \text{ kg/hr}$$

$$\text{average vapor density} = 2.8 \text{ kg/m}^3$$

$$A_a = 0.449 \text{ m}^2 ; U_a = 6097.92/(3600 \times 2.8 \times 0.449) = 1.35 \text{ m/s}$$

$$D_f = (D_c + L_w)/2 = 0.745 \text{ m}$$

$$\text{Average liq rate} = 2266.67 \text{ kg/hr}$$

$$\text{Average liq density} = 797.5 \text{ kg/m}^3$$

$$q = 2266.67/(797.5 \times 3600) = 7.89 \times 10^{-4} \text{ m}^3/\text{s}$$

$$w = q/D_f = 1.06 \times 10^{-3} \text{ (m}^3/\text{s)/m}$$

$$N_g = \frac{0.776 + 0.00457h_w - 0.238U_a\rho_g^{0.5} + 105w}{N_{scg}^{0.5}}$$

$$N_{scg} = \mu_g/\rho_g D_g = 1.093$$

$$D_g = 0.42 \times 10^{-5} \text{ m}^2/\text{s}$$

$$N_g = 0.553$$

$$K_{la} = 1.24$$

$$\theta_l = A_a h_l / 1000 q = 20.75 \text{ s}$$

$$N_l = K_{la} \theta_l ; K_{la} = (3.875 \times 10^8 D_l)^{0.5} (0.4 U_a \rho_g^{0.5} + 0.17) = 1.24$$

$$N_l = 25.73$$

$$m_{top} = \alpha_{ij} / (1 + \{\alpha_{ij} - 1\} X_i)^2 = 6.9 / (1 + \{6.9 - 1\} \times 0.99)^2 = 0.147$$

$$m_{bottom} = 0.194$$

$$G_m/L_m = 6097.92/2266.67 = 2.69$$

$$\lambda_t = m_{top}(G_m/L_m) = 0.395 ; \lambda_b = m_{bottom}(G_m/L_m) = 0.523$$

$$\lambda_m = 0.459$$

$$N_{og} = 1/(1/N_g + \lambda_m/N_l) = 0.5476$$

$$E_{og} = 1 - e^{-N_{og}} = 0.4216$$

CALCULATION OF E_{mv} (Murphee tray efficiency)

$$Z_l = D_c \cos(\theta_c/2) = 0.56\text{m}$$

$$\theta_l = 20.75 \text{ s}$$

$$D_e = 6.675 \times 10^{-3} U_a^{1.44} + 0.922 \times 10^{-4} h_l - 0.00562 = 8.02 \times 10^{-3} \text{ m}^2/\text{s}$$

$$U_a = 1.35 \text{ m/s}; h_l = h_l^1 (\text{let}) = 36.46 \text{ mm}$$

$$N_{pe} = Z^2/D_e \theta_l = 3.52$$

From fig 18.29(a)

$$\lambda E_{og} = 0.459 \times 0.407 = 0.1935$$

$$\text{for } N_{pe} = 3.52 \text{ \& } \lambda E_{og} = 0.1935; E_{mv}/E_{og} = 1.05 \text{ therefore } E_{mv} = 1.05 \times 0.4276 = 0.443$$

OVERALL COLUMN EFFICIENCY (E_{OC}):-

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

$$L/G(\rho_g/\rho_l)^{0.5} = 0.022$$

At 80% flooding

$$\psi \text{ from fig 18.22 } \psi = 0.18$$

$$E_a = 0.4158$$

$$N_a = 3/0.4158 = 7.2 \approx 7 \text{ trays}$$

$$\text{Therefore height of column} = 7 \times 500 = 3500\text{mm}$$

STRIPPING SECTION

Plate hydraulics

Let $t_s=500$ mm, $d_h=5.0$ mm, $l_p=15$ mm on triangular pitch

$t_T=3.0$ mm and $A_h/A_p=0.1$ (say)

$$(L_b/G_b)(\rho_g/\rho_l)^{0.5} = 0.0797 \text{ (max at bottom)}$$

for $t_s=18$ inch. $C_{sb, flood}=0.27$ ft/s

$$\begin{aligned} U_{nf} &= C_{sb, flood}(\sigma/20)^{0.2} \{(\rho_l - \rho_g)/\rho_g\}^{0.5} \\ &= 0.27(28.48/20)^{0.2} \{(780-3)/3\}^{0.5} \\ &= 4.66 \text{ ft/s} = 1.42 \text{ m/s} \end{aligned}$$

