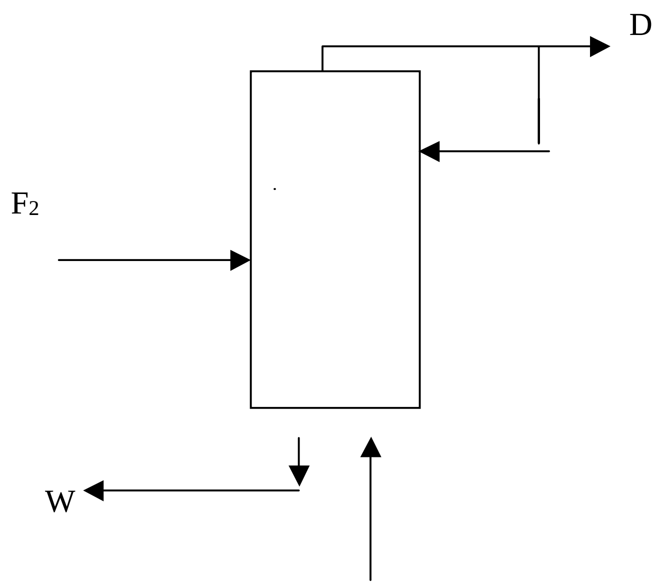
DESIGN OF MAJOR EQUIPMENT

DESIGN OF A DISTILLATION COLUMN TO SEPARATE O-XYLENE AND 1-3-5 TRIMETHYL BENZENE

PROCESS DESIGN:



F_2 = 9673.39 kg / hr = 96.57 kmol / hr, T = 150^{0}C.

X_{OX} = 0.727, X_{TMB} = 0.2746

D = 4421 kg / hr = 41.59 kmol / hr, T = 145^{0}C

X_{OX} = 0.99, X_{TMB} = 0.01

W = 5252.38 kg / hr = 16.69 kmol / hr, T = 164 ^{0}C

X_{OX} = 0.05 , X_{TMB} = 0.95

T-x-y data is obtained from the Chem-cad software for ideal solution.

Chem-cad 5.1.0

XY data for O-Xylene / 1,3,5-Mesitylene

K value model: UNIF

Mole Fractions

T Deg F	P atm	X1	Y1
328.421	1.000	0.00000	0.00000
326.225	1.000	0.05000	0.07833
324.072	1.000	0.10000	0.15262
321.960	1.000	0.15000	0.22309
319.888	1.000	0.20000	0.28995
317.856	1.000	0.25000	0.35340
315.864	1.000	0.30000	0.41362
313.911	1.000	0.35000	0.47078
311.995	1.000	0.40000	0.52506
310.116	1.000	0.45000	0.57660
308.275	1.000	0.50000	0.62556
306.469	1.000	0.55000	0.67208
304.698	1.000	0.60000	0.71628
302.962	1.000	0.65000	0.75829
301.260	1.000	0.70000	0.79823
299.592	1.000	0.75000	0.83620
297.956	1.000	0.80000	0.87232
296.353	1.000	0.85000	0.90666

294.780	1.000	0.90000	0.93933
293.240	1.000	0.95000	0.97042
291.729	1.000	1.00000	1.00000

Streams F_2, D and W are all saturated liquid,

q = 1

q / q-1 = ∞

From graph,

X_D / Rm+1 = 0.35

X_D = 0.99 => R_m = 3.213

Assume reflux ratio, R = 1.25 R_m = 4.01625

L / D = 113.956

X_D / R+1 = 0.99 / 4.01625 + 1 = 0.197

$\bar{L}$ – L / R = q = 1

$\bar{L}$ = L + F = 167.025 + 96.57

= 263.595 kmol / hr.

$\bar{G}$-G / F = q -1 = 0

∴ $\bar{G}$ = G = 208.61 kmol / hr.

$\bar{L}$ / G = 1.2636

From graph,

Total number of trays in enriching section = 14

Total number of trays in stripping section = 16

Feed tray = 15

Total number of ideal trays = 31

TOWER HYDRAULICS

	Enriching Section		**Stripping section**	
	Top	**Bottom**	**Top**	**Bottom**
Liq (kmol/hr.)	167.025	167.025	263.595	263.595
Gas (kmol/hr.)	208.61	208.61	208.61	208.61
X	0.99	0.45	0.45	0.05
Y	0.99	0.56	0.56	0.01
T_{liq} (^0C)	145.0	150.0	150.0	164
T_{vap} (^0C)	145.0	152.5	152.5	164
$(M_{avg})_{liq}$ kg/kgmol.	106.167	110.2	110.2	119.3
$(M_{avg})_{vap}$ kg/kgmol.	106.167	108.66	108.66	119.2
Liq (kg/hr.)	17732.54	18372.75	28995.45	31473.2
Vap (kg/hr.)	22147.498	22644.61	22644.61	24866.31
ρ_l (kg/m^3)	836.84	833.67	833.67	826.59
ρ_v (kg/m^3)	3.093	3.155	3.155	3.330
$L/G(\rho_g / \rho_l)^{0.5}$	0.0486	0.0499	0.0787	0.0809

TRAY TOWER DESIGN

Assume:

(1) Plate spacing, t_s = 457.2 mm

(2) Hole diameter, d_h = 5 mm

(3) Hole pitch, l_p = 17.5 mm

(4) Tray thickness, t_T = 3 mm

(5) Hole area / Perforated area = A_h / A_p = 0.1

Assume equilateral triangular pitch

(6) Column dia, Dc:

Based on entrainment flooding.

All relations from Perry's handbook, 6th edition.

Fig. 18-10, $C_{sb} = U_{nf} [20/\sigma]^{0.2} [\rho_g/\rho_l-\rho_g]^{0.5}$ ft/s.

C_{sb} = 0.27

$\therefore U_{nf}$ = 4.988 ft/s

Assume $U_n = 0.8\ U_{nf}$

= 3.99 ft/s = 1.216 m/s.

