MAJOR EQUIPMENT DESIGN

DISTILLATION COLUMN

(ETHYL-BENZENE RECOVERY)

Process Design

For calculation simplification let us assume the feed entering the distillation or E-B recovery column in binary mixture.

Mol. Wt. of E-B = 106

Mol. Wt. of styrene = 104

i.e. $x_F = 0.267$; $x_D = 0.495$; $x_W = 0.049$

CALCULATION FOR q :-

The benzene toluene tower is been operated under 160 mm Hg pressure. **(from Dryden)**

So the reboiler must be operated at an equilibrium temperature. Assuming the reboiler acts as an ideal stage.

i.e. $P_T = x_{1*}P_1° + x_{2*}P_2°$

where x1 and x2 are the mole fraction of styrene and EB recovery tower.

Hence, feed temperature calculated = 95.0°C

$\therefore$, $q = (Hv – Hf)/(Hv – H_l)$

$\lambda_i = 4.35\ T_{ci}*(1-P_{ri})^{0.69} * \log P_{ri}/(1-T_{ri}^{-1})$

Where P* = 50 mm Hg

Critical Point Data	Pc,kPa	Tc,°C
Styrene	3810	369
Ethyl Benzene	3701	343.05

And T* = 63.138°C

λst = 36275 J/mol

λEB = 37860 J/mol

Now, in gaseous state[2]   Cp = 138.737 kJ/kmol°k(styrene)

At 70°C   Cp = 151.745 kJ/kmol°k (EB)

$\bar{\lambda}$ = 36698.19 kJ/kmol

$\bar{C_p}$ = 142.21 kJ/kmol°k

q = 0.876

So, slope of the q line = q/(q-1)

= -7.0645

So, from the graph reflux ratio is calculated.

Intercept: 0.13 = $x_D/(R+1)$

R_{min} = 2.81

Let, the reflux ratio be maintained 1.4 times the minimum,

i.e. R = 3.93

So, the conditions of the distillation column are specified.

	ENRICHING SECT		**STRIPPING SECT**	
	Top	Bottom	Top	Bottom
Temp. liquid, °C	61.25	63.2	63.2	65.1
Temp. vapor, °C	62.0	64.6	64.6	65.2
Liq. Flow rate, kmol/hr	482.22	482.22	701.73	701.73
Vapor. Flowrate,kmol/hr	604.923	604.923	573.35	573.85
Vapor density,kg/m3	0.251	0.248	0.248	0.247
Liquid density,kg/m3	850.94	855.44	855.44	861.06
Avg. mol.wt. (vapor.)	104.99	104.68	104.68	104.091
Avg. mol wt. (liq.)	104.99	104.534	104.534	104.098
Mole fraction, x	0.495	0.267	0.267	0.049
Mole fraction, y	0.495	0.340	0.340	0.049
$L/G * (\rho_G/\rho_L)^{0.5}$	0.0136	0.0135	0.021	0.021

Surface tension(σ) dyne/cm	30.217	30.795	30.795	31.37

ENRICHING SECTION

Tray spacing

$t_s = 500$ mm

Hole diameter

$d_h = 10$ mm.

Tray thickness

$T_t = 0.6d_h = 9$ mm.

Plate diameter calculation

$(\rho 1)_{bottom} = 855.44$ kg/m^3.

$(\rho g)_{bottom} = 0.248$ kg/m^3.

$(\rho 1)_{top} = 850.94$ kg/m^3.

$(\rho g)_{top} = 0.251$ kg/m^3.

$\mathbf{(L/G)*(\rho_g/\rho_l)^{0.5}} = 0.0136$ (max. at top)

(From Perry 7th edition fig. 14-25)

$c_{sb} = 0.095$ m/s.

$\mathbf{u_{nf} = c_{sb} * (\sigma/20)^{0.2} *[(\rho_1 - \rho_g)/ \rho_g]^{0.5}}$

$u_{nf} = 6.0064$ m/s.

where $\sigma = 30.217$ mN/m.

$u_n = 0.82\ u_{nf} = 4.925$ m/s.

Net area for gas flow

$A_n = A_c - A_d = \dfrac{\text{Volumetric gas flow rate}}{u_n} = 14.27\ m^2.$

Weir length = 0.75D$_c$

A_c = 0.785 D_c^2

A_d = 0.088 D_c^2

Substituting and evaluating,

D_c = 4.5 m.

L_w = 3.375 m.

A_c = 15.904 m^2.