let $U_n = 0.8 U_{nf} = 1.19$ m/s

Vol flow rate of vapour = $2124.83/3600 \times 3 = 0.59$ m³/s (max at bottom)

$$A_n = \text{vol flow rate of vapour}/U_n = 0.1967/1.136 = 0.173 \text{ m}^2$$

Let $L_w/D_c = 0.75$

$$\Theta_c = 2\text{Sin}^{-1}(L_w/D_c) = 97.2^\circ$$

$$A_c = 0.785 D_c^2$$

$$A_d = 0.785 D_c^2 (\theta_c/360) - 0.25 L_w/D_c \text{Cos}(\theta_c/2)$$

$$A_d = 0.0879 D_c^2$$

$$A_n = A_c - A_d$$

Substituting the values

$$0.173 = 0.785 D_c^2 - 0.0879 D_c^2$$

$$D_c = 0.498 \text{ m}, \text{ take } D_c = 0.5 \text{m}$$

So $L_w = 0.75 \times 0.5 = 0.375$ m take $D_c = 0.38$ m

$$\Theta_c = 2\text{sin}^{-1}(L_w/D_c) = 2\text{sin}^{-1}(0.5/0.38) = 98.93^\circ ; \alpha = 180 - \Theta_c = 81.07^\circ$$

$$A_c = 0.19625 \text{ m}^2 ; A_d = 0.022 \text{ m}^2$$

$$A_c - 2A_d = A_a$$

$$A_a = 0.15225 \text{ m}^2$$

$$A_{cz} = 2(L_w \times 25 \times 10^{-3}) = 0.019 \text{ m}^2$$

$$A_{wz} = 2[0.785 D_c^2 (\alpha/360) - 0.785 (D_c - 0.025)^2 (\alpha/360)] = 8.62 \times 10^{-3} \text{ m}^2$$

$$A_p = A_c - 2A_d - A_{cz} - A_{wz} = 0.125 \text{ m}^2$$

$$A_h = 0.1 \times 0.125 = 0.0125 \text{ m}^2$$

$$n_h = 0.0125 / 0.785 (5 \times 10^{-3})^2 = 637$$

WEEP CHECK

$K_1=0$ because of sieve plate

$A_h/A_a = 0.082$; $t_T/d_h = 0.6$ therefore $C_v=0.74$

$K_2=50.8/C_v^2=92.77$

Vol rate of vapour at the top = $1785.64/(3600 \times 2.9) = 0.171 \text{ m}^3/\text{s}$ (max)

Vol rate of vapour at the bottom = $2124.83/(3600 \times 3) = 0.196 \text{ m}^3/\text{s}$ (min)

Hole area = 0.0125 m^2

U_h at top = $0.171/0.0125 = 13.68 \text{ m/s}$ (min)

U_h at bottom = $0.196/0.0125 = 15.68 \text{ m/s}$ (max)

h_d at top = $K_2(\rho_g/\rho_l)U_h^2 = 63.33 \text{ mm}$ clear liq (min)

h_d at bottom = $K_2(\rho_g/\rho_l)U_h^2 = 87.73 \text{ mm}$ clear liq (max)

$h_\sigma = 409(\sigma/d_h\rho_l) = 2.93 \text{ mm}$ clear liq

$h_{ow} = 664F_w(q/L_w)^{2/3}$; $q=2296.13/(3600 \times 795) = 8.02 \times 10^{-4} \text{ m}^3/\text{s}$ (min at top)

$q^1 = 12.72 \text{ gpm}$

$L_w=0.38 \text{ m}$ or 1.247 ft ;

$q^1/L_w^{2.5} = 7.33$; $L_w/D_c = 0.76$ therefore $F_w = 1.05$

$h_{ow} = 1.05 \times 664 \times (8.02 \times 10^{-4}/0.38)^{2/3} = 11.47 \text{ mm}$ of clear liq.