Net area for flow, $A_n = A_c - A_d$

Vapor flow rate = 24866.31 / (3600*3.33)

= 2.0743 m^3/s

A_n = 2.0743 / 1.216 = 1.706 m^2.

Assume $L_w / D_c = 0.75$

$\sin(\theta c/2) = (L_w/2) / (D_c/2)$

$\theta_c = 88.8^0$

$A_c = \pi D_c^2/2 = 0.785 D_c^2$

$A_d = 0.0879 D_c^2$

$A_n = 0.785 D_c^2 - 0.06856 D_c^2$

$D_c = 1.512$ m

$A_c = 1.766 m^2$

$A_d = 0.127 m^2$

Active area, $A_a = A_c - 2A_d = 1.5115 m^2$.

$L_w = 1.05$ m

(7) Perforated area, A_p

$\theta_c = 88.85\ ^0C$

$\alpha = 180 - \theta_c = 91.14\ ^0C$

Area of calming + distribution zone, A_{cz}

$A_{cz} = 2^*(1.05 * 45 * 10^{-3}) = 0.0945 m^2$.

$A_{wz} = 0.325 m^2$

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

$= 1.3385 m^{2.}$

$A_h = 0.1 A_p = 0.13385 m^2$

No. of holes, $n_h = 0.13385 / \pi/4^* (5^*10^{-3})^2$

= 6817 holes.

(9) Weir height, $h_w = 40$ mm

(10) Weeping check:

Bottom of stripping section

Vapor flow rate = $1.56 m^3 /s$

$A_h = 0.13385\ m^2$

$U_n = (1.989\ /\ 0.13385) = 14.86\ m/s.$

$hd = K_1 + K_2\ \rho_g U^2{}_h / \rho_1$

Assume sieve plates

$K_1 = 0,\ K_2 = 50.8 / C_v^2$

$A_h\ /\ A_a = 0.13385\ /\ 1.5115 = 0.088$

$t_T / d_h = 0.6$

$C_v = 0.73$

$K_2 = 95.33$

$\therefore\ h_d = F_w * 664 * [q / L_w]^{2/3}$

q_1 (liquid load) = 31473.2 / (60*826.59)

= 0.634 m^3/min.

$L_w = 1.05\ m\ = 3.44\ ft$

$q\ /\ L_w^{2.5} = 2.36,\quad L_w\ /\ D_{cw} = 0.694$

$F_w = 1.03$

$h_{ow} = 21.57\ mm$

<u>Head loss due to bubble formation,</u>

$h_\sigma = 409\ [\ \sigma\ /\ \rho_1 d_n]$

$\therefore\ h_\sigma = 3.745$ mm liq.

Now, $h_d + h_\sigma = 81.545$ mm liq.

$h_w + h_{ow} = 61.57$ mm

$(A_h /\ A_a) = 0.088$

Minimum value to avoid weeping, $h_d + h_\sigma = 16$ mm

Since actual >minimum there is no weeping

(11) Downcomer flooding:

(a) Hydraulic gradient:

$h_d > 2.5$ mm

Let h_{hg} = 0.5 mm

$h_{ds} = h_w + h_{ow} + h_{hg} / 2$ = 71.82 mm

$h_L = \beta h_{ds}$

U_a = (6.29 / 4.7687) = 1.3189 m / s = 4.327 ft / s

ρ_a = 3.155 kg / m^3 = 0.1972 lb / ft^3

$F_a = U_a \rho^{0.5}{}_g$

β = 0.58

ϕ = 0.18

h_L'= 41.65 mm

(b) Loss under downcomer, h_{da}

$h_{da} = 165.2\ (q / A_{da})^2$

Assume clearance C = 1" = 25.4 mm.

$h_{ap} = h_{ds} - C$ = 47 mm

$A_{da} = L_w h_{ap}$ = 0.04935 m^2

h_{da} = 2.538 mm liquid

$h_l = h_d + h_L'$ = 119.45 mm liquid

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

= 119.45+40+21.57+0.5+2.538

= 197.058 mm

h_{dc}' / Φ_{dc} = 197.058 / 0.5 = 394.116 mm liq

t_s = 457.2 mm

As $h_{dc}' < t_s$ there is no flooding

Summary of tray calculations

D_c = 1.512 m

L_w = 1.05 m

h_w = 40 mm

t_s = 457.2 mm

d_h = 5 mm

l_p = 17.5 mm

t_t = 3 mm

n_h = 6817 holes

(12) **Column Efficiency (AIChe method):**

Enriching section

L_{avg} = 115.38 kmol / hr =12478.34 kg / hr

G_{avg} = 157.49 kmol / hr =16911.275 kg / hr

$T_{liq-avg}$ = 147.5 ^{0}C , $T_{vap-avg}$ = 148.75^{0}C

ρ_{Lavg} = 835.25 kg / m^3

ρ_{Gavg} = 3.124 kg / m^3

Liquid vis_{ox} at 147.5^{0}C = 0.24 cP

Liquid vistmp at 147.5^{0}C = 0.2568 cP

D_L = 8.8752 * 10^{-5} cm^2 / sec

D_G = 0.04326 cm^2 / sec

$N_{scg} = \mu_g / \rho_g D_g$ = 0.694

Similar calculations are repeated for the stripping section

	Enriching Section	**Stripping Section**
Liq. flow rate: kmol/hr.	167.025	263.595
Liq. flow rate: kg/hr.	18052.64	30234.325
Vap. flow rate : kmol/hr	208.61	208.61
Vap. flow rate : kg/hr.	22396.05	23755.46
$\overline{\rho}_L$ (kg/m³)	835.255	830.13
$\overline{\rho}_V$ (kg/m³)	3.124	3.243
T_{liq}(^oC)	147.5	157
T_{vap}(^oC)	148.75	158.0
μ_{liq}, cP	0.2428	0.239
μ_{vap}, cP	938.38×10^{-5}	923.94×10^{-5}
D_L , cm^2/s	8.8752×10^{-5}	9.204×10^{-5}
D_G , cm^2/s	0.04326	0.0449
N_{scg}	0.694	0.634
X’	0.72	0.23
Y’	0.775	0.285

