PROCESS DESIGN OF ACID TOWER (Major equipment)

(Vacuum distillation Tower)

Feed to the distillation tower = 115.3 kmol/ hr of acrylic acid + 15.08 kmol / hr of acetic acid.

= 130.38 kmol/ hr.

Top product from the distillation tower is 95 wt% acetic acid.
Bottom product from the distillation tower is 99.5 wt% acrylic acid .

Feed:

Flow rate of feed = 130.38 kmol/ hr.
Mol fraction of acetic acid in feed = 15.08 / 130.38 = 0.1156
Average molecular weight of feed = 70.37 kg/kmol

Distillate:
Flow rate of distillate = 15.029 kmol/hr
Mol fraction of acetic acid =(95/60)/ [(95/60)+ (5/72)] = 0.958
Average molecular weight of distillate = 60.5 kg/kmol .

Residue:
Flow rate of residue = 115.36 kmol/hr.
Mol fraction of acetic acid = (0.5/ 60) / [(99.5/72)+ (0.5/ 60)] = 0.006
Average molecular weight = 71.92 kg/kmol.

VLE data :

Liquid molefrac of acetic acid. x	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
Vapor molefrac of acetic acid. y	0.0	0.21	0.37	0.51	0.63	0.715	0.795	0.86	0.92	0.96	1.0
T ˚C	74.22	72.22	69.46	67.13	64.83	62.57	60.33	58.12	57.32	55.94	53.79

Feed is a liquid at its boiling point

q=1; i.e. q line is vertical line passing through $x=y=x_F$.

From x-y plot ,

$x_D / (R_m + 1) = 0.13$

$R_m = 6.369$

Optimum reflux ratio R= 15

Number of ideal stages in enriching section = 7
Number of ideal stages in stripping section = 4+1(reboiler)

	ENRICHING SECTION		STRIPPING SECTION	
	TOP	BOTTOM	TOP	BOTTOM
Liquid kmol/hr	225.43	225.43	355.81	355.81
Vapor kmol/hr	240.46	240.46	240.46	240.46
M_{avg} liq kg/kmol	60.5	70.37	70.37	71.92
M_{avg}vap kg/kmol	60.5	68.96	68.96	71.92
x	0.958	0.1156	0.1156	0.006
y	0.958	0.22	0.22	0.006
T_{liq} ˚C	54.4	72	72	74.1
T_{vap} ˚C	55.8	72.2	72.2	74.2
Liq kg/hr	13638.5	15863.5	25038.3	25589.8
Vap kg/hr	14547.8	16582.12	16582.12	17293.88
Liquid density kg/m^3	1083.94	1074.8	1074.8	1078.32
Vap density kg/m^3	0.1569	0.1704	0.1704	0.1767
$(L/G)(\rho_l/\rho_g)^{0.5}$	0.0113	0.012	0.018	0.01894

AVERAGE CONDITIONS AND PROPERTIES

	ENRICHING SECTION	STRIPPING SECTION
Liquid flow kmol/hr kg/hr	225.43 14751.0	355.81 25314.05
Vapor flow kmol/hr kg/hr	240.46 15564.96	240.46 16938.0
T_{liq} ˚C	63.2	73.05
T_{vap} ˚C	64	73.2
ρ_{liq} kg/m^3	1079.37	1076.56
ρ_{vap} kg/m^3	0.1636	0.1735
μ_{liq} cP	0.69	0.603
μ_{vap} cP	0.00937	0.009412
σ_{liq} dyn/cm	28.985	28.208
D_L cm^2 / sec	3.463 x 10^{-5}	3.343 x 10^{-5}
D_V cm^2/sec	1.082	1.134

ENRICHING SECTION

I Tray Hydraulics:

Tray spacing t_s = 500mm
Hole diameter d_h = 5mm
Hole pitch L_p = 15mm (Δlar)
Tray thickness t_T = 3mm
$A_h / A_p = 0.10$

II Tower Diameter :

$(L/G)(\rho_l/ \rho_g)^{0.5} = 0.012$ (max at the bottom)
(From PERRY : fig 18-10 ; p.no. 18-7)

For t_s = 18 in ,
Capacity parameter, $C_{sb\ (flood)} = 0.29$ ft/s
Gas velocity through net area at flood $U_{nf} = C_{sb\ (flood)} x\ [\sigma / 20\ ] x\ [(\rho_l - \rho_g) / \rho_g\ ]^{0.5}$

σ - liq surface tension = 28.985 dyn/ cm
ρ_l = 1079.37 kg/m^3
ρ_g = 0.1636kg/ m^3

U_{nf} = 25.36 ft/s = 7.732 m/s
For 75% flooding condition , U_n = 0.75 x 7.732 = 5.799 m/s

Net area A_N = Max. vol. flow rate of vapor / U_n
= 16582.12 / (3600 x 0.1636 x 5.799) = 4.85 m^2

Ratio of weir length to tower dia i.e. $L_W / D_C = 0.75$
$\theta_c = 2 \sin^{-1}(L_W / D_C) = 97.2^\circ$
Column C.S.area , $A_C = (\pi / 4\ ) D_C^2 = 0.785\ D_C^2$
Down comerC.S.area, $A_D = (\pi / 4\ ) D_C^2\ (\theta_c / 360\ ) - (L_W /2)\ (D_C / 2\ ) \cos(\theta_c / 2)$
$= 0.0879\ D_C^2$

$A_N = A_C - A_D$
D_C = 2.637 m
Take D_C = 2.65 m
L_W = 0.75 x 2.65 = 1.98 m = 2m
A_C = 5.515 m^2

$A_D = 0.6172\ m^2$
$A_N = 4.901\ m^2$

Active area $A_A = A_C - 2\ A_D = 4.28\ m^2$
$L_W / D_C = 0.754$
$\theta_c = 98.0^\circ$
$\alpha = 81.99^\circ$

Perforated area A_P :

Area of distribution and calming zone

$A_{cz} = 2\ (L_W \times 100 \times 10^{-3}) = 0.4\ m^2$

Area of waste peripheral zones

$A_{wz} = 2 \times [(\pi / 4)\ D_C^2\ (\alpha / 360) - (\pi / 4)(D_C - 0.12)^2\ (\alpha / 360)$
$= 0.22\ m^2$

$A_p = A_C - 2\ A_D -$ Acz - Awz
$= 3.658\ m^2$

Hole area $A_H = 0.1 \times A_p = 0.3658\ m^2$

Number of holes = $0.3658 / [(\pi / 4) \times 0.005^2] = 18630$

III Weeping Check :

Weir height $h_w = 10mm$

Pressure drop across the dispersion unit

$h_d = k_1 + k_2\ (\rho_g / \rho_l)\ U_h^2$

For sieve trays $k_1 = 0$, $k_2 = 50.8 / C_v^2$

(From PERRY : fig 18-14; p.no. 18-9)

For $t_T / d_h = 0.6$; $A_H / A_A = 0.0854$

$C_v = 0.74$

$k_2 = 92.77$

Vol. flow of vapor at top = 14547.8 / (3600 x 0.1569) = 25.75 m^3 /s

Vol. flow of vapor at bottom = 16582.12 / (3600 x 0.1704) = 27.03 m^3/s

Linear gas velocity through perforations U_h :