$h_w = 50 \text{ mm}$ (assume)

$h_d + h_\sigma = 66.26$

$h_w + h_{ow} = 61.47$

for $A_h/A_a = 0.082$ & $h_w + h_{ow} = 61.47$ therefore $h_d + h_\sigma = 16 \text{ mm}$ design values

D.C FLOODING

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

h_{hg} is neglected

$q = 2732.29/(3600 \times 780) = 9.73 \times 10^{-4} \text{ m}^3/\text{s}$ (max at bottom)

$q^1 = 15.42 \text{ gpm}$

$q^1/L_w^{2.5} = 8.885$ & $L_w/D_c = 0.76$ therefore $F_w = 1.07$

$h_{ow} = 664F_w(q/L_w)^{2/3} = 13.3 \text{ mm}$ of clear liq max at bottom

$$h_{ds} = 50 + 13.3 + 0 = 63.3 \text{ mm}$$

$$U_a = 2124.83 / (3600 \times 3 \times A_a) = 1.29 \text{ m/s or } 4.24 \text{ ft/s (max at bottom)}$$

$$\rho_g = 3 \text{ kg/m}^3 = 0.187 \text{ lb/ft}^3$$

$$F_{ga} = U_a (\rho_g)^{0.5} = 1.84$$

$$\beta = 0.6 ; \phi_t = 0.2$$

$$h_l^1 = \beta h_{ds} = 37.98 \text{ mm}$$

$$h_s = h_l^1 / \phi_t = 189.9 \text{ mm}$$

$$h_{da} = 165.2 (q / A_{da})^2 ; \text{ take } C = 25 \text{ mm } h_{ap} = h_{ds} - C = 63.3 - 25 = 38.3$$

$$A_{da} = L_w h_{ap} = 0.0145 \text{ m}^2$$

$$h_{da} = 0.744 \text{ mm}$$

$$h_t = h_{d(\text{top})} + h_l^1 = 63.33 + 37.98 = 101.31 \text{ mm}$$

$$h_{dc} = 101.31 + 50 + 13.3 + 0.744 + 0 = 165.35 \text{ mm}$$

$$\text{take } \phi_{dc} = 0.5 \text{ therefore } h_{dc}^1 = 165.35 / 0.5 = 330.7 \text{ mm}$$

hence $h_{dc}^1 < t_s$ therefore flooding will not take place.

STRIPPING SECTION

CALCULATION OF E_{og} (point efficiency)

$$h_w = 50 \text{ mm}$$

$$\text{average vapor rate} = 1955.24 \text{ kg/hr}$$

$$\text{average vapor density} = 2.95 \text{ kg/m}^3$$

$$A_a = 0.15225 \text{ m}^2 ; U_a = 1955.24 / (3600 \times 2.95 \times 0.15225) = 1.21 \text{ m/s}$$

$$D_f = (D_c + L_w) / 2 = 0.44 \text{ m}$$

$$\text{Average liq rate} = 2514.21 \text{ kg/hr}$$

$$\text{Average liq density} = 787.5 \text{ kg/m}^3$$

$$q = 2514.21 / (787.5 \times 3600) = 8.87 \times 10^{-4} \text{ m}^3/\text{s}$$

$$w = q / D_f = 2.016 \times 10^{-3} \text{ (m}^3/\text{s)/m}$$

$$N_g = \frac{0.776 + 0.00457 h_w - 0.238 U_a \rho_g^{0.5} + 105 w}{N_{scg}^{0.5}}$$

$$N_{scg} = \mu_g / \rho_g D_g = 1.093$$

$$D_g = 0.42 \times 10^{-5} \text{ m}^2/\text{s}$$

$$N_g = 0.69$$

$$K_{la} = 1.24$$

$$\theta_1 = A_a h_l / 1000 q = 6.52 \text{ s}$$

$$N_1 = K_{la} \theta_1 ; K_{la} = (3.875 \times 10^8 D_l)^{0.5} (0.4 U_a \rho_g^{0.5} + 0.17) = 1.24$$

$$N_1 = 8.085$$

$$m_{top} = \alpha_{ij} / (1 + \{ \alpha_{ij} - 1 \} X_i)^2 = 0.194$$

$$m_{bottom} = 1.81$$

$$G_m / L_m = 6097.92 / 2266.67 = 2.69$$

$$\lambda_t = m_{top} (G_m / L_m) = 0.15 ; \lambda_b = m_{bottom} (G_m / L_m) = 1.41$$

$$\lambda_m = 0.78$$

$$N_{og} = 1 / (1 / N_g + \lambda_m / N_1) = 0.647$$

$$E_{og} = 1 - e^{-N_{og}} = 0.476$$

CALCULATION OF E_{mv} (Murphee tray efficiency)