<u>Enriching section</u>

(a) Point Efficiency, E_{OG}

$N_g = 0.776 + 0.2285\, h_w - 0.238\, U_a\, \rho_g^{0.5} + 105W / (N^{0.5}_{scg})$

$W = (6.117 * 10^{-3} / 1.281) = 4.775 * 10^{-3}\, m^3 / m.s$

$U_a = 1.3189\ m/s$

$h_w = 40\ mm$, $N_{Scg} = 0.694$

$N_g = 4.1756$

$N_L = K_L a \theta_L$

$K_L a = (3.875 \times 10^8 D_L)^{0.5} (0.4\, U_a \rho_g^{0.5} + 0.17)$

$= 2.0446\ m/s$

$\theta_L = (h_L A_a) / (1000q) = 15.27$

$N_L = 31.22$

$\lambda = M\, G_m / L_m$ $M_{TOP} = 0.733$

$Gm / Lm = 157.49 / 115.38$ $M_{BOTTOM} = 0.8125$

$\lambda = 0.934$

$Nog = 1 / ((1/0.4205) + (0.934/31.22)) = 3.71$

$\therefore N_{og} = 3.71$

$E_{OG} = 1 - e^{-NOG} = 0.97556$

(b) Murphree Plate Efficiency, E_{mv}

$\lambda E_{OG} = 0.934 * 0.97556 = 0.9112$

for $N_{pc} = 1.5$ and $\lambda E_{OG} = 0.9112$

From fig. 18.29a,

$E_{mv} / E_{og} = 1.1$

$\therefore E_{mv} = 1.073$

Since the time taken for the separation is large enough, we can consider that full separation is taking place.

Therefore $E_{mv} = E_{og} = 0.97556$.

(c) Overall column efficiency, E_{oc}

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

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

For $L/G(\rho_g / \rho_l)^{0.5} = 0.4985$ and 75% flooding we have

$\psi = 0.05$

Therefore,

$E_a = (1 / (1+ 0.97556 (0.0526)))*0.97556$

$E_a = 0.9279$

$E_{oc} = \log(1+ 0.9279(0.9279-1)) / \log 0.9279 = 0.9253$

$E_{oc} = N_T / N_a$,

$N_{acE} = 14 / 0.9253 = 15.13$

Similarly for the stripping section the calculated results are.

Stripping Section

(a) Point Efficiency, E_{OG}

U_a = 23755.46 / (3600* 3.243*1.21) = 1.682 m / s

W = (6.67 * 10^{-3} / 1.2345) = 5.406 * 10^{-3} m^3 / m.s

∴ N_g=0.776+0.116*40*$10^3$0.29*1.3189*$(3.243)^{0.5}$+0.0217*4.775*10^{-3} / 0.024566

= 3.744

$N_l = K_l a \theta_l$

$K_L a$ = (3.875*10^8*8.8752*10^{-9})$^{0.5}$*(0.4*1.3189*$3.243^{0.5}$+0.17)

= 2.077

θ_l = 15.27sec.

∴ N_L = 31.71

M_{TOP} = 0.833

M_{BOTTOM} = 1.5

λ_{av} = 0.32187

∴ N_{OG} = 1 / ((1 / 3.744)+(0.32187 / 31.71)) = 3.606

∴ E_{OG} = 1-e^{-Nog} = 0.973

(b) Murphee Plate Efficiency, E_{mv}

λ E_{OG} = 0.32187*0.973 = 0.313

for N_{pc} =1.5 and λ E_{OG} = 0.313

From fig. 18.29a,

E_{mv} / E_{og} = 1.08

∴ E_{mv} = 1.051

Since the time taken for the separation is large enough, we can consider that full separation is taking place.

Therefore $E_{mv} = E_{og} = 0.973$

(c) Overall column efficiency, E_{oc}

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

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

for $L/G(\rho_g / \rho_l)^{0.5} = 0.0798$ and 75% flooding we have $\psi = 0.028$

Therefore,

$E_a = (1 / (1 + 0.973(0.0526)))*0.973$

$E_a = 0.9467$

$E_{oc} = \log(1 + 0.9467(0.32187-1)) / \log 0.32187$

$= 0.9061$

$E_{oc} = N_T / N_a$,

$N_{acE} = 14 / 0.9061 = 15.45$.

Therefore total number of trays in enriching and stripping section are as follows

N_T = 15.13 + 15.45 = 30.58 ≈ 31 trays

Tower Height = $31*457.2*10^{-3}$ = 14.167 m ≈ 15 m

MECHANICAL DESIGN OF MAJOR EQUIPMENT

MECHANICAL DESIGN OF DISTILLATION COLUMN

1. Shell minimum thickness:

Considering the vessel as an internal pressure vessel.

$t_s = ((P*D_i) / ((2*f_t*J)- P)) + C$

Where t_s = thickness of shell, mm

P = design pressure, kg/cm^2

D_i = diameter of shell, mm

f_t = permissible/allowable tensile stress, kg/cm^2

C = Corrosion allowance, mm

J = Joint factor

Considering double welded butt joint with backing strip

J= 85% = 0.85

Thus, t_s = ((1.11432*1512)/(2*0.85*855-1.11432)) + 3 = 4.16mm

Taking the thickness of the shell as minimum specified value= 8mm

2. Head Design- Shallow dished and Torispherical head:

Thickness of head = $t_h = (P*R_c*W) / (2*f*J)$

P =internal design pressure, kg/cm^2

R_c = crown radius = diameter of shell, mm=1512mm

W=stress intensification factor or stress concentration factor for torispherical head

$W = ¼ * (3 + (R_c/R_k)^{0.5})$

R_k = knuckle radius, which is at least 6% of crown radius, m

$R_k = 6\% * R_c = 0.06*1512 = 119.4$ mm

$W = ¼ * (3 + (R_c/R_k)^{0.5}) = ¼ * (3 + (1/0.06)^{0.5}) = 1.7706$ mm

$t_h = (1.11432*1512*1.7706) / (2*950*0.85) = 2.7538$ mm

Including corrosion allowance thickness of head is taken as 8mm

Pressure at which elastic deformation occurs

$P_{(elastic)} = 0.366*E * (t / R_c)^2$

$= 0.366*1.88*10^5* (6/1512)^2$

$= 0.6255$ MN / m^2 = 6.3761 kg/cm^2

The pressure required for elastic deformation, $P_{(elastic)}$> (Design Pressure)

Hence, the thickness is satisfactory. The thickness of the shell and the head are made equal for ease of fabrication.