U_h (at top)= 25.75 / A_H = 25.75 / 0.3658 = 70.95 m/s

U_h (at bottom)= 27.03 / A_H = 74.48 m/s

h_d (at top) = 92.77 x (0.1569/ 1083.94) x $(70.95)^2$ = 67.59 mm clear liq

h_d (at bottom) = 92.77 x (0.1704/ 1074.8)x $(74.48)^2$ = 81.59 mm clear liq

Head loss due to bubble formation h_σ

$h_\sigma = 409\ (\sigma / \rho_l\ d_h)$

σ - surface tension =28.985 mN/m

$\rho_l = 1079.37\ kg/m^3$

$d_h = 5mm$

$h_\sigma = 409 \times (28.985 / 1079.37 \times 5) = 2.2mm$

Height of crest over weir h_{ow}

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

q = liquid flow

= 13638.5/ (3600 x 1083.94) = 0.003495 m^3/s = 55.39 gal/min

L_w = 2m = 6.56 ft

(From PERRY : fig 18 -16 ; p.no 18-11)

For $q / L_W^{2.5} = 55.39 / 6.56^{2..5} = 0.502$

$L_W / D_C = 0.754$

$F_W = 1.01$

$h_{ow} = 1.01 \times 664 \times (0.003495/2)^{2/3} = 9.73$ mm

$h_d + h_\sigma = 67.59 + 2.2 = 69.79$ mm

$h_{ow} + h_w = 10 + 9.73 = 19.73$ mm

(From PERRY : fig 18-11 p.no. 18-7)

For $A_H / A_A = 0.0854$

$h_{ow} + h_w = 19.73$ mm

$h_d + h_\sigma = 14$ mm < design value of 69.79 mm

Hence no weeping occurs

IV Down comer Flooding Check:

Down comer back up $h_{dc} = h_t + h_w + h_{ow} + h_{da} + h_{hg}$

h_t = total pressure drop across the plate , mm liq

h_w = height of weir at plate outlet , mm liq

h_{ow} = height of crest over weir , mm liq

h_{da} = head loss due to liq flow under down comer apron , mm liq

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

Calculated height of clear liquid over the dispersers , h_{ds} mm liq

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

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

q = liquid flow

= 15863.5/ (3600 x 1074.8) = 0.0040998 m^3/s = 64.98 gal/min

L_w = 2m = 6.56 ft

(From PERRY : fig 18 -16 ; p.no 18-11)

For $q / L_W^{2.5} = 64.98 / 6.56^{2..5} = 0.589$

$L_W / D_C = 0.754$

$F_W = 1.01$

$h_{ow} = 1.01 \times 664 \times (0.0040998 / 2)^{2/3} = 10.82$ mm

$h_{ds} = h_{ow} + h_w = 10.82 + 10 = 20.82$ mm liq

Total pressure drop h_t :

$h_t = h_d + h_l'$

h_l' - pressure drop across the aerated liquid

$h_l' = \beta\, h_{ds}$

(From PERRY : fig 18-15 ; p.no. 18-10)

linear gas velocity through the active area U_a :

$U_a = 16582.12 / (3600 \times 0.1704 \times 4.28)$

$= 6.362$ m/s $= 20.87$ ft/s

$\rho_g = 0.1704$ kg/m^3 $= 0.0106$ lb/ft^3

$F_{ga} = U_a\, \rho_g^{0.5} = 20.87 \times 0.0106^{0.5} = 2.152$

Relative froth density $Ø = 0.19$

Aeration factor $\beta = 0.59$

$h_l` = 0.59 \times 20.82 = 12.283$ mm liq

Actual height of froth $h_f = h_l`/ Ø = 12.28 / 0.19 = 64.65$ mm

Head loss due to down comer apron $h_{da} = 165.2\, (q/ A_{da})^2$

$q = 0.0040998$ m^3/s

Take C = 13 mm

$h_{ap} = h_{ds} - C = 20.82 - 13 = 7.82$ mm

$A_{da} = L_W\, h_{ap} = 2 \times 0.00782 = 0.016$ m^2

had $= 165.2\, (.0040998 / 0.016)^2 = 10.84$ mm

$h_t = h_d + h_l` = 81.59 + 12.28 = 93.87$ mm

$h_{dc} = 93.87 + 10 + 10.82 + 10.84 = 125.53$ mm

Actual backup $h`_{dc} = h_{dc} / Ø_{dc} = 125.53 / 0.5 = 251.06$ mm $< t_s = 500$ mm

Hence down comer flooding does not occur

STRIPPING SECTION

I Tray Hydraulics:

Tray spacing $t_s = 500$mm

Hole diameter $d_h = 5$mm

Hole pitch L_p = 15mm (Δlar)
Tray thickness t_T = 3mm
$A_h / A_p = 0.10$

II Tower Diameter :

$(L/G)(\rho_l/ \rho_g)^{0.5}$ = 0.01894 (max at the bottom)
(From PERRY : fig 18-10 ; p.no. 18-7)

For t_s = 18 in ,
Capacity parameter, $C_{sb\ (flood)}$ = 0.29 ft/s
Gas velocity through net area at flood $U_{nf} = C_{sb\ (flood)} x\ [\sigma / 20\ ] x\ [(\rho_l - \rho_g) / \rho_g\ ]^{0.5}$

σ - liq surface tension = 28.208 dyn/ cm
ρ_l = 1078.32 kg/m^3
ρ_g = 0.1767kg/ m^3

U_{nf} = 24.26 ft/s = 7.396 m/s
For 75% flooding condition , U_n = 0.75 x 7.396 = 5.547 m/s

Net area A_N = Max. vol. flow rate of vapor / U_n
= 17293.88 / (3600 x 0.1767 x 5.547) = 4.901 m^2

Ratio of weir length to tower dia i.e. L_W / D_C = 0.75
$\theta_c = 2 \sin^{-1}(L_W / D_C) = 97.2^\circ$
Column C.S.area , $A_C = (\pi / 4\ ) D_C^2 = 0.785\ D_C^2$
Down comerC.S.area, $A_D = (\pi / 4\ ) D_C^2\ (\theta_c / 360\ ) - (L_W /2)\ (D_C / 2\ ) \cos(\theta_c/ 2)$
$= 0.0879\ D_C^2$

$A_N = A_C - A_D$

D_C = 2.65 m
L_W = 0.75 x 2.65 = 1.98 m = 2m
A_C = 5.515 m^2
A_D = 0.6172 m^2
A_N = 4.901 m^2

Active area $A_A = A_C - 2\ A_D$ = 4.28 m^2
L_W / D_C = 0.754
$\theta_c = 98.0^\circ$
$\alpha = 81.99^\circ$

Perforated area A_P :

Area of distribution and calming zone
$A_{cz} = 2\ (L_W \times 100 \times 10^{-3})$ = 0.4 m^2
Area of waste peripheral zones

$A_{wz} = 2 \times [(\pi / 4) D_C^2 (\alpha / 360) - (\pi / 4)(D_C - 0.12)^2 (\alpha / 360)$
$= 0.22\ m^2$

$A_p = A_C - 2 A_D - Acz - Awz$
$= 3.658\ m^2$

Hole area $A_H = 0.1 \times A_p = 0.3658\ m^2$

Number of holes = $0.3629 / [(\pi / 4) \times 0.005^2] = 18630$

III Weeping Check :

Weir height h_w = 10mm

Pressure drop across the dispersion unit

$h_d = k_1 + k_2 (\rho_g / \rho_l) U_h^2$

For sieve trays $k_1 = 0$, $k_2 = 50.8 / C_v^2$

(From PERRY : fig 18-14; p.no. 18-9)