$$Z_l = D_c \cos(\theta_c / 2) = 0.331 \text{ m}$$

$$\theta_1 = 6.52 \text{ s}$$

$$D_e = 6.675 \times 10^{-3} U_a^{1.44} + 0.922 \times 10^{-4} h_l - 0.00562 = 6.67 \times 10^{-3} \text{ m}^2/\text{s}$$

$$U_a = 1.35 \text{ m/s} ; h_l = h_l^1 \text{ (let)} = 36.46 \text{ mm}$$

$$N_{pe} = Z^2 / D_e \theta_1 = 2.52$$

From fig 18.29(a)

$$\lambda E_{og} = 0.78 \times 0.476 = 0.52$$

$$\text{for } N_{pe} = 2.52 \text{ \& } \lambda E_{og} = 0.52 ; E_{mv} / E_{og} = 1.09 \text{ therefore } E_{mv} = 1.09 \times 0.476 = 0.52$$

OVERALL COLUMN EFFICIENCY (E_{OC}):-

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

$$L / G (\rho_g / \rho_l)^{0.5} = 0.079$$

At 80% flooding

ψ from fig 18.22 $\psi = 0.03$

$E_a = 0.512$

$N_a = 3/0.512 = 5.85 \approx 6$ trays

Therefore height of column = $6 \times 500 = 3000$ mm

FINAL DESIGN VALUES

	ENRICHING SECTION	STRIPPING SECTION
t_s mm	500	500
d_h mm	5	5
$l_p \Delta$ pitch	15	15
t_T mm	3	3
n_h	2048	637
D_c m	0.85	0.5
L_w m	0.64	0.38
h_w mm	50	50
% Flooding	80	80
E_{og}	0.4216	0.476
E_{mv}	0.443	0.52
E_{oc}	0.4158	0.512
N_a	7	6
Section height, mm	3500	3000

Overall height of column 6500mm or 6.5 metres

MECHANICAL DESIGN OF DISTILLATION TRAY TOWER

Diameter = 500mm (taken for designing)

Operating pressure = 400mmHg (vacuum) ; therefore gauge pressure = 360mmHg

Taking 10% allowance $P_d = 396$ mm Hg taking $P_d = 400$ mmHg = 0.544 kg/cm^2

Operating average temperature = 130°C

Design temperature = 150°C

Base chamber height = 750 mm

Top chamber height = 750 mm

Material used is *carbon steel*

Specific gravity of carbon steel = 7.7

Permissible tensile stress = 950 kg/cm^2 (upto 250°C)

Insulation material is mineral wood , 75mm thick , density = 130 kg/m^3

Shell minimum thickness t_s

$$t_s = P_d D_i / 2f_t J - P_d + C \quad \text{take } C = 3 \text{ mm}$$

$$t_s = 0.544 \times 500 / 2 \times 950 \times 1 - 0.544 + 3 = 3.14$$

but for high vessels under external pressure take shell thickness $t_s = 8 \text{ mm}$

HEAD:- Torispherical heads

Let thickness = 8mm same as shell

$$t = P_d R_c C_s / [2f_t J + P_d (C_s - 0.2)]$$

$$C_s = \frac{1}{4} [3 + (R_c / R_k)^{0.5}]$$

Take $R_c = 400 \text{ mm}$; $J = 1$

On solving $C_s = 71.24$

Therefore $R_k = 5.026 \times 10^{-3}$

But $R_k > 0.06 R_c$; therefore $R_k = 24 \text{ mm}$

NOZZLES:-

Feed Nozzle:- $m = \rho AV$

$$m = 1.716 \text{ kg/s ; } V = 20 \text{ m/s ; } \rho = 2.9 \text{ kg/m}^3$$

therefore area $A = 0.0296 \text{ m}^2$; diameter = 194 mm

Top Nozzle:- $m = \rho AV$

$$m = 1.672 \text{ kg/s ; } V = 20 \text{ m/s ; } \rho = 2.7 \text{ kg/m}^3$$

therefore area $A = 0.031 \text{ m}^2$; diameter = 198 mm

Bottom Nozzle:- $m = \rho AV$

$$m = 0.759 \text{ kg/s ; } V = 1 \text{ m/s ; } \rho = 780 \text{ kg/m}^3$$

therefore area $A = 9.73 \times 10^{-4} \text{ m}^2$; diameter = 35 mm

Reflux Nozzle:- $m = \rho AV$

$$m = 0.6198 \text{ kg/s ; } V = 1 \text{ m/s ; } \rho = 800 \text{ kg/m}^3$$

therefore area $A = 7.75 \times 10^{-4} \text{ m}^2$; diameter = 32 mm

SHELL THICKNESS CHECK AT DIFFERENT HEIGHT'S:-

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

(a) Axial stress:- $f_{ap} = P_d D_i / 4(t_s - C)$ on substituting values $f_{ap} = 11.33 \text{ kg/cm}^2$