Weight of Head:

Diameter = O.D + (O.D/24) + ($2*s_f$) + ($2*i_{cr}/3$) --- ($eq^{n.}$ 5.12 Brownell and Young)

Where O.D. = Outer diameter of the dish, inch

i_{cr} = inside cover radius, inch

s_f = straight flange length, inch

From table 5.7 and 5.8 of Brownell and Young

s_f =1”

i_{cr} = 1¼”

Also, O.D.= 1512 mm = 59.527"

Diameter = 59.527 + (59.527/24) + (2*1) + (2*1¼/3) =

d = 64.84" = 1646.95 mm

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

$= ((\pi * 64.84^2 * 0.2362)/4) * (590/1728) = 221.2$ lb

= 100.32 kg

3. Shell thickness at different heights

At a distance 'X'm from the top of the shell the stresses are:

Axial Tensile Stress due to Pressure:

$$f_{ap} = \frac{P * D_i}{4(t_s - c)} = \frac{1.11432*1512}{4(8-3)} = 84.24 \text{ kg/cm}^2$$

This is the same through out the column height.

Compressive stress due Dead Loads

a. Compressive stress due to Weight of shell up to a distance 'X' meter from top.

f_{ds} = weight of shell/cross-section of shell

$= (\pi/4) * (D_o^2 - D_i^2) * \rho_s * X / (\pi/4) * (D_o^2 - D_i^2)$

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

Where D_o and D_i are external and internal diameter of shell.

ρ_s = density of shell material, kg/m³

D_m = mean diameter of shell,

t_s = thickness of shell,

c = corrosion allowance

Now, $\rho_s = 8500$ kg/m³=0.0085kg/cm³

$f_{ds} = \rho_s * x = (0.85*X)$ kg/cm²

b. Compressive stress due to weight of insulation at a height X meter

$$f_{d(ins)} = \frac{\square * D_{ins} * t_{ins} * \square_{ins} * X}{\square * D_m * (t_s - c)} = \frac{\text{weight of insulation per unit height X}}{\square * D_m * (t_s - c)}$$

Where D_{ins}, t_{ins}, $\square_{ins}$ are diameter, thickness and density of insulation respectively.

$$D_m = (D_c + (D_c + 2t_s)) / 2$$

$$D_{ins} = D_c + 2t_s + 2t_{ins} = 151 + (2*0.8) + (2*5.08) = 153.416 \text{ cm.}$$

$$D_m = (1512 + (1512 + (2*0.8))) / 2 = 153.416 \text{ mm}$$

$$f_{d(ins)} = \frac{\square * 153.416 * 5.08 * 575 * X}{\square * 151.2 * (0.8 - 0.3)} = 5927.62 * X \text{ kg} / \text{m}^2$$

$$f_{d(ins)} = 0.59276 * X \text{ kg} / \text{cm}^2$$

c. Stress due to the weight of the liquid and tray in the column up to a height X meter.

$$f_{d, liq.} = \frac{\sum \text{weight of liquid and tray per unit height X}}{\square * D_m * (t_s - c)}$$

The top chamber height is 0.3 m and it does not contain any liquid or tray. Tray spacing is 500 mm.

Average liquid density = 836.84 kg / m^3

Liquid and tray weight for X meter

$$F_{liq\text{-}tray} = [(X-0.3)/\ 0.5 + 1] * (\pi * D_i^2/4) * \rho_l$$

$$= [(X-0.3)/\ 0.5 + 1] * (\pi * 1.51^2 / 4) * 836.84$$

$$= [2X + 0.4] * 1502.57 \text{ kg}$$

$$f_{d\,(liq)} = F_{liq\text{-}tray} * 10 /\ (\Box * D_m * (t_s - c))$$

$$= [2X + 0.4] * 1502.57 * 10 /\ (\Box * 1512 * (8 - 3))$$

$$= 1.26X + 0.253 \text{ kg / cm}^2$$

d Compressive stress due to attachments such as internals, top head, platforms and ladder up to height X meter.

$$f_{d\,(attch.)} = \frac{\sum \text{weight of attachments per unit height X}}{\Box * D_m * (t_s - c)}$$

Now total weight up to height X meter = weight of top head + pipes +ladder, etc.,

Taking the weight of pipes, ladder and platforms as 25 kg / m = 0.25 kg / cm

Total weight up to height X meter = (100.32+25X) kg

$$f_{d\,(attch.)} = (100.32+25X) * 10 /\ \Box * 151 * (8 - 3) = 0.704 + 0.1754 \text{ kg / cm}^2$$

Total compressive dead weight stress:

$$f_{dx} = f_{ds} + f_{ins} + f_{d\,(liq)} + f_{d\,(attch)}$$

$$= 0.85X + 0.59272X + [1.26X+0.253] + [0.704 + 0.175X]$$

$$f_{dx} = 2.877X + 0.957 \text{ kg / cm}^2$$

4. Tensile stress due to wind load in self supporting vessels:

$$f_{wx} = M_w / Z$$

Where M_w = bending moment due to wind load = (wind load* distance) / 2

$= 0.7*P_w*D*X^2/2$

Z = modulus for the section for the area of shell $\approx \pi*D_m^2*(t_s-c)/4$

Thus, $f_{wx} = 1.4*P_w*X^2/\ \pi*D_m*(t_s-c)$

Now $P_w = 25\ lb/ft^2$ --- (from table 9.1 Brownell and Young)