For $t_T / d_h = 0.6$; $A_H / A_A = 0.085$

$C_v = 0.74$

$k_2 = 92.77$

Vol. flow of vapor at top = 15682.12 / (3600 x 0.1704) = 25.56 m^3 /s

Vol. flow of vapor at bottom = 17293.88 / (3600 x 0.1767) = 27.186 m^3/s

Linear gas velocity through perforations U_h :

U_h (at top)= 25.56 / A_H = 25.56 / 0.3658 = 69.875 m/s

U_h (at bottom)= 27.186 / A_H = 74.32 m/s

h_d (at top) = 92.77 x (0.1704/ 1074.8) x $(69.875)^2$ = 71.79 mm clear liq

h_d (at bottom) = 92.77 x (0.1767/ 1078.32)x $(74.32)^2$ = 83.96 mm clear liq

Head loss due to bubble formation h_σ

$h_\sigma = 409 (\sigma / \rho_l d_h)$

σ - surface tension =28.208 mN/m

ρ_l = 1076.56 kg/m^3

d_h = 5mm

h_σ = 409 x (28.208 / 1076.56 x 5) = 2.14mm

Height of crest over weir h_{ow}

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

q = liquid flow

= 25038.3/ (3600 x 1074.8) = 0.00647 m^3/s = 102.57 gal/min

L_w = 2m = 6.56 ft

(From PERRY : fig 18 -16 ; p.no 18-11)

For $q / L_W^{2.5} = 102.57 / 6.56^{2..5} = 0.929$
$L_W / D_C = 0.754$
$F_W = 1.02$

$h_{ow} = 1.02 \times 664 \times (0.00647 / 2)^{2/3} = 14.81$ mm

$h_d + h_\sigma = 71..79 + 2.14 = 73.93$ mm
$h_{ow} + h_w = 10 + 14.81 = 24.81$ mm

(From PERRY : fig 18-11 p.no. 18-7)
For $A_H / A_A = 0.085$
$h_{ow} + h_w = 24.81$ mm

$h_d + h_\sigma = 14$ mm < design value of 73.93 mm
Hence no weeping occurs

IV Down comer Flooding Check:

Down comer back up $h_{dc} = h_t + h_w + h_{ow} + h_{da} + h_{hg}$
h_t = total pressure drop across the plate , mm liq
h_w = height of weir at plate outlet , mm liq
h_{ow} = height of crest over weir , mm liq
h_{da} = head loss due to liq flow under down comer apron , mm liq
h_{hg} = liquid gradient across plate , mm liq (neglected)

Calculated height of clear liquid over the dispersers , h_{ds} mm liq
$h_{ds} = h_w + h_{ow} + h_{hg}$

$h_{ow} = F_w (664) (q/ L_W)^{2/3}$
q = liquid flow
= 25589.8/ (3600 x 1078.32) = 0.00659 m^3/s = 104.48 gal/min
L_w = 2m = 6.56 ft

(From PERRY : fig 18 -16 ; p.no 18-11)
For $q / L_W^{2.5} = 104.48 / 6.56^{2..5} = 0.9473$
$L_W / D_C = 0.754$
$F_W = 1.02$

$h_{ow} = 1.01 \times 664 \times (0.00659 / 2)^{2/3} = 14.99$ mm

$h_{ds}=h_{ow} + h_w + h_{hg} = 14.99 + 10 = 24.99$ mm liq

Total pressure drop h_t :

$h_t = h_d + h_l'$

h_l' - pressure drop across the aerated liquid

$h_l' = \beta\, h_{ds}$

(From PERRY : fig 18-15 ; p.no. 18-10)

linear gas velocity through the active area U_a :

$U_a = 17293.88 / (3600 \times 0.1767 \times 4.28)$

$= 6.352$ m/s $= 20.83$ ft/s

$\rho_g = 0.1767$ kg/m^3 $= 0.01102$ lb/ft^3

$F_{ga} = U_a\, \rho_g^{0.5} = 20.83 \times 0.01102^{0.5} = 2.187$

Relative froth density $Ø = 0.19$

Aeration factor $\beta = 0.59$

$h_l` = 0.59 \times 24.99 = 14.74$ mm liq

Actual height of froth $h_f = h_l`/ Ø = 14.74 / 0.19 = 77.6$ mm

Head loss due to down comer apron $h_{da} = 165.2\, (q/ A_{da})^2$

$q = 0.00659$ m^3/s

Take C = 13 mm

$h_{ap} = h_{ds} - C = 24.99 - 13 = 11.99$ mm

$A_{da} = L_W\, h_{ap} = 2 \times 0.01199 = 0.02398$ m^2

$h_{da} = 165.2\, (.00659 / 0.02398)^2 = 12.476$ mm

$h_t = h_d + h_l` = 83.96 + 14.74 = 98.7$ mm

$h_{dc} = 98.7 + 10 + 14.99 + 12.476 = 136.166$ mm

Actual backup $h`_{dc} = h_{dc} / Ø_{dc} = 136.166 / 0.5 = 272.332$ mm $< t_s = 500$ mm

Hence down comer flooding does not occur.

COLUMN EFFICIENCY

ENRICHING SEC TION

Point efficiency :

$E_{og} = 1 - \exp (- N_{og})$

N_{og} = overall transfer unit

$N_{og} = 1 / [(1/ N_g) + (\lambda / N_l)]$

N_g = gas phase transfer units

$N_g = [0.776 + 0.00457\ h_w - 0.238\ U_a\ \rho_g^{\ 0.5} + 105\ W] / N_{scg}^{\ 0.5}$

h_w = weir height = 10mm

U_a = gas velocity through active area

= 15564.96 / (3600 x 0.1636 x 4.28)

= 6.174 m/s

W = liquid flow rate m^3 / s.m

$W = q / D_f$;

$D_f = (D_C + L_W)/ 2 = 2.32$ m

Average liq flow rate = 14751 kg/hr

Average liq density = 1079.36 kg / m^3

q = 14751 / (3600 x 1079.36) = 0.00379 m^3/s

W = 0.00379 / 2.32 = 0.001636 m^3 /m.s

N_{scg} = gas phase Schmidt number

$= \mu_g / \rho_g D_g = 0.528$

N_g =[0.776+0.00457 x10-0.238 x 6.174 x $0.1636^{.5}$ +105 x 0.00163]/ $0.528^{0.5}$

= 0.55

$N_l = k_l\ a\ \theta_l$

k_l = liq phase transfer coefficient m/s

a = effective interfacial area for mass transfer , m^2/m^3

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

D_l = liq phase diffusion = 3.463 x 10-9 m^2/s

$k_l\ a = 1.354\ \ s^{-1}$

θ_l = residence time of liquid in froth ,s

$= h_L\ A_A /(1000\ q)$

$h_L = h_l$` = 12.28 mm

θ_l = 12.28 x 4.28 / (1000x .003463) = 13.87 s

N_l = 1.354 x 13.87 = 18.77

m_{top} = 0.333 ; m_{bottom} = 1.01 ; $G_m / L_m = 1.653$

$\lambda_t = m_t (G_m / L_m) = 0.55$

$\lambda_b = m_b (G_m / L_m) = 1.669$

$\lambda_{avg} = 1.105$

$N_{og} = 1 / [1/ N_g + \lambda/N_l) = 0.533$

$E_{og} = 1- \exp (- 0.533) = 0.413$

Murphee vapor efficiency :