(b) Stresses due to dead load :

(i) Compressive stress due to weight of shell (f_{ds}):-

$$f_{ds} = \frac{\pi/4(D_o^2 - D_i^2)\rho_s X}{\pi/4(D_o^2 - D_i^2)}$$
$$= 7.7 \times 10^{-6} X \text{ kg/cm}^2$$

(ii) Compressive stress due to weight of insulation(f_{di}):-

$$f_{di} = \frac{\pi(D_{ins} T_{ins} \rho_{ins})X}{\pi D_m(t_s - C)}$$

$$D_{avg} = (0.5 + 0.85)/2 = 0.675 \text{ mm}$$

$$D_{ins} = 75 \times 2 + 675 = 825 \text{ mm}$$

$$D_m = 825 + 8 = 833 \text{ mm}$$

$$f_{di} = 3.22 \times 10^{-5} X \text{ kg/cm}^2$$

(iii) Compressive stress due to liq. In the column upto height X

$$f_{d(\text{liq})} = \frac{(\sum \text{liquid weight / unit height})X}{\pi D_m(t_s - C)}$$

$$f_{\text{liq}} = [(X-0.75)/0.75 + 1] \pi D_i^2 / 4 \times 800$$

$$f_{\text{liq}} = 2.134 \times 10^{-3} X \text{ kg/cm}^2$$

(iv) stress due to attachment ($f_{d(\text{att})}$)

$$f_{d(\text{att})} = \frac{(\sum \text{wt of attachments per unit height})X}{\pi D_m(t_s - C)}$$

$$\text{wt. of attachments} = 150 \text{ kg/m}$$

$$\text{therefore } f_d = 11.46 \times 10^{-3} X \text{ kg/cm}^2$$

(c) Stress due to wind load:- f_{wx}

$$f_{wx} = \frac{1.4 P_w X^2}{\pi D_m(t_s - C)}$$

$$\pi D_m(t_s - C)$$

$$\text{wind pressure} = 125 \text{ kg/m}^2 = 125 \times 10^{-6} \text{ kg/mm}^2$$

$$f_{wx} = 1.34 \times 10^{-6} X^2 \text{ kg/cm}^2$$

neglecting seismic load

equating all the stresses to zero

$$f_{wx} - (f_{dx} + f_{d(\text{liq})} + f_{di} + f_{ds}) - f_{ap} = 0$$

solving for X ; X = 10.9 m

hence thickness taken as 8mm is sufficient as column ht is 6.5m

SUPPORT:-

(a) stress due to dead weight $f_{ws} = W / \pi(D_s + t_s)t_s$

Skirt diameter = 500 mm (D_s)

Dead weight attachments = 46000 kg

$$F_{bs} = \frac{46000}{\pi(D_s + t_s)t_s} \text{ kg/mm}^2$$

$$\pi(D_s + t_s)t_s$$

(b) stress due to wind load $f_{bs} = 4M_w / \pi(D_s + t_s)t_s$

$$M_w = \frac{0.7P_w D_o X^2}{2}$$

$$P_w = 1.25 \times 10^{-4} \text{ kg/mm}^2$$

$$M_w = 9.24 \times 10^6 \text{ kgmm}$$

$$f_{bs} = \underline{7393.75} \text{ kg/mm}^2$$

$$\pi(500 + t_s)t_s$$

$$\text{total compressive stress} = \frac{46000}{\pi(500 + t_s)} + \frac{7393.75}{\pi(500 + t_s)t_s}$$

$$\text{Now } f_{s(\max)} = \frac{0.125Et_s \cos\alpha}{D_s}$$

$$E_{250^\circ\text{C}} = 19.5 \times 10^3 \text{ kg/mm}^2 \quad ; \quad \text{cylindrical skirt (} \cos\alpha = 1 \text{)}$$

$$f_{s(\max)} = 4.875 \times 10^{-6} t_s$$

$$f_{\text{compressive}} < f_{\max}$$

$$\text{at } t_s = 8 \text{ mm} \quad f_{\text{compressive}} < f_{\max}$$

$$\text{at } t_s = 8.25 \text{ mm} \quad f_{\text{compressive}} = f_{\max}$$

but at any condition $f_{\max} > f_{\text{compressive}}$ therefore $t_s = 8 \text{ mm}$