$= 122.06\ kg/m^2$

Bending moment due to wind load

$M_{wx} = 0.7*122.06*1.51*X^2/2 = 170.03$ kg-m

$f_{wx} = 1.4*122.06*X^2/\ \pi*1.51*(8-3) = 7.204X^2\ kg/cm^2$

5. Stresses due to Seismic load:

$f_{sx} = M_{sx}/\pi*D_m^2*(t_s-c)/4$

Where bending moment M_{sx} at a distance X meter is given by

$M_{sx} = [C*W*X^2/3]*[(3H-X)/H^2]$

Where C = seismic coefficient,

W= total weight of column, kg

H = height of column

Total weight of column = $W = C_v*\pi*\rho_m*D_m*g*(H_v+(0.8*D_m))*t_s*10^{-3}$

----- (eq$^{n.}$ 13.75, page 743, Coulson and Richardson 6th volume)

Where W = total weight of column, excluding the internal fittings like plates, N

C_v = a factor to account for the weight of nozzles, manways, internal supports, etc.

= 1.5 for distillation column with several manways, and with plate Support rings or equivalent fittings

H_v = height or length between tangent lines (length of cylindrical section)

g = gravitational acceleration = 9.81 m/s^2

t = wall thickness

ρ_m = density of vessel material, kg / m^3

D_m = mean diameter of vessel = D_i + (t *10^{-3})

= 1.512+8 *10^{-3} = 1.52 mm

W= 1.5*π*8500*1.952*9.81* (4+ (0.8*1.512))*8*10^{-3} = 14999.451 N

= 1528.99 kg.

Weight of plates: ------- (Coulson and Richardson 6th volume)

Plate area = π*1.51^2 / 4 – 0.127(is A_d) = 1.669m^2

Weight of each plate = 1.2*1.67 =2.003 kN

Weight of 31 plates = 31*2.003= 62.093 = 6329.56 kg.

Total weight of column = 1528.99 + 632956 = 7858.55 kg

Let C = seismic coefficient = 0.08

M_{sx} = [0.08*7858.55*X^2 / 3] × [((3*15)-X) / 15^2]

= 209.56X^2 * [0.2-0.004X] kg-m

f_{sx} = M_{sx}*10^3/π*$D_m{}^2$* (t_s-c) / 4

= 209.56X^2 * [0.2-0.004X] *10^3/(π*151.2^2* (8-3) / 4)

= [41.912X^2- 0.838X^3], kg / cm^2

On the up wind side:

Total stress acting on the up wind side:

$f_{t,max}$ = (f_{wx} or f_{sx}) + f_{ap} -f_{dx}

Since the chances of, stresses due to wind load and seismic load, to occur together is rare hence it is assumed that the stresses due to wind load and earthquake load will not occur simultaneously and hence the maximum value of both is therefore accepted and considered for evaluation of combined stresses.

Thus,

$f_{t,max}$ =7.204X^2 + 84.24 -[2.877X + 0.957]

i.e., 7.204X^2 – 2.877X +84.24-0.85 *950 = 0

7.204X^2- 2.877X – 723.26 =0

=> X = 5.297 m

On the down side:

Maximum stress acting on the down side is given by the following equation:

$f_{c,max} = (f_{wx} \text{ or } f_{sx}) - f_{ap} + f_{dx}$

$f_{t,max} = 7.204X^2 - 84.24 + [2.877X + 0.957]$

The column height is 5m, for which the maximum value is

$f_{t,max} = 7.204 * 5^2 - 84.24 + [2.877 * 5 + 0.957]$

$= -111.20 \text{ kg/cm}^2$

This shows that the stress on the down wind side is tensile. Hence further calculation is done by taking $f_{t,max}$ as allowable stress to find the height up to that column can resist the maximum stress acting on it. If the height calculated is more than the actual height of the column, then selected material and hence the design will be acceptable.

$f_{t,max} = 7.204X^2 - 84.24 + [2.877X + 0.957]$

Let $f_{t,max} = 0.85 * 950 = 807.5 \text{ kg/cm}^2$

Hence $7.204X^2 - 84.24 + [2.877X + 0.957] - 807.5 = 0$

We get X=10.94 m

Actual height of the column is 5 m. Therefore the design is acceptable because of the height up to that it can resist the maximum permissible stress is much more larger than the actual height of the column.

Hence

Thickness of the shell 6.0 mm

Height of the head	0.378 m (is Dc/4)
Skirt support height	1 m
Height of the tower	12.4 m

Design of Support:

a) Skirt Support:

The cylindrical shell of the skirt is designed for the combination of stresses due to vessel dead weight, wind load and seismic load. The thickness of skirt is uniform and is designed to withstand maximum values of tensile or compressive stresses.

Data available:

(i) Diameter =1512 mm.

(ii) Height = 4000 mm = 5.0 m

(iii) Weight of vessel, attachment =7858.55 kg.

(iv) Diameter of skirt (straight) = 1512 mm

(v) Height of skirt = 1.0 m

(vi) Wind pressure = 122.06 kg/m^2

1. Stresses due to dead Weight:

$f_d = \sum W/ (\pi * D_{ok} * t_{sk})$

f_d = stress,

$\sum W$ = dead weight of vessel contents and attachments,

D_{ok} = outside diameter of skirt,

t_{sk} = thickness of skirt,

$f_d = 7858.55/ (\pi * 151.2 * t_{sk}) = 17.4/ t_{sk}$ kg/cm^2

2. **Stress due to wind load:**

$p_w = k*p_1*h_1*D_o$

p_1 = wind pressure for the lower part of vessel,

k = coefficient depending on the shape factor

= 0.7 for cylindrical vessel.