Peclet number $N_{pe} = Z_l^{\ 2} / D_E\ \theta_l$

Z_l = length of liquid travel ,m

$= D_c \cos (\theta_c / 2) = 1.73$ m

D_E = Eddy diffusion coefficient

$= 6.675 (10^{-3}) U_a^{\ 1.44} + 0.922 (10^{-4}) h_l - 0.00562$

$= 0.0904\ m^2 / s$

$N_{pe} = 1.73^2 / 0.0873 \times 13.87 = 2.47$

$\lambda E_{og} = 1.105 \times 0.413 = 0.456$

(From PERRY : fig 18-29a ; p.no. 18-18)

$E_{mv} / E_{og} = 1.16$

$E_{mv} = 0.479$

Overall Column Efficiency :

$(L/ G) (\rho_g / \rho_l)^{0.5} = 0.0116$

From PERRY for 80% flooding ; $\psi = 0.25$

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

$E_a = 0..413$

$E_{oc} = \log [1+ E_a (\lambda - 1)] / \log \lambda$

$= 0.425$

$E_{oc} = N_{theoritical} / N_{actual}$

$N_{act} = 7 / 0.425 = 17$

Tower height = 500 x 17= 8500mm

STRIPPING SECTION

Point efficiency :

$E_{og} = 1 - \exp (- N_{og})$

N_{og} = overall transfer unit

$N_{og} = 1 / [(1/ N_g) + (\lambda / N_l)]$

N_g = gas phase transfer units

$N_g = [0.776 + 0.00457\ h_w - 0.238\ U_a\ \rho_g^{\ 0.5} + 105\ W\ ] / N_{scg}^{\ 0.5}$

h_w = weir height = 10mm

U_a = gas velocity through active area

= 16938 / (3600 x 0.1735 x 4.28)

= 6.336 m/s

W = liquid flow rate m^3 / s.m

$W = q / D_f$;

$D_f = (D_C + L_W)/ 2 = 2.32$ m

Average liq flow rate = 25581 kg/hr

Average liq density = 1076.56 kg / m^3

q = 25581 / (3600 x 1076.56) = 0.0066 m^3/s

W = 0.0066 / 2.32 = 0.002838 m^3 /m.s

N_{scg} = gas phase Schmidt number

$= \mu_g / \rho_g D_g = 0.478$

N_g =[0.776+0.0045 x10-0.238 x 6.336 x $0.1735^{.5}$ +105 x 0.002838]/ $0.478^{0.5}$

= 0.711

$N_l = k_l\ a\ \theta_l$

k_l = liq phase transfer coefficient m/s

a = effective interfacial area for mass transfer , m^2/m^3

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

D_l = liq phase diffusion = 3.343 x 10-9 m^2/s

$k_l\ a = 1.395\ \ s^{-1}$

θ_l = residence time of liquid in froth ,s

$= h_L\ A_A /(\ 1000\ q)$

$h_L = h_l$` = 14.99 mm

θ_l = 14.99 x 4.28 / (1000x .0066) = 9.72s

N_l = 1.395 x 9.72= 13.56

m_{top} =1.142 ; m_{bottom} = 1.15 ; $G_m / L_m = 1.047$

$\lambda_t = m_t\ (G_m / L_m\ ) = 1.195$

$\lambda_b = m_b\ (G_m / L_m) = 1.204$

$\lambda_{avg} = 1.119$

$N_{og} = 1 / [\ 1/ N_g + \lambda/N_l\ ) = 0.669$

E_{og} = 1- exp (- 0.669) = 0.488

Murphee vapor efficiency :

Peclet number $N_{pe} = Z_l^{\ 2} / D_E\ \theta_l$

Z_l = length of liquid travel ,m

$= D_c \cos (\theta_c / 2\ ) = 1.73$ m

D_E = Eddy diffusion coefficient

$= 6.675\ (10^{-3})\ U_a^{\ 1.44} + 0.922\ (10^{-4})\ h_l - 0.00562$
$= 0.091\ m^2 / s$

$N_{pe} = 1.73^2\ / 0.091 \times 9.72 \quad = 3.38$
$\lambda\ E_{og} = 1.119 \times 0.488 = 0.55$

(From PERRY : fig 18-29a ; p.no. 18-18)
$E_{mv} / E_{og} = 1.19$
$E_{mv} = 0.581$

Overall Column Efficiency :

$(L/ G)\ (\rho_g / \rho_l)^{0.5} = 0.019$
From PERRY for 80% flooding ; $\psi = 0.17$
$E_a / E_{mv} = 1 / [\ 1 + E_{mv}\ (\psi / (1- \psi)\ )\ ]$
$E_a = 0.519$

$E_{oc} = \log [\ 1+ E_a\ (\lambda - 1\ )] / \log \lambda$
$= 0.533$

$E_{oc} = N_{theoritical} / \ N_{actual}$

$N_{act} = 4 / 0.533 = 8$

Tower height = 500 x 8 = 4000mm

MECHANICAL DESIGN OF VACUUM DISTILLATION COLUMN

Material of construction - Stainless steel
Type 304 SA- 167 grade 3
Composition - 18 Cr- 8 Ni
Maximum allowable stress - 117.2 N/mm^2 = 17000 psi
Design pressure = 1 bar (external) = 14.7 psi
Maximum temperature = 75˚C
Design temperature = 85˚C
Column inner diameter d_i = 2.65 m = 8.694 ft = 104.328 in
Tray spacing = 500 mm
Number of trays = 25
Height of top chamber = 2 m
Height of the base chamber = 2 m
Total height of the column = 16.5 m = 54.13 ft

Shell thickness with Stiffeners :

Tray spacing = l = 500 mm = 1.64 ft = 19.86 in
Assume a shell thickness of ¼ in

l/d_o = 19.68 / [104.328 + 0.5] = 0.187

d_o / t = 104.828 / 0.25 = 419.312

From chart for detemining shell thickness of cylindrical vessels under external pressure

factor A = f / E = ε = 0.01

B = 7800

P_{allow} = B / (d_o/ t) = 7800 / 419 .3 = 18.6 psi

This pressure is higher than the desired external pressure of 15 psi for full vacuum . Hence it is adequate.

Shell thickness = 6.35 mm + corrosion allowance = 8mm = 0.315 in.

Shell plate of this thickness weighs p= 10.2 lb / ft^2

Shell weight = π d l p = π x 8.694 x 54.13 x 10.2 = 15080.22 lb

Design of circumferential stiffeners

Assuming a 6 in. channel weighing 10.5 lb / ft^2

I - required moment of inertia of stiffening ring = 15.1 in^4

Area of section A_y = 3.07 $in.^2$

B = P_{allow} d_o / [t_s + (A_y / l)] = 15 x 104.828 / [0.315 + (3.07 / 19.68)]
= 3338.5

From chart for B= 3338

ε = 0.0003

I = (d^2 l / 12) [t_s + A_y / l] ε = 2.193 in^4

As the required moment of inertia is less than that produced by the assumed 6 in.channel, the design is satisfactory.