DESIGN OF CONDENSER

Flow rate of vapor = $3771.48/3600 = 1.05 \text{ kg/s}$

Vapor is condensing at 113.8°C and water at 30°C is available for cooling

Outlet water temperature = 40°C

$$\lambda = 567.34 \text{ KJ/KG}$$

$$Q = m\lambda = 567.34 \times 1.05 = 595.07 \text{ Kw}$$

$$L_{\text{mtd}} = \frac{(113.8 - 30) - (113.8 - 40)}{\ln \left\{ \frac{(113.8 - 30)}{(113.8 - 40)} \right\}}$$

Film transfer coefficient

$$\text{Shell side condensing vapor} = T_w = 0.5\{113.8 + (30 + 40)/2\} = 74.4^\circ\text{C}$$

$$T_f = (74.4 + 113.8)/2 = 94.1^\circ\text{C}$$

$$\rho_l = 800 \text{ kg/m}^3 ; \mu_l = 0.3 \text{ cp} ; K = 0.16 \text{ w/m.k} ; C_p = 1.915 \text{ KJ/Kg}^\circ\text{C}$$

$$\text{Assume } U_d = 450 \text{ w/m}^\circ\text{C}$$

$$\text{Area for heat transfer} = 595.07 \times 10^3 / 450 \times 78.7 = 16.8 \text{ m}^2 = Q / U(T_m)$$

$$N_t = 16.8 / 0.0587 \times 3.66 = 78.2 \quad (\text{length of tube } 12 \text{ ft})$$

SHELL SIDE:

¾ od 1 inch Δ pitch TEMA P or S 1-2 exchanger

$$\text{Shell dia} = 305 \text{ mm } N_t = 78$$

$$\text{Corrected area} = 16.76 \text{ m}^2$$

$$\text{Corrected } U_d = 451.15 \text{ w/m}^2 \text{ }^\circ\text{C}$$

$$N_{\text{Re}} = 4 \times 1.05 / (\pi \times 0.019 \times 78 \times 0.3 \times 10^{-3}) = 3007$$

$$h = 1.47 \{ (k^3 \rho^2 g / \mu^2) \}^{1/3} (N_{\text{Re}})^{-1/3}$$

$$h = 670.8 \text{ w/m}^2 \text{ }^\circ\text{C}$$

TUBE SIDE:

$$\text{Area of tubes} = a_t = 194.7 \times 10^{-6} \times 78 / 2 = 7.59 \times 10^{-3} \text{ m}^2$$

$$Q = m C_p \Delta t$$

$$595.07 = m \times 4.187 \times 10$$

$$\text{Or } m = 14.21 \text{ kg/s}$$

$$\text{Velocity in the tubes} = 14.21 / (1000 \times 7.59 \times 10^{-3}) = 1.87 \text{ m/s} > 1 \text{ m/s}$$

$$N_{Re} = (1000 \times 1.87 \times 0.0157) / 10^{-3} = 29539$$

$$h_i d_i / k = 0.023 (Pr)^{1/3} (N_{Re})^{0.8}$$

$$h_i = 6145.1 \text{ w/m}^2 \text{ } ^\circ\text{C}$$

$$h_{id} = h_i (d_i / d_o) = 5080 \text{ w/m}^2 \text{ } ^\circ\text{C}$$

$$1/U_c = 1/h_{id} + 1/h_i + \text{dirt}$$

$$\text{dirt} = 5 \times 10^{-4} \text{ m}^2 \text{ } ^\circ\text{C/w}$$

$$U_c = 457.12 \text{ w/m}^2 \text{ } ^\circ\text{C}$$

There fore $U_c > U_d$

PRESSURE DROP CALCULATIONS

BELL'S METHOD:

SHELL SIDE:

$$\mu_i = 0.3 \text{ cp} ; T_{\text{vap}} = 113.2^\circ\text{C} ; C^1 = 1 - 3/4 = 6.35 \text{ mm}$$

$$B = D_s = 0.305 \text{ m}$$

$$P_t = 1 \times 25.4 = 25.4 \text{ mm}$$

$$A_s = D_s C^1 B / P_t$$

$$\text{Therefore } a_s = 0.07625$$

$$D_e = 4 \{ \sqrt{3P_t^2/4 - \pi D_o^2/8} \} / (\pi D_o/2) = 18.3 \text{ mm}$$

$$G_s = w/a_s = 1.05/0.07625 = 13.77 \text{ kg/m}^2\text{s}$$

$$(N_{Re})_s = G_s D_e / \mu = 13.77 \times 18.3 \times 10^{-3} / 0.3 \times 10^{-3} = 840$$

$$f = 1.87 (N_{Re})^{-0.2} = 0.486$$

$$\text{no of baffles} = 2$$

$$N_b + 1 = l/l_s ; \text{therefore } l_s = 1.22\text{m}$$

Let 25 % baffle cut

$$L_c = 0.305 \times 0.25 = 0.07625 \text{ m}$$

$$L_c / D_s = 0.25$$

$$\rho_v = 2.7 \text{ kg/m}^3$$

$$\Delta P_s = \{ f (N_b + 1) D_s G_s^2 \} / D_e \rho_v$$

$$= 1.7 \text{ Kpa}$$

$$\Delta P_s = 1.7/3 = 0.567 \text{ Kpa} < 14 \text{ Kpa}$$

TUBE SIDE:

$$N_{Re} = 29539$$

$$F = 0.079(N_{Re})^{-1/4} = 6.026 \times 10^{-3}$$

$$\Delta P_1 = 2fG_t^2/\rho_t D_1 = 9793.61 \text{ N/m}^2$$

$$\Delta P_t = 2.5G_t^2/2\rho_t = 4371.13 \text{ N/m}^2$$

$$(\Delta P_1)_{total} = 4(9793.61 + 4371.13) = 56658.96 < 70000 \text{ N/m}^2$$

FINAL DESIGN VALUES

1 Shell 2 tube passes

Vapor on shell side & cooling liq on tube side

¾ 16 BWG tubes I.D = 0.62" O.D = 0.75"

Shell dia = 305 mm

No of tubes = 78 ; length of tubes = 3.66m

Overall heat transfer coefficient = $U = 450 \text{ w/m}^2 \text{ }^\circ\text{C}$

Pressure drops: shell side = 0.567 Kpa

Tube side = 56.67 Kpa

Baffle spacing = 1.22m

No of baffles = 2 with 25% baffle cut

Shell side heat transfer coefficient = $670.8 \text{ w/m}^2 \text{ }^\circ\text{C}$

Tube side heat transfer coefficient = $5080 \text{ w/m}^2 \text{ }^\circ\text{C}$

MECHANICAL DESIGN OF CONDENSER

SHELL SIDE

Shell passes = 1 ; tube passes = 2

Material :- Carbon steel

Inside shell dia = 305 mm

Design pressure = $1.2 P_o = 1.2 \times 57.8 \times 10^{-4} = 6.935 \times 10^{-3} \text{ Kg/cm}^2$

Allowable stress = 950 Kg/cm^2

TUBE SIDE

No of tubes = 78

Material :- Carbon steel

$d_o = 19.05 \text{ mm}$; $d_i = 16 \text{ mm}$; $L = 3.66 \text{ m}$

design pressure (P_d) = $1.2 P_o = 1.2 \times 0.5775 = 0.693 \text{ Kg/cm}^2$

Shell Thickness :- t_s

$$t_s = P_d D_s / 2 f_t J - P_d + C$$

let $J = 1$ and $C = 3 \text{ mm}$

$$t_s = 3 \text{ mm (approx)}$$

take shell thickness to be 4 mm

Tube Thickness:- t_s

$$t_s = P_d D_o / 2 f_t J - P_d + C$$

take $J = 1$ and $C = 2 \text{ mm}$

Tube Sheet:-

$$t_{ts} = 0.5 D_s (P/f)^{0.5}$$

$$= 0.5 \times 0.305 \times (0.693/950)^{0.5} = 4.12 \text{ mm}$$

but for tube dia of 19mm min tube sheet thickness is $t_s = 15 \text{ mm}$

End Covers:- 2 in numbers & thickness = 25mm

Baffles:- 2 in numbers & thickness = 6mm

Spacers:- 13mm thickness

Nozzles:- 4 in number

Tube side:- $m = \rho AV$

$$V = 1.87 \text{ m/s} ; m = 14.21 \text{ kg/s} ; \rho = 1000 \text{ kg/m}^3$$

$$\text{Therefore area } A = 7.56 \times 10^{-3} \text{ m}^2 ; \text{ diameter} = 98 \text{ mm}$$