A_d = 1.782 m^2.

Active area

$A_a = A_c - 2A_d$ = 12.34 m^2.

A_{cz} = 2 (L_w x 0.2) = 1.35 m^2.

α = 82.8° and **θ** = 97.2°

A_{wz} = 0.635 m^2.

$A_p = A_a - A_{cz} - A_{wz}$

= 10.355 m^2.

Total hole area

(A_h/A_p) = 0.1

A_h = 1.0355 m^2.

No. of holes = 13200

Weir height

h_w = 8 mm.

Check for weeping

h_d = head loss due to dry force.

$$= k_1 + k_2 \frac{\rho_g}{\rho_1} v_h^2$$

$k_1 = 0$

$k_2 = 50.8/C_v^2$

$$A_h/A_a = 0.1 \quad : \quad T_t/d_h = 0.5$$

From pg. 18-5 fig. 18-14 Perry

$c_v = 0.74 * (A_h/A_a) + \exp (0.29 (T_t/D_h)-0.56)$

$= 1.03$

$k_2 = 47.88$

$h_d = 75.16$ mm

h_{ow} = Height of liquid crest formed

$h_{ow} = 664 \left| \frac{q}{L_w} \right|^{2/3} * F_w$ where $q = 16.5 \times 10^{-03}\ m^3/s$.

$F_w = 1.01$

$h_{ow} = 19.31$ mm

$h_\sigma = (409\sigma)/ \rho_1 d_h$ = 1.452 mm**.**

$h_d + h_\sigma = 76.612$ mm.

$h_w + h_{ow} = 27.32$ mm.

$A_h/A_a = 0.1$

From Perry fig. 18-11 pg. 18-7

$h_d + h_\sigma >$ graphical value.

$\therefore$ weeping does not occur**.**

<u>Down comer flooding</u>

Down comer back up :-

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

h_{hg} = hydraulic gradient

h_t = total pressure drop across plate

h_{da} = head loss due to liquid flow under down comer apron

Again,

$h_t = h_d + h_1$

$h_d = 128.15$ mm**.**

$\mathbf{h_1 = \beta h_{ds}}$

$\mathbf{\beta = 0.0825 * \ln(q/Lw) - 0.269 * \ln F_{vh} + 1.679}$

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

$$\mathbf{h_{hg}} = \frac{1000 f u_f^2 L_f}{g r_h}$$

$$\mathbf{r_h} = \frac{h_f D_f}{h_f + D_f}$$

Again, f is a function of Reynold's number.

Where,

$$\mathbf{N_{reh.}} = \frac{r_h u_f \rho_1}{\mu_1}$$

Where,

$$\mathbf{u_f} = \frac{1000q}{h_1 D_f}$$

$\mathbf{D_f = (D_c+L_w)/2}$ = 3.9375 m

$\mathbf{F_{ga} = U_a(\rho_g/ \rho_l)^{0.5}}$

$\mathbf{h_f = h_1 / \phi_t}$ = 123.083 mm.

$\mathbf{\varphi = \exp(-12.55\ Ks^{0.91})}$

$\mathbf{K_s = U_a[\rho_g/(\rho_l - \rho_g)]^{0.5}}$

=0.0978 [U_a= gas vel. Through active area= 5.70 m/s]

hence,φ=0.2201

And

$\mathbf{h_l = \varphi[h_w + 15330 * C*(q/\varphi)^{2/3}]}$

where, $\mathbf{C = 0.0327 + 0.0286 * \exp[-0.1378 h_w]}$

=0.0327+ 0.0286*exp[-0.1378*8]

= 0.04219

h_l=27.09 mm of clear liquid

U_f=0.1549 m/s

R_h=0.11584 m

$\mathbf{\mu_{la} = [\Sigma x_i * \mu_i^{1/3}]^3}$

= 0.484 cp

$\mathbf{N_{reh.}=31540}$

From PERRY fig 14.34(7th ed)

f= 0.02

Lf =2.976 m

hhg= 1.25 mm of clear liq

hds= 27.925 mm

ht= 83.08 mm clear liq

$$\mathbf{h_{da} = 162.5} \left| \frac{q}{A_{da}} \right|$$

$h_{ap} = h_{ds} – c$

c= 14 mm.

h_{ap} = 13 mm.