Weight of 25 such stiffening rings are = 25 x π x 8.694 x 10.5
= 7169.6 lb
Weight of the shell = 15080.2 + 7169.6 = 22249.8 lb

Design of Elliptical dished closure

A elliptical dished closure ; a/b = 2

Average radius of curvature / vessel dia = r_c / d = 0.9 for a/b ratio of 2
thickness t_h = 5/16 in.
r_c = 0.9 x 105 = 94.5 in.
r_c / 100 x t_h = 94.5 / 100 x 0.3125 = 3.024
From chart, ε = 0.0004
B = 5250
P_{allow} = B/ r_c / t_h = 17.36 psi < 15 psi
As the vessel is designed for 1 atm (14.7 psi)
Hence thickness of 8mm is taken

Calculation of Stresses:

Compressive stress resulting from external pressure

Induced compressive axial stresses
f_{ap} = P d_i / 4 x [t_s - C] = 1533.62 psi
Circumferential stress
f = P d_i / 2 [t_s - C] = 3067.24 psi

Compressive stress caused by dead loads :

Stress induced by shell and insulation;
At any distance X ft from the top of a vessel having a constant shell thickness.

$f_{dead\ wt.\ shell}$ = (π / 4) (D_o^2 - D_i^2) X ρ_s / [(π / 4) x (D_o^2 - D_i^2) x 144]
= ρ_s X / 144 = 3.4 X
ρ_s = density of shell material = 490 lb/ft^3

$f_{dead\ wt.\ ins}$ = π D_{ins} ρ_{ins} X t_{ins} / 144 π D_m (t_s - C)
= ρ_{ins} t_{ins} X / 144 [t_s - C]
= 3.33 X
D_m = mean dia of the shell , ft
ρ_{ins} = 40 lb/ ft3
D_{ins} = D_o
t_{ins} = insulation thickness, 3 in.
$f_{dead\ wt.\ attachment}$ = Σ W / π d [t_s - C]

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

Dia d = OD + OD/24 + 2 sf x 2/3 icr ; icr =0 ; sf = 3in.

d= 115.19 in. ; l = head thickness = 8mm= 0.315 in.

Weight of the head = 923.56 lb

Weight of ladder = 25 lb / ft

Weight of 12 in. schedule 30 pipe = 438 lb/ft

Weight of pipe insulation = 39.3 lb/ft

Total weight = (923.56 + 108.1 X) lb

$f_{dead\ wt.\ attachment}$ = [923.56 + 108.1X] / π x 104.578 x 0.25

= 11.24 + 1.32X

$f_{dead\ wt.\ (liq\ +\ trays)}$ = $[[(X/2) - 1]\ 25\ (\pi\ d^2 / 4)] / [\ 12\ \pi\ D\ (t_s - C)]$

Assume tray loading including liq = 25 lb/ ft2

= 18.125 [(X/2) - 1]

= 9.062 X - 18.125

Total stress due to dead weight

f_{dx} = 3.4 X + 3.33 X + 11.24 + 1.32 X + 9.062 X - 18.125

= 17.115 X - 6.885

Calculation of stress due to wind load

Assumption : design wind pressure of 25 psf will be used in the design calculation.

Over head vapor line = 12 in OD

d_{eff} = insulated tower + vapor line

= (104.828 +6) + (12+6) = 128.828 in.

$f_{wx} = 2\ P_w\ X^2\ d_{eff} / \pi\ d_o^{\ 2}\ (t_s - C)$

$= 0.745\ X^2$

Calculation of combined stress under operating condition

Upwind side - Maximum tensile stress (upwind side) at point X with an unguyed vessel under external pressure and absence of eccentric loads

$f_{t\ (max)} = f_{wx} - f_{ap} - f_{dx}$

$= 0.745\ X^2 - 17.11\ X - 1526.735$

For allowable stress of 17000 psi and joint efficiency = 0.85

$17000 \times 0.85 = 0.745\ X^2 - 17.11\ X - 1526.735$

X = 97.09 ft

Down wind side - Maximum tensile stress (upwind side) at point X with an unguyed vessel under external pressure and absence of eccentric loads.

$f_{c\,(max)} = f_{wx} + f_{ap} + f_{dx}$

$= 0.745\ X^2 + 17.115\ X + 1526.73$

Allowable compressive stress due to stiffening effect of tray support rings

Equivalent thickness of shell $t_y = t_s + (A_y / d_y)$

A_y = CSA of one circumferential stiffeners

= 3.07 in^2

d_y = distance between circumferential stiffeners

= 19.68 in (tray spacing)

$t_x = t_s$

$t_y = 0.315 + (3.07 / 19.68) = 0.47$ in.

$f_c = [1.5 \times 10^6 / r]\sqrt{(t_y\ t_x)}$

$= 9117.52 \leq 1/3$ y.p

y.p. - minimum yield point = 30000psi

$9117.52 = 0.745\ X^2 + 17.115\ X + 1526.73$

X = 90.10 ft

To check the shell for empty condition , no trays, no insulation, no pressure , vapor line in place, only wind load acting .

Calculation of stresses

Upwind side:

Calculation dead weight

$f_{dead\ wt.\ shell} = 3.4\ X$

$f_{dead\ wt.\ attachments} = \Sigma W / \pi\ d\ [t_s - C]$

wt. of top head = 923.56 lb

wt. of ladder = 25 lb/ft

wt. of vapor line = 43.8 lb/ft

total = 923.56 + 68.8 X

$f_{dead\ wt.\ attachments} = 68.8\ X + 923.56 / \pi \times 104.3 \times 0.25$

$= 0.839\ X + 11.27$

$f_{dx} = 3.4\ X + 0.839\ X + 11.27$

$= 4.239\ X + 11.27$

Wind side stress

d_{eff} is increased by 17 in for caged ladder

$d_{eff} = 104.828 + 17 = 121.828$ in.

$f_{wx} = 15.89 \times 121.828 \times X^2 / 104.828^2 \times 0.25$

$= 0.704\ X^2$

Calculation of combined stress for condition of partial erection.

Upwind side:

$f_{t\,(max)} = f_{wx} - f_{dx}$

$17000 \times 0.85 = 0.727\ X^2 - 4.239\ X - 11.27$

$X = 143.97$ ft

Down wind side :

$f_{c(max)} = f_{wx} + f_{dx}$

$f_{c(max)} = 1.5 \times 10^6\ (t / r)$

$= 1.5 \times 10^6 \times (0.315 / 52.414) = 9014.76$ psi

$9014.76 = 0.727\ X^2 + 4.239\ X + 11.27$

$X = 111.34$ ft

Therefore the design is satisfactory with regard to loading conditions in which the wind load rather the seismic load is controlling .

Thus the controlling stress condition is under operating load with a superimposed wind.

For this reason , specify 6 courses of 8 ft wide , 8mm plate and 1 course of 6 ft wide , 8mm thickness plate.

<u>Flanges, Gasket, Bolt :</u>

Gasket material - Serrated steel (asbestos filled)

Gasket factor m = 2.75

Minimum design seating stress y = 3700

Flange material - ASTM A- 201 grade B

Allowable stress of flange = 15000 psi

Bolting steel - ASTM A -193 grade B-7

Allowable stress of bolting material = 15000 psi

Calculation of gasket width :

$d_o / d_i = \sqrt{[(y - Pm) / (y - P(m+1))]}$

$d_o / d_i = 1.002$

Assume d_i of gasket $d_i = 105.828$ in

$d_o = 1.002 \times 105.828 = 106.03$ in

Minimum gasket width = [106.03 - 105.828]/ 2 = 0.211 in

Use a 0.5 in. gasket width

Mean gasket dia $G = 105.828 + 0.5 = 106.328$ in.

Calculation of bolt loads:

Load to seat gasket $W_{m2} = H_y = b\,\pi\,G\,y$

Basic gasket seating width $b_o = 0.5 / 2 = 0.25$ in.

$b = b_o$ if $b_o \leq 0.25$ in.