Shell side:- $m = \rho AV$

$$V = 20 \text{ m/s (let)} ; m = 1.05 \text{ kg/s} ; \rho = 2.7 \text{ kg/m}^3$$

$$\text{Therefore area } A = 0.0194 \text{ m}^2 ; \text{ diameter} = 157 \text{ mm}$$

Gasket Selection :-

asbestos gasket 1.6mm thick

$$m = 2.75 \text{ \& } y = 2.6 \text{ Kg/mm}^2$$

$$N/2 = 5 \text{ mm} = b ; N = 10 \text{ mm}$$

Take gasket width as = 20 mm

Inner dia of gasket = 305mm & mean gasket dia(G) = 325 mm

BOLT LOAD:-

operating conditions $W_{m1} = H + H_p$

$$= \pi/400G^2P + 2\pi bGmP/100$$

$$= \pi/400(325)^2 \times 0.693 + 2\pi \times 5 \times 325 \times 2.75 \times 0.693/100$$

$$= 575 + 195$$

$$= 770 \text{ Kgf}$$

Bolting up condition:- $W_{m2} = \pi bGy = \pi \times 5 \times 325 \times 2.6 = 13273.23 \text{ Kgf}$

Therefore W_{m2} controls

$$S_f = S_a = 13.18 \text{ Kgf/mm}^2 \text{ (nominal bolt stress)}$$

$$A_{m1} = W_{m1}/S_f = 770/13.18 = 58.42 \text{ mm}^2$$

$$A_{m2} = W_{m2}/S_a = 13273.23/13.18 = 1007.07 \text{ mm}^2$$

$$A_m = 1007.07$$

$$A_f = 2\pi yGN/S_a = 4031.35 \text{ mm}^2$$

Actual bolt area should be between A_m and A_f

$$\text{Bolt circle dia} = B = D_o + (2d_o)2 ; d_o = 10 \text{ mm}$$

$$= 325 + 40 = 375 \text{ mm}$$

$$\text{let } A_f = 2518 \text{ mm}^2 = \pi/4 d_o^2 N_B$$

$$N_B = 32 \text{ bolts}$$

FLANGES:-

$$\text{Flange outer dia} = D_o + 4d_o + d_o + \text{allowance}$$

$$= 305 + 40 + 10 + 15 = 370 \text{ mm}$$

$$\text{flange thickness} = t_f = G(P/K_f)^{0.5} + C$$

$$\text{for carbon steel } f = 8.6 \text{ Kgf/mm}^2$$

$$K_f = 1/0.3 + 15W_m h_g / D_H$$

$$W_m = W_{m2} = 13273.23$$

$$h_g = \frac{B - G}{2}$$

$$= 10 \text{ mm}$$

$$H = 575 \text{ Kgf}$$

Substituting the values

$$t_f = 35 \text{ mm}$$

SUPPORTS:-

$$W/A = f_t/1 + 1/18000(K)^{-2} \quad \text{take } 1/K = 100$$

$$\text{From steel tables } A = 56.2 \text{ m}^2$$

Weight of heat exchanger (W)

$$\text{Weight of shell } W_1 = \pi/4(d_o^2 - d_i^2)l\rho$$

$$\rho = 7700 \text{ Kg/m}^3$$

$$\text{therefore } W_1 = 278.75 \text{ kg}$$

$$\text{weight of tubes} = W_2 = \pi/4 N_t (d_o^2 - d_i^2)l\rho = 181.2 \text{ kg}$$

$$\text{weight of liquid in tubes} = 23.53 \text{ kg}$$

$$\text{weight of liquid in shell} = 0.909 \text{ kg}$$

$$\text{weight of end covers} = 36 \text{ kg}$$

$$\text{weight of tube sheets} = 38 \text{ kg}$$

$$\text{therefore total weight} = 560 \text{ kg (approx)}$$

$$\text{taking 10\% extra allowance weight is} = 616 \text{ kg}$$

weight per support = 308 kg

$$W/A = f_t/1 + 1/18000(K)^{-2}$$

Substituting the values $W/A = 610.7 \text{ kg/cm}^2$ (X_1)

Weight per area = $308/56.2 = 5.48 \text{ kg/cm}^2$ (X_2)

Since $X_2 < X_1$ therefore the support is suitable