$A_{da} = L_w h_{ap} = 0.04387\ m^2$

$\mathbf{h_{da}}$ = 23.42 mm.

h_{dc}= 135.05 mm of clear liq

$h'_{dc} = h_{dc}/ \varphi_t$= 270.1 mm. where φ_t= 0.5

$h'_{dc} < t_s$

∴ hence no flooding occur.

Column efficiency

Eog → Emv → E oc

Eog = 1 – exp(- Nog)

$$N_{og} = \frac{1}{\frac{1}{N_g} + \frac{\lambda}{N_l}}$$

where,**λ= mGm/Lm**

for gas phase transfer unit

$\mathbf{N_g= k_g*a*\theta}$

For sieve plate

$$K_{ga} = 316*D_g^{1/2}*(1030*f + 867*f^2)/ h_l^{0.5}$$

= 636.9 m/s

where; D_g= 5.4*10^5 m/s

$$\theta_g = \varepsilon*h_f*A_a/1000Q$$

ϕ = hl/hf and, **ε= 1-ϕ**

$\therefore$, ϕ= 0.2201

and, ε = 0.7799

$\therefore$, θ_g=0.01678 s

$\therefore$, N_g= 10.67 m

<u>For liquid transfer unit</u>

$$N_1 = k_1 a \theta_1$$

$$k_1a = \left(3.875\times 10^8 D_1\right)^{0.5}\left(0.40 U a \rho_g^{0.5} + 0.17\right)$$

= 1.434 m/s [Dl= 3.08*10^9 m/s]

Residence time

$$\theta_1 = (1-\varepsilon)*h_f*A_a/1000q$$

= 20.23 s

$\therefore$, N_l =29.017 m

In Enriching section

$$\lambda_{top} = \left|\frac{mL}{G}\right|_{top}$$

m = slope of equilibrium curve at the top.

λ_{top} = 1.296

N_{og} = 6.3105

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

E_{og} = 0.998

Murphee stage efficiency

Emv=1/λ*[exp(λ*Eog)-1]

= 2.041

The very high value of Emv (over 1)suggest there is high liquid entrapment takes place under such high vacuum. While the previous calculation suggest the liquid hold up and point efficiency, under such situation for safe design we made an assumption, i.e., Eog ≈ Emv .

∴, Emv= 0.998

now,

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

For corresponding L/G(ρg/ρl)$^{0.5}$ and 82% flooding value

ψ= 0.22

∴, Ea= 0.7788

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

E_{oc} = 0.80

$$\text{Again, by definition Eoc} = \frac{\textbf{Ideal no. of trays}}{\textbf{Actual no. of trays}}$$

∴,the actual number of trays in the enriching section= 7/0.8= 9 trays

Stripping section

Tray spacing

$t_s = 500$ mm

Hole diameter

$d_h = 15$ mm.

Tray thickness

$T_t = 0.6d_h = 9$ mm.

Plate diameter

$(\rho_1)_{bottom} = 861.06$ kg/m^3.

$(\rho_g)_{bottom} = 0.247$ kg/m^3.

$(\rho_1)_{top} = 855.44$ kg/m^3.

$(\rho_g)_{top} = 0.248$ kg/m^3.

$\mathbf{(L/G)*(\rho_g/\rho_l)^{0.5}} = 0.021$` (max. at top)

From Perry 7th edition fig. 14-25

$c_{sb} = 0.085$ m/s.

$\mathbf{u_{nf} = c_{sb} * (\sigma/20)^{0.2} * [(\rho_1 - \rho_g)/\rho_g]^{0.5}}$

$u_{nf} = 5.44$ m/s.

where $\sigma = 31.27$ mN/m.

$u_n = 0.80\ u_{nf} = 4.462$ m/s.

Net area for gas flow

$$A_n = A_c - A_d = \frac{\text{Volumetric gas flow rate}}{u_n} = 15.08 \text{ m}^2.$$

Weir length = $0.75D_c$

$\mathbf{A_c = 0.785\ D_c^2}$

$\mathbf{A_d = 0.088\ D_c^2}$

Substituting and evaluating,

$D_c = 4.65$ m.

L_w = 3.49 m.

A_c = 16.98 m^2.

A_d = 1.903 m^2.

Active area

$A_a = A_c – 2A_d$ = 13.174 m^2.

A_{cz} = 2 (L_w x 0.25) = 1.86 m^2.

α = 82.8° and **θ** = 97.2°

A_{wz} = 0.66 m^2.

$A_p = A_a – A_{cz} – A_{wz}$

= 10.654 m^2.

Total hole area

(A_h/A_p) = 0.1

A_h = 1.0654 m^2.