D_o = outside diameter of vessel,

The bending moment due to wind at the base of the vessel is given by

$M_w = p_w *H/2$

$f_{wb} = M_w/Z = 4 *M_w/(\pi*(D_{ok})^2*t_{sk}$

Z- Modulus of section of skirt cross-section

p_w = 0.7*122.06*1.0*1.51 = 1937.82 kg

$M_w = p_w *H/2$ = 1937.82 *5/2 = 4844.5 kg-m

Substituting the values we get,

$f_{wb} = 59.58/ t_{sk}\ kg/cm^2$

3. **Stress due to seismic load:**

Load = C*W

C = seismic coefficient,

W= total weight of column.

Stress at base, $f_{sb} = (2/3) * (C*H*W)/ (\pi *(R_{ok})^2 * t_{sk}$

C=0.08

$f_{sb} = (2/3) * (0.08*450*7858.55)/(\pi *(151.2/2)^2 * t_{sk} = 11.05\underline{/ t_{sk}}\ kg/cm^2$

Maximum tensile stress:

$f_{t, max} = (59.58/t_{sk}) – (11.05/ t_{sk}) = (48.53\ t_{sk})\ kg/cm^2$

Permissible tensile stress = 925 kg/cm^2

Thus, 925 = $(48.5/ t_{sk})$

=> t_{sk} = 0.0525 cm = 0.525 mm

Maximum compressive stress:

$f_{c, max} = (59.58 / t_{sk}) + (11.05 / t_{sk}) = (70.63 / t_{sk})$ kg / cm^2

Now,

$f_{c, (permissible)} <= (⅓)$ yield point

= 1500 / 3 = 500 kg / cm^2

Thus, t_{sk} = 70.63 / 500= 0.1415 cm = 1.415 mm

As per IS 2825-1969, minimum corroded skirt thickness = 7 mm

Thus use a thickness of 7 mm for the skirt.

Design of skirt bearing plate:

Assume both circle diameter = skirt diameter + 32.5 =151+ 32.5 = 183.7 cm

Compressive stress between Bearing plate and concrete foundation:

$f_c = (\sum W / A) + (M_w / Z)$

$\sum W$ = dead weight of vessel contents and attachments,

A = area of contact between the bearing plate and foundation,

Z = Section Modulus of area,

M_w = the bending moment due to wind,

f_c=(7858.55*4) / (π*(183.7^2-151^2))+(0.7*122.06*3*42.3^2) / (2*π*(183.7^4-151.22) / (32*183.7)

= 0.242 + 0.116

f_c = 0.358 kg / cm^2

Which is less than the permissible value for concrete.

Maximum bending moment in bearing plate

Stress, f = (6*0.358* 16.25^2) / (2 *t_B^2) = 283.60 / t_B^2

Permissible stress in bending is 1000 kg / cm^2

Thus, t_B^2 = 283.60 / 1000 => t_B = 0.532 cm = 5.32

Therefore a bolted chair has to be used.

<u>Anchor Bolts:</u>

Minimum weight of Vessel = W_{min} = 3000 kg. ------ (Assumed value)

$f_{c,min} = (W_{min} / A) - (M_w / Z)$

$= [(4*3000)/ (\pi * (183.7^2 - 151^2))] - (0.7* 122.06* 3 *42.3^2*/(2* \pi*(183.7^4 - 151^4)/(32*183.7))$

$= 0.350 – 1.39 = - 1.042$ kg/cm^2

Since f_c is negative, the vessel skirt must be anchored to the concrete foundation by anchor bolts.

$P_{bolts}=fc(min)A/n$

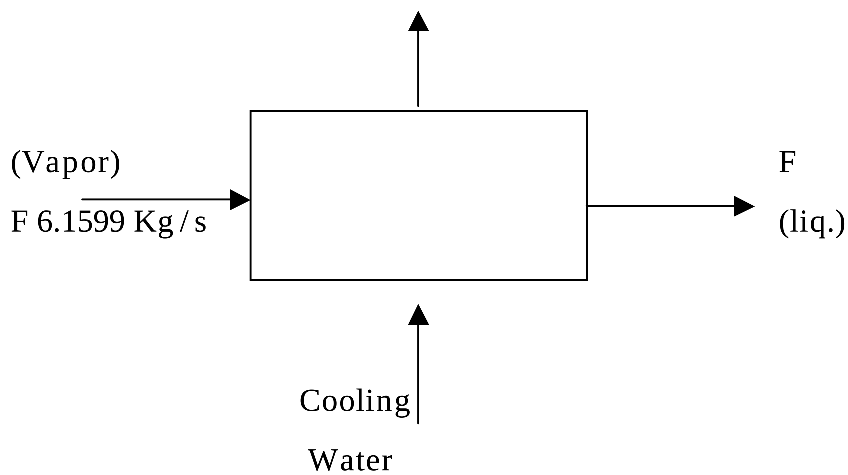
Assuming there are 20 bolts,

$P_{bolts} = (1.042/20) * ((\pi * (183.7^2 -151^2))/4) = 445.43$ kg

PROCESS DESIGN OF MINOR EQUIPMENT

DESIGN OF A TOTAL CONDENSOR

PROCESS DESIGN:



Hot vapors enter at 145°C and are condensed and leave at the same temperature.

Cooling water is available at 25°C can be heated up to 45°C.

T_{bulk} = (25+45)/2 = 35°C, T_{cond} = 145°C

T_{wall} = (145+35)/2 = 90^0C

Condensate avg temp. = (90 + 145)/2 = 117.5°C

(1) **Heat balance**:

M_cC_{pc} $(\Delta T)_c$ = Qc

Q_h = 2.1245 x 10^6 J / s.