$W_{m2} = H_y = 0.25\,\pi \times 106.328 \times 3700 = 308986.3$ lb

Load to keep joint tight under operation $H_p = 2\,\pi\,b\,G\,m\,P$

$= 6751.76$ lb

Load from pressure $H = \pi\,G^2\,P / 4 = 130527.64$ lb

Total operating load $W_{m1} = H + H_p = 137279.4$ lb

Since $W_{m2} > W_{m1}$; Controlling load is $W_{m2} = 308986.3$ lb

Calculation of minimum bolting area :

$A_{m2} = W_{m2} / f_b = 308986.3 / 15000 = 20.59$ in^2

Optimum bolt size :

For a 7/8 in bolt ; root area = 0.419 in^2

No. of bolts = 52

Bolt circle dia C = 108.25 in

Flange OD = bolt circle dia + 2 x (15 / 16) = 110.12 in

Check gasket width :

$A_{b\,actual} = 52 \times 0.419 = 21.788$ in^2

Minimum gasket width = $A_{b\,actual} \times f_{allow} / 2\,\pi\,y\,G = 0.1322$ in < 0.5 in.

Hence acceptable .

Moment Computations:

For bolting up condition:

Design load = $W = ½\,(A_b + A_m)\,f_a$

$= ½\,(20.59 + 21.788)\,15000 = 317835$ lb

Corresponding lever arm is given by

$h_G = ½\,(C - G) = 0.961$ in.

Flange moment , $M_a = W\,h_G = 305439.43$ in lb

For operating condition : ($W = W_{m1}$)

$H_D = (\pi / 4)\,B^2\,P = 0.785 \times 104.33^2 \times 14.7$

= 125606.26 lb

Lever arm , h_D = (C -B)/ 2 = 1.96 in

Moment M_D = H_D x h_D = 246188.25 in lb

H_G = W - H = W_{m2} - H = 6751.76 lb

Lever arm h_G = (C - G)/ 2 = 0.961 in.

M_G = H_G x h_G = 6488.44 in. lb

H_T = H - H_D

= 4921.64 in.lb

Lever arm h_T = (h_D + h_G)/ 2 = 1.46 in.

Moment M_T = H_T h_T = 7188.15 in.lb.

Summation of moments for the operating condition

M_o = M_D + M_G + M_T = 259864.7 in.lb

Therefore the bolting up is controlling M_{max} = 305439..43 in. lb.

Calculation of flange thickness

$t = \sqrt{(Y M_{max} / f B)}$

K = A/B = Flange OD / shell ID = 110.12 / 104.838 = 1.0504 in

For K = 1.05 , Y = 40

t = 2.8 in. plate .

CHAPTER VI

PROCESS DESIGN OF INTER STAGE COOLER (Minor equipment)

(Shell and tube heat exchanger)

I) Exchanger Duty:

Q = 5535049 kJ/hr

= 1537.5 kJ/sec

Coolant used is Water at 27˚C.

Cooling water balance:

Q = m Cp ΔT

1537.5 = m x 4.187 x (42 - 27)

m_w = 24.498 kg/ sec.

Flow rate of liq mix to be cooled:

m_{mix} = 28786.7 kg/ hr

= 7.996 kg/sec

Liquid mixture Balance:

$Q = m_{mix} \times Cp_{mix} \times (T_i - 80)$

$1537.5 = 7.996 \times 3.212 \times (T_i - 80)$

$T_i = 140$ ˚C.

Hence the liquid mixture must be cooled from a temperature of 140˚C to a temperature 40˚C.

Properties : (at mean temperatures)

Properties	Water	Liquid Mixture
Density ρ kg/ m^3	993.68	992.99
Specific heat Cp kJ/kg˚K	4.187	3.212
Viscosity μ cp	1.00	0.1612
Thermal conductivity K W/m˚K	0.578	0.513

II Log Mean Temperature Difference (ΔT_{lm})

$\Delta T_{lm} = [(T_1 - t_2) - (T_2 - t_1)] / \ln [(T_1 - t_2)/(T_2 - t_1)]$.

$(T_1 - t_2) = 140 - 42 = 98$

$(T_2 - t_1) = 80 - 27 = 53$

$\Delta T_{lm} = 73.21$˚C.

$R = (T_1 - T_2) / (t_2 - t_1) = 4$

$S = (t_2 - t_1) / (T_1 - t_1) = 0.132$

{From PERRY Fig 10-14, P.No.: 10-27}

$F_T = 0.97$.

III Routing of Fluids:

Water - Tube side

Liquid Mixture - Shell Side

IV Heat Transfer Area:

{From PERRY Table 10-10 P.No.: 10-44}

Assumed Value of Overall heat transfer Coefficient:
U_d = 570 W/m^2 K.
Dirt factor = 5.283 x 10^{-4} m^2 K/ W.

$Q = U A(\Delta T_{lm}) F_T$.
A= (1537.5 x 10^3) / (570 x 73.21 x 0.97)
= 37.98 m^2

V Number of Tubes:

Choose D_0 (Tube outside dia) = ¾ in = 0.01905 m
D_i (Tube inside dia) = 0.62 in = 0.01575 m
Length = L = 14 ft = 4.2672 m

Heat transfer Area :a = πD_o = π x 0.01905 = 0.05987 m^2 / m length
Heat transfer Area for one tube = 0.05987 x 4.2672 = 0.2555 m^2 / tube
Number of Tubes = 37.98 / 0.2555 = 149

From Tube Count Table (PERRY : table 11-3 ; P.No. 11-13)
TEMA P or S ; for 1-2 pass
Number of tubes N_t = 198
Shell ID = 438 mm
Corrected Heat Transfer Area = 198 x 0.2555= 50.589 m^2
Corrected U_d = 427.977 W/m^2 K.

VI Tube Side (Cooling water) Velocity and Heat transfer Coefficient h_i

Flow Area = $a_t = \pi / 4 \times D_i^2 \times (N_t / N_p)$
= 0.01928 m^2

Velocity = $v_t = (m_t / \rho \ a_t)$ = 24.498 / 993.68 x 0.01905
= 1.278 m / sec

Reynolds Number $N_{Re} = v_t \ D_i \ \rho / \mu$
= 1.278 x 0.01575 x 993.68 / 1.00 x 10^{-3}
= 20001.28

Prandtl Number $N_{Pr} = \mu Cp / K$ = (1.00 x 10^{-3} x 4.187 x 10^3)/ 0.578
= 7.2439

Nusselt Number $N_{Nu} = 0.023 (N_{Re})^{0.8} \ (N_{Pr})^{1/3}$
= 143.19

Heat transfer coefficient $h_i = N_{Nu}\ K / D_i$
$= 5254.89\ W/m^2\ K.$

VII Shell Side (Liquid Mixture) Velocity and Heat Transfer Coefficient h_o

Assumption : Shell Dia is equal to tube bundle dia.