No. of holes = 13565

Weir height

h_w = 6 mm.

Check for weeping

h_d = head loss due to dry force.

$$= k_1 + k_2 \frac{\rho_g}{\rho_1} v_h^2$$

$k_1 = 0$

$k_2 = 50.8/C_v^2$

$$A_h/A_a = 0.1 \quad : \quad T_t/d_h = 0.5$$

From pg. 18-5 fig. 18-14 Perry

$c_v = 0.74 * (A_h/A_a) + \exp (0.29 (T_t/D_h)-0.56)$

= 1.03

k_2 = 47.85

h_d = 55.32 mm

h_{ow} = Height of liquid crest formed

$$\mathbf{h_{ow} = 664} \left|\frac{q}{L_w}\right|^{2/3} \mathbf{* F_w} \text{ where } q = 23.8 \times 10^{-03} \text{ m}^3/\text{s}.$$

F_w = 1.01

h_{ow} = 24.12 mm

$\mathbf{h_\sigma = (409\sigma)/ \rho_1 d_h}$ = 1.5 mm**.**

$h_d + h_\sigma$ = 56.82 mm.

$h_w + h_{ow}$ = 30.12 mm.

A_h/A_a = 0.1

From Perry fig. 18-11 pg. 18-7

$h_d + h_\sigma >$ graphical value.

$\therefore$ weeping does not occur**.**

<u>Down comer flooding</u>

Down comer back up :-

$\mathbf{h_{dc} = h_t + h_w + h_{ow} + h_{da} + h_{hg}}$

h_{hg} = hydraulic gradient

h_t = total pressure drop across plate

h_{da} = head loss due to liquid flow under down comer apron

Again,

$\mathbf{h_t = h_d + h_1}$

h_d = 55.32 mm**.**

$\mathbf{h_1 = \beta h_{ds}}$

$\mathbf{\beta = 0.0825 * \ln(q/Lw) - 0.269 * \ln F_{vh} + 1.679}$

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

$$\mathbf{h_{hg}} = \frac{1000 f u_f^2 L_f}{g r_h}$$

$$\mathbf{r_h} = \frac{h_f D_f}{h_f + D_f}$$

again f is a function of Reynold's number.

Where,

$$N_{reh.} = \frac{r_h u_f \rho_1}{\mu_1}$$

Where,

$$u_f = \frac{1000q}{h_1 D_f}$$

.$D_f = (D_c+L_w)/2 = 4.07$ m

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

$h_f = h_l / \varphi$ = 148.0 mm.

$\varphi = \exp(-12.55\ Ks^{0.91})$

$K_s = U_a[\rho_g/(\rho_l-\rho_g)]^{0.5}$

=0.0869 [U_a= gas vel. Through active area= 5.70 m/s]

Hence,**φ=0.2567**

And

$h_l = \varphi[h_w + 15330 * C*(q/\varphi)^{2/3}]$

where, $C = 0.0327+ 0.0286*\exp[-0.1378*h_w]$

$= 0.0327+ 0.0286*\exp[-0.1378*6]$

= 0.04521

h_l = 37.38 mm of clear liquid

U_f = 0.1539 m/s

R_h = 0.1379 m

$\mu_l = [\Sigma x_i*\mu_i^{1/3}]^3$

= 0.482 cp

$N_{reh.}$ = 37534

From PERRY fig 14.34(7th ed)

f= 0.02

L_f = 3.057 m

h_{hg}= 1.1 mm of clear liq

h_{ds} = 30.67 mm

h_t = 65.72 mm clear liq

$h_{da} = 162.5 \left| \frac{q}{A_{da}} \right|$

h_{ap} = 14 mm.

A_{da} = $L_w h_{ap}$ = 0.04886 m^2

h_{da} = 39.2 mm.

h_{dc}= 136.14 mm of clear liq

h'_{dc} = h_{dc}/ φ_t = 272.28 mm. where φ_t= 0.5

$h'_{dc} < t_s$ $\therefore$ **hence no flooding occur.**

Column efficiency

Eog → Emv → E oc

Eog = 1 – exp(- Nog)

$$N_{og} = \frac{1}{\frac{1}{N_g} + \frac{\lambda}{N_l}}$$

where,**λ= mGm/Lm**

for gas phase transfer unit

N_g= k_g*a*θ

For sieve plate

K_{ga}= $316*D_g^{1/2}*(1030*f+ 867*f^2)/ h_l^{0.5}$

= 521.2 m/s

where; $D_g = 5.434*10^{-5}$ m/s

θ_g= $\varepsilon*h_f*A_a/1000Q$

ϕ = hl/hf and, **ε= 1-ϕ**

$\therefore \phi = 0.2567$

$\therefore \theta_g = 0.02128$s

$\therefore N_g$= 11.09 m

For liquid transfer unit

$\mathbf{N_l = k_l a \theta_l}$

$\mathbf{K_l a} = \left(3.875\times10^{8} D_1\right)^{0.5}\left(0.40 U a \rho_g^{0.5} + 0.17\right)$