C_{pc} = 4180 J / Kg K

ΔT_c = 45 –25 = 20°C

$\therefore m_c$ = 1.7346 Kg / s

(2) <u>LMTD</u>:

145--------→145

45 --------→ 25

No. Temp. Crossing

$\therefore F_T$ = 1

LMTD = 109.69°C

Assume U_d = <u>400 W/m² °K</u>

1 1 / 4" O.D. with a triangular pitch, P_T = 1.25 inch

L = 4.88m, d_0 = 3.175 cm = 0.03175m

$\therefore$ A = 50.93 m² = N_t π d_o L

$\therefore$ N_t = 104.61 ≅ 105 tubes

<u>TEMA P, 1 - 1</u> shell and tube

Shell ID = 19¼" = 489mm

N_t = 117 tubes

$\therefore (U_d)_{corrected}$ = 357.7 W / m²K

$(A)_{corrected}$ = 56.95 m²

Properties of condensate and vapor at 117.5 °C

Properties	K (W / m K)	P (Kg / m9)	U (Cp)	Cp (J / Kg °K)	λ (J / Kg)
Vapor		0.093	938.38×10^{-5}	-----	3.4494×10^{3}
Condensate	0.1558	836.84	0.2428	1991.1	-----

Shell Side Heat transfer Coefficient:

$h_o = 1.467 * (K_3 P_L^2 g / \mu_L^2)^{1/9} * (Re)^{-1/3}$

$Re = (4*6.1599) / (0.2428*10^{-3} * \pi * 0.03175*117)$

$= 8695.72$

$h_o = 1.467*[(0.1558)^9 (836.84)^2 * 9.81 / (0.2428 * 10^{-3})^2]^{1/3} * (8695.72)^{-1/3}$

$h_o = 567.04 W / m^2 °K$

Tube side heat transfer coefficient

Tube O.D 1" 15 DWO

Wall thickness = 0.154 inch

ID = 0.0284 m

$A_{flow} = \pi / 4 (ID)^2 = 6.33*10^{-05} m^2$

$G = \frac{1.7346}{0.0741} = 23.41 Kg / m^2 5$

Properties of water at 35°C

K (W / mK) = 0.62

ρ(kg / m³) = 993

$\mu(C_p) = 1.01$

Cp = 4.187

$Re = \frac{GD}{\mu} = 70831.51$

$P_t = \mu C_p / K = 0.175$

$Nu = 0.023 (Re)^{0.8} (Pr)^{0.4} = 68.63$

$\frac{H_\tau D_\tau}{K_\tau} = 68.63$

$\therefore \quad h_\tau = 2105.86\ W/m^2K$

$\therefore \quad h_{io} = h_i * d_o / d_i$

$Uc = h_{io} * h_o / (h_{io} + h_o)$

$\therefore\ U_c = 614.34 W/m^2K$

Assume a *dirt coefficient* *of* *1500 W/m²K*

$\therefore\ U_d = Uc*1500/(Uc+1500)$

$\therefore\ U_d = 435.839\ W/m^2K$

Assumed $U_d = 57.7\ W/m^2\,°K$

∴ Satisfactory heat transfer design

Pressure drop calculations:

Shell side calculations:

$f = 0.0035 + 0.264/Re^{0.42} = 0.00935$

$\Delta P = 4f\{D_e L/B\} G^2 / (d_e p_v \phi)$

$\phi = [\mu/\mu]^{0.14} = 1.03$

Let B = 3 De = 3 x 489 = 1467 mm

L = 4 .88m

$P_t = 0.03968$ m, $C = P_t - d_0 = 7.93 \times 10^{-3}$

$de = (0.5*P_2 t \sin 60 - 0.5*0.785*D_o 2)/0.5*\pi*d_o$

$= 0.02258$ m

$A = D_e CB / P_T = (0.02258*1467*10^{-3}*7.93*10^{-3} / 0.03968 = 0.0517$

$G = 6.1599 / 0.0517 = 119.147$

$\Delta P = 14.9\ KN / m^2$

$\therefore$ ΔP is within acceptable limits (i.e. $< 70 kN / m^2$)

<u>Tube side pressure drop:</u>

$f = 0.0035 + 0.264 / Re^{0.42} = 5.92*10^{-3}$

$\Delta P = 4fL_n G^2 / 2d_t p = 19078.67 N / m^2$

$\Delta P_{max} = 70,000\ N / m^2$.

$\therefore$ ΔP is within acceptable limits.

MECHANICAL DESIGN OF MINOR EQUIPMENT

1. SHELL THICKNESS:

   t_s= PD / (2fJ+P)

   let J=85%

   = 0.1114*488.95 / (2*0.85*95+0.1114)

   = 6.3mm

Minimum thickness of shell including corrosion resistance is taken as 8 mm

2. HEAD THICKNESS:

Shallow dished and torispherical head.

$t_h = PR_e / 2fJ$

$W = ¼ \times (3+\sqrt{(Re/Rk)}$

$= 1.77$

$t_h = 0.611$ mm

IS:4503-1967:

Minimum thickness including corrosion allowance must be 10mm hence t_h=10 mm

3. TANSVERS BAFFLES:

Baffle spacing =1.63 m

Thickness of baffles(t_s) = 6mm

4. TIE RODS AND SPACERS:

From IS:4503-1967

For shell diameter 400-700 mm

Diameter of rod is 10 mm and number of rods = 6

5. FLANGE DESIGN:

Design pressure = P = 0.1114 N/mm^2 (external)

Flange material: IS 2004-1962 Class 2 Carbon Steel

Bolting steel: 5% Chromium, Molybdenum Steel

Gasket Material: Asbestos composition

Shell OD = 0.497m = B

Shell Thickness = 0.008m = g

Shell ID = 0.48895m

Allowable stress for flange material = 100 MN / m^2

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

(a) Determination of gasket width

$d_O / d_i = [(y-Pm) / (y-P(m+1))]^{0.5}$

Assume a gasket thickness of 0.6mm

y = minimum design yield seating stress = 44.85 MN / m^2

m = gasket factor = 3.5

d_O / d_i = 1.001m

do=0.4894 m

Minimum gasket width = (0.4896-0.48895) / 2 = 0.000325m

Taking minimum width as 10 mm

Then d_o = 0.509m

Basic gasket seating width = 6 mm =b

Diameter at location of gasket load reaction G = d_i + N = 498.9m

(b) Estimation of bolt loads

<u>Load due to design pressure</u>

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

= 0.02178 MN

Where P is the design pressure

<u>Load to keep joint tight under operation:</u>

$H_p = \pi G(2b)mp$

$= \pi(0.4989)(2*0.00612)(3.5)(0.1114)$

H_p = 0.00748 MN

Total Operating Load $W_o = H + H_T = 0.0292$ MN

Load to seat the gasket under bolting condition:

$W_g = \pi Gby$

$= 0.43$ MN

$W_g > W_o$ Hence, the controlling load is $W_g = 0.4302$ MN

(c) Calculation of Minimum bolting area:

$A_m = A_g = W / S = 0.4302 / S$

S_o = allowable stress for bolting material

$A_m = A_g = 0.4302 / 138 = 0.00312$ m

(d) Calculation of optimum bolt size:

$g_1 = g / 0.707 = 1.415g$

Choose M18×2 Bolts

Minimum number of bolts = 44

Radial clearance from bolt circle to point of connection of hub or nozzle and back of flange = R = 0.027 m

$B_s = 60$mm (Bolt spacing)

$C = nB_s / \pi = 0.63$

$C = ID + 2(1.415g + R)$

$= 0.497 + 2[(1.415)(0.008) + 0.027]$

$= 0.777$ m

Choose C = 0.777m

Bolt circle diameter = 0.777m

(d) Flange outside diameter (A)

$A = C + \text{bolt dia} + 0.02$

$= 0.815$ m

(e) Check for gasket width

$A_b S_G$ / (πGN)

where S_G is the Allowable stress for the gasket material=138

A_b is actual bolt area=44*1.54*10^{-4}=0.006776 m^2

$A_b S_G$ / (πGN)=59.66MN / m^2<2y condition is satisfied.

(f) Flange Moment Calculations

For operating condition:

$W_o = W_1 + W_2 + W_3$ -----equation (17.6.6)

$W_1 = \pi * B^2 * P / 4 = 0.0216$ MN

$W_2 = H - W_1 = 0.000177$ MN

$W_3 = W_o - H = 0.00748$ MN

$M_o = W_1 * a_1 + W_2 * a_2 + W_3 * a_3$ ---- equation (7.6.7)

For loose type lap joint flanges,

$a_1 = (C-B) / 2 = 0.14m$

$a_3 = (C-G) / 2 = 0.1395m$

$a_2 = (a_1 + a_3) / 2 = 0.139m$

$M_o = 4.088*10^{-3}$ MJ

For bolting up condition:

$M_g = Wa_3$------equation (7.6.8)

$W = (A_b + A_g) S_g / 2$

$A_g = W_g / S_g = 0.862 / 138 = 3.1174 \times 10^{-3} m^2$

$A_g = 6.776*10^{-3}$

W= 683MN / m^2

M_g = .09488MJ

$M_g > M_o$

Hence, M_g is controlling.

(g) *Calculation of flange thickness*

$t^2 = M\ C_F\ Y\ /\ (B\ S_F)$ --- equation(7.6.12)

S_F is the allowable stress for the flange material= 100MN / m^2

K =A / B = 0.764 / 0.446= 1.71

For K = 1.71, Y = 4.4

Assuming C_F =1

$t^2 = 8.59*10^{-3}$

t = 0.0926m

Actual bolt spacing $B_S = \pi C / n$ = (3.14)(0.777) / (44) = 0.0555m

Bolt Pitch Correction Factor

$C_F = [B_s\ /\ (2d+t)]^{0.5}$

= 0.431

$\sqrt{C_F}$ =0.6568

t(act) = $t*\sqrt{C_F}$ = 0.0608m

Select 85mm thick flange. Both flanges have the same thickness.

6. <u>SADDLE SUPPORT DESIGN:</u>

Material : Carbon Steel

Shell diameter = 488.95mm

R = D / 2

l = 4880mm

Torispherical Head:

Crown radius = D, knuckle radius = 0.06*D

Total Head Depth = $\sqrt{(Do*ro/2)}$= 84.68mm = H

Shell Thickness = Head Thickness = 8mm

f_t = 95 MN / m^2

Weight of the shell and its contents = 2727.95 kg = W

Distance of saddle center line from shell end = A = R / 4=61.118mm

Longitudinal Bending Moment

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

$Q = W/2(L+4H/3) = 6695.81$kg-m

$M_1 = 25.13$ kg-m

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

$= 7304.78$ kg-m

Stresses in shell at the saddle

$f_1 = M_1/(\pi R^2 t) = 11.85\ kg/cm^2$

$f_2 = M_2/(k_2 \pi R^2 t) = 344.41 kg/cm^2$

$f_3 = M_2/(\pi R^2 t) = 344.41 kg/cm^2$

Since $k_1=k_2=1$

All stresses are within allowable limits. Hence, the given parameters can be considered for design.

Axial stress in the shell due to internal pressure:

$f_p = PD/(4t)$

$= 29.41\ kg/cm^2$

Sum of f_p and f_3 is well within the limit of permissible stress.

NOZZLE DESIGN

For condenser:

1. Feed nozzle for cooling liquid:

   Assumed liquid velocity $v = 3\ m/s$

   Mass of liquid in $M = 2.45 \cdot 10^{-3}\ kg/s$

   Area of nozzle required $A = M/(\rho \cdot v)$

= 0.04645m^2

Therefore diameter of the nozzle = √0.00312

$\underline{d_N}$ = 5.59 cm

2. Cooling liquid outlet nozzle:

It is same as that of inlet nozzle, hence the diameter of the nozzle = 5.59 cm

3. Vapor inlet nozzle:

Vapor velocity is assumed as	25 m / s
Mass of vapor in is	1.7346 kg / s
Density of vapor entering	0.58 kg / m^3
Area of nozzle required	1.036*10 -3m2

Therefore

Diameter of the nozzle	36.32 cm

4. Reflux liquid inlet nozzle:

Liquid flow rate	4.93187 kg / s
Density of the reflux	836.83 kg / m^3
Liquid velocity through nozzle	1.5 m / s (assumed)
Area required for assumed velocity	3.929*10^{-3}

Hence,

Diameter of the nozzle	70.72 mm