Pitch : Equilateral Triangular Pitch is used.
P' = standard pitch = 1 in = 25.4 mm.
p_p = pitch parallel to flow = $(\sqrt{3} / 2)\ P' = 21.997$ mm
p_n = pitch normal to flow = $(1 / 2)\ P' = 12.7$ mm

S_m = Cross flow area at center of shell
$= [(P' - D_o)\ L_s]\ D_s / P'$
L_s = baffle spacing .
$= D_s / 2 = 0.219$ m
N_b = number of baffles
$N_b + 1 = L / L_s = 20$
$N_b = 19$

$S_m = 0.02398\ m^2$

Shell side velocity = $v_s = m_s / S_m\ \rho$
$= 7.996 / 0.0479 \times 992.99$
$= 0.3357$ m/sec

Reynolds Number $N_{Re} = v_s\ D_o\ \rho / \mu$
$= 0.3357 \times 0.01905 \times 992.99 / 0.16128 \times 10^{-3}$
$= 39374.1$
Prandtl Number $N_{Pr} = \mu\ Cp / K = (0.16128 \times 10^{-3} \times 3.205 \times 10^{3}) / 0.513$
$= 1.0076$

Nusselt Number $N_{Nu} = j_H\ (N_{Re})\ (N_{Pr})^{1/3}$
(From PERRY : Fig 10- 19 ; P.No 10-29)
$j_H = 5 \times 10^{-3}$
$N_{Nu} = 197.36$

Heat transfer coefficient ho = $N_{Nu}\ K / D_o$
$= 5314.94\ W/m^2\ K.$

VIII Overall Heat Transfer Coefficient U_o

$(1/U_o)_{clean} = 1/h_o + 1/h_i\ (D_o / D_i) + D_o \ln (D_o / D_i) / 2 K_w$
$K_w = 50\ W/m^2\ K.$

$(1/U_o)_{clean} = [1/5314.94] + [(1/5254.89)(0.01905/0.01575)]$
$+ [(0.01905 \ln(0.01905/0.01575)) / (2 \times 50)]$
$= 4.5459 \times 10^{-4}$

$(1/U_o)_{dirt} = 4.5459 \times 10^{-4} + 5.283 \times 10^{-4}$
$U_o = 1017.4\ W/m^2\ K$
Which is greater than the assumed U_o
Hence design is acceptable.

IX Tube Side Pressure Drop

Friction factor (f) $= 0.079 \times (N_{Re})^{-0.25}$
$= 0.079 \times (20001)^{-0.25}$
$= 0.0066$

Pressure Drop $\Delta P_L = (4 f L v_t^2 / 2 g D_i) \rho g$
$= 2 \times 0.0066 \times 4.2672 \times 1.278^2 \times 993.68 / 0.01575$
$= 5842.0\ N/m^2$
Pressure Drop $\Delta P_E = 2.5 (\rho v_t^2 / 2)$
$= (2.5 \times 993.68 \times 1.278^2) / 2$
$= 2028.7\ N/m^2$

Total Pressure Drop $\Delta P_T = N_p [\Delta P_E + \Delta P_L]$
$= 2 \times [5842.0 + 2028.7]$
$= 15741.48\ N/m^2$
$= 15.74$ kPa. which is less than permissible $\Delta P = 70$kPa

X Shell Side Pressure Drop

$\Delta P_s = 2 \Delta P_E + (N_b - 1) \Delta P_C + N_b \Delta P_W$

ΔP in Cross Flow Section :

$\Delta P_C = [(b f_k w^2 N_C) / \rho S_m^2] (\mu_w / \mu_b)$

f_k (shell side friction factor) = 0.15 {PERRY:Fig 10-25a ;P.no.10-31}
b= 2 x 10-3 (constant)
w = 7.996 kg / sec
$S_m = 0.02398\ m^2$
N_C = Number of cross flow zones
$= \{D_S [1 - (2 L_C / D_s)]\} / P_P$
L_C = Baffle cut = $0.25 D_S = 109.5$ mm
$N_C = 438 \times [1 - (2 \times 109.5 / 438)] / 22$
$= 10$

ΔP_C = (2 x 10-3 x 0.15 x 7.996 ^{2} x 10) / 992.99 x 0.02398 ^{2}
= 0.335 kPa

ΔP in end zones

$\Delta P_E = \Delta P_C$ [1 + (N_{CW} / N_C)]

N_{CW} = Number of effective cross flow region in each window
= 0.8 L_C / P_p
= 4
N_C = 10
ΔP_E = 0.335 x [1+ 4/10] = 0.469 kPa

ΔP in window zones

ΔP_W = [b w ^{2} (2+ 0.6 N_{CW})] / S_m S_w ρ

b = 5 x 10 -4 (constant)
S_w = Area for flow through window
= S_{wg} - S_{wt}
S_{wg} = gross window area
(From PERRY :Fig 10 -18 ; P.No. 10 - 29)
For L_C / D_S =0.25 ; D_S = 17 ¼ in.
S_{wg} = 0.029 m^2
S_{wt} = window area occupied by tubes
=(N_t / 8) (1- F_c) π D_o^2
F_C = Fraction of total tube in cross flow
(From PERRY : Fig 10 - 16 ; P.No. 10 - 28) F_c = 0.67
S_{wt} = (198 / 8) x (1- 0.67) x π x 0.01905 ^{2} = 0.009311 m^2
S_w = 0.029 - 0.009311 = 0.0196 m ^{2}

ΔP_W = [5x 10^{-4} x 7.996 ^{2} x (2 + 0.6 x 4)] / (0.02898 x 0.0196 x 992.99)
= 0.3013 kPa

Total Pressure Drop
$(\Delta P_S)_{Total}$ = 2 (ΔP_E) + (19 - 1) ΔP_C + (19) ΔP_W
= 12.692 kPa < 70 kPa (max allowable)

MECHANICAL DESIGN

Shell Side

Material of construction : Carbon Steel
Permissible Stress (f) : 95 N/ mm^2
Fluid : Liquid mixture from absorber bottom
Working Pressure : 1 atm = 0.1013 N/ mm^2
Design Pressure (P_d) : 0.11143 N/ mm^2
Inlet temperature : 140 ˚ C
Outlet temperature : 80˚C
Nominal Shell Diameter : 438 mm
Length : 14 ft

Shell thickness $t_S = P_d D_S / [2 f J + P_d]$ (J joint efficiency = 0.85)
= 0.1143 x 438 / [2x 95 x 0.85 + 0.11143]
= 0.3019 mm
Corrosion allowance = 3mm
Minimum thickness of 8mm is chosen

Head thickness $t_h = P_d R_C W / 2 f J$
R_C - crown radius = 438 mm
R_1 - knuckle radius = 10% of R_C = 43.8 mm
W - stress intensifying factor
$= ¼ [3 + \sqrt{(R_C / R_1)}]$
= 1.54

t_h = 0.11143 x 438 x 1.54 / 2 x 95 x 1
= 0.39 mm
Corrosion allowance = 3mm
Thickness taken same as shell = 8mm

Baffles, tie rods and spacers
19 transverse baffles are used with 25 % baffle cut
Baffle spacing = D_S / 2 = 219 mm
Thickness of baffles = 6mm
Number of tie rods = 6
Diameter of tie rods = 10mm

Flanges, gasket, bolts
Flange material used - ASTM A-201grade B
Allowable stress f_f = 100 N/ mm^2
Material used for bolts - 5% Cr Mo steel

Allowable stress f_b = 138 N/ mm^2
Gasket material - Asbestos composition
Gasket factor m = 2.75 :
Minimum design seating stress y= 3700
Shell outside dia = 454 mm (B): Shell thickness = 8mm (g_o)

Gasket inner dia d_i = 464 mm
Gasket width N = 12mm
Gasket outside dia d_o = 488mm
Gasket thickness = 1.6mm
Basic gasket seating width b_o = N/2 = 6mm
Dia at location of gasket load reaction $G = d_i + N$ = 476mm

Estimation of bolt load

Load due to design pressure

$H = \pi G^2 P_d / 4$

= 0.01982 MN

Load to keep joint tight under operation

$H_p = \pi G (2 b) m P_d$ (m - gasket factor = 2.75)

= 0.005498 MN

Total operating load $W_o = H + H_p$ = 0.0253 MN

Load to seat gasket under bolting up condition

$W_g = \pi G b y$

= 0.2287 MN

Since $W_g > W_o$, W_g is the controlling load

Minimum bolting area $Am = W_g / f_b$

= 0.00166 m^2

Bolt size = M 18 x 2
Actual number of bolts = 64
Minimum bolt circle C = 0.54 m
Flange outside dia A= C+ bolt dia +0.02

= 0.58 m

Flange moment

a) For operating condition

$W_0 = W_1 + W_2 + W_3$

$W_1 = \pi B^2 P_d / 4$

= 0.018 MN

$W_2 = H - W_1$

= 0.00178 MN

$W_3 = W_0 - H$

= 0.005498 MN

$M_o = W_1 a_1 + W_2 a_2 + W_3 a_3$

$a_1 = (C - B) / 2$

= 0.043

$a_3 = (C - G) / 2$ = 0.032

$a_2 = (a_1 + a_2)/2$

$M_o = 0.0010166$ MJ

b) For bolting up condition

$M_g = W \times (a_3)$

$W = [(A_m + A_b) / 2] f_b$

$= 0.581$ MN

$M_g = 0.0185$ MJ

Since $M_g > M_o$, $M = M_g$

Flange thickness = $t^2 = (M C_F Y / B f_f)$

$= 0.0576$ m

Actual bolt spacing $B_s = \pi C / 44$

$= 0.0385$ m

Bolt pitch correction factor $C_F = B_s / (2 \times d + t)$

d - bolt dia = 18mm

$C_F = 0.641$

Actual flange thickness = $\sqrt{C_F} \times 0.0576 = 0.0461$ m

= 50mm

Shell side Nozzle

Nozzle dia :

$m_{mix} = \rho_{mix} \times A \times v_s$

$7.996 = 992.99 \times A \times 0.3357$

$A = 0.0239\ m^2$

$A = (\pi/4) \times D_n^2$: $D_n = 175$ mm

Nozzle thickness $t_n = P_d D_n / [2 f J - P_d]$

$= 0.1026$ mm

Corrosion allowance = 3mm

$t_n = 3$mm

Tube side

Tube and tube sheet material - Stainless steel

Grade : S

Type : 304

Nominal composition : 18 Cr 8Ni

Maximum permissible stress = 106.52 N/ mm^2

Number of tubes = 198

Tube outer dia = 19.05 mm

Tube inner dia =15.75 mm

Length = 14 ft

Pitch (Δ lar) = 25mm

Fluid - water

Working pressure = 5 atm

Design pressure = 0.557 N/ mm^2

Inlet temperature = 27 ˚C
Outlet temperature = 42˚C

Tube thickness

$t_h = P_d \ D_o / [\ 2\ f\ J + P_d\ ]$
$= 0.0496$ mm
t_h = 2mm (minimum thickness)

Tube Sheet

thickness $t_{Sh} = F\ G \sqrt{(\ 0.25\ P_d / f)}$
$= 1.25 \times 476 \sqrt{(0.25 \times 0.557 / 106.52)}$
$= 21.5$ mm
Assuming standard fit , tube hole diameter = d + 0.2 = 19.2mm

Channel and channel cover

Nozzle dia t_N
$m_t = \rho_t \ A\ v_t$
$24.498 = 993.68 \times A \times 1.278$
$A_N = 0.0193\ m^2$; $D_N =$ 157 mm

Nozzle thickness $t_n = 0.11143 \times D_N / [\ 2 \times 95 - 0.11143]$
$=0.092$ mm
Corrosion allowance = 3mm
t_h = 3mm
Channel inner dia = shell ID = 438mm
Effective channel cover thickness t_{ch} :
$t_{ch} = G \sqrt{(\ K\ P_d / f)}$
K = 0.3 for ring type gasket
$t_{ch} = 0.476 \sqrt{(0.3 \times 0.557 / 95)}$
$= 20$mm
Corrosion allowance = 3mm
t_{ch} = 23 mm
Minimum cross over area for flow = 1.3 x flow area of tube / pass
$b\ D_s = 1.3 \times (\pi/4) \times 0.01575^2 \times (198/ 2)$
b= 44mm
b is chosen as $3 \times D_N = 3 \times 157 = 471$mm

Saddle Support

Equal angle support
Material of construction - Carbon steel
Density = 7800kg/m^3
Outside shell dia = 454mm

Length of the shell and channel= 5209.2 mm

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

r_o - knuckle radius = 6% of dia = 27.24 mm

$H = \sqrt{(454 \times 27.24 / 2)} = 78.63$ mm

$A = 0.5 \times R = 113.5$ mm

Total weight of exchanger:

Wt . of shell + Wt. of channel = $(\pi /4) (D_o^2 - D_i^2) (L + 2b) \rho_{steel}$

= 455.29 kg

Wt. of tube = $n_t (\pi /4) (D_o^2 - D_i^2) \rho_{steel}$ = 594.41 kg

Wt. of tube sheet = $2 (\pi /4) (D_s^2) \ t \ \rho_{steel}$ = 50.53 kg

Wt. of liquid in shell + channel

= (Shell volume - tube volume)ρ_{mix} + liq in channel

= $[(\pi /4) (D_s^2 L - n_t(\pi /4) D_o^2 L] \rho_{mix}$

$+ 2 (\pi /4) D_s^2 \ b \ \rho_{tube\ liq}$

= 540.26 kg

Wt. of liquid in tube = $n_t (\pi /4) D_i^2 \ L \ \rho_{tube\ liq}$

= 163.46 kg

Wt. of end cover = $2 (\pi /4) D_s^2 \ t_{ec} \ \rho_{steel}$ = 18.804 kg

Toatal weight = 1822. 75 kg

To account for the weight of baffles, tie rods , spacers, pass partition, plates, nozzles, bolts, nuts, total weight obtained above is multiplied by 1.3

W (wt. / support) = 1.3 x 1822.75 / 2 = 1184.78 kg

Longitudinal Bending Moment

$M_1 = Q A [1 - \{ [1 - (A/ L) + (R^2 - H^2)/ 2AL] / [1 + (4/3 \times H/L)]\}$

$M_2 = (Q L/4)\{ [1 + 2 (R^2 - H^2)/ L2] / [1 + (4/3 \times H/L)] - (4A/L) \}$

$Q = W [L + 4xH/3)] = 10359.87$ kg

$M_1 = 4.995$ kg m

$M_2 = 5696.58$ kg m

Stress in Shell at the saddle

$f_1 = M_1 / k_1 \pi R^2 t$

$= 4.995 / 1 \times \pi \times 0.008 \times 0.227^2 = 0.3856$ kg/ cm^2

$f_2 = M_1 / k_2 \pi R^2 t$

$= 0.3856$ kg/ cm^2 ($k_1 = k_2 = 1$)

Sress are within the permissible values.

Stress in the shell at midspan

$f_3 = M_2 / \pi R^2 t = 439.868$ kg/ cm^2

Axial stress in the shell due to internal pressure

$$f_p = PD / 4t = 0.1143 \times 0.438 / 4 \times 0.008 = 15.94 \text{ kg/ cm}^2$$

Combined stress ($f_p + f_1$) , ($f_p - f_2$) and ($f_p + f_3$) are well within the permissible values.