$= 1.314$ m/s [$D_l = 3.1624*10^{-9}$ m/s]

Residence time

$\mathbf{\theta_l = (1-\varepsilon)*h_f*A_a/1000q}$

= 21.02 s

∴, $N_l = 27.62$ m

$$\lambda_{top} = \left|\frac{mL}{G}\right|_{top}$$

m = slope of equilibrium curve at the top.

$\lambda_{avg} = 0.948$

$N_{og} = 6.3105$

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

$E_{og} = 0.99$

Murphee stage efficiency

The very high value of Emv (over 1)suggest there is high liquid entrapment takes place under such high vacuum. While the previous calculation suggest the liquid hold up

and point efficiency, under such situation for safe design we made an assumption, i.e., Eog ≈ Emv .

∴, $\mathbf{E_{mv} = 0.99}$

now,

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

For corresponding $L/G(\rho_g/\rho_l)^{0.5}$ and 80% flooding value

$\mathbf{\psi = 0.22}$

∴, $\mathbf{E_a} = 0.833$

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

$\mathbf{E_{oc}}$ = 0.83

∴,the actual number of trays in the enriching section= 15/0.83= 18 trays

∴ The entire length = actual no. of trays * tray spacing
of the tower

= (18.0 + 9.0)*0.5 m

= 13.5 m

MINOR EQUIPMENT DESIGN

Condenser

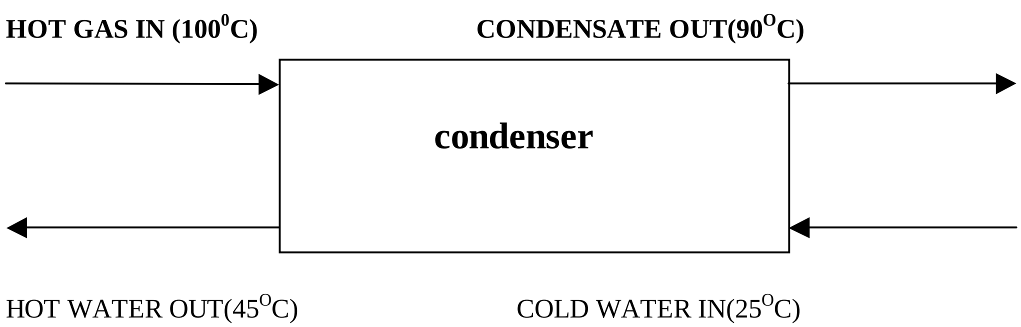
(Process Design)

The condenser to be designed over here is been placed after the reactor in the process. The stream coming out of the reactor contains steam as well as some non-condensable gases (like hydrogen) and organic vapors.

The gas out of the reactor is passed through the vaporizer where the gas temperature falls from 600 to 454^{o}C. Even at this temperature, the load on the condenser is very high, so to make the process more economical a boiler is positioned in between the vaporizer and condenser in order to recover the waste heat from the flue gas stream.

Therefore, after the super heat recovery the stream is entering the reactor at its normal boiling point temperature. The condenser is operated under atmospheric pressure. Hence, the normal boiling point of the mixture is calculated 90^{o}C.

To perform the given operation the load is very high for a single condenser, so to avoid overloading of the condenser two condenser of identical performance are put in series.



- Hot condensing gases enters at 100^{o}C temperature and leaves at 90^{o}C (I.e., effective boiling condensing gases)
- Cold fluid enters at 25^{o}C and leaves at 40^{o}C.

INITIAL CALCULATION:

Average latent heat of condensation of the condensing vapor = 1299.24 kJ/kg

Total mass of the condensing vapour feed into each condenser=9.27 kg/s.

Specific heat of water at 30^{0}C =4.184 kJ/kg

Mass of process water required= 9.27*1299.24/(4.184*(45-25)) kg/s.

= 190.68 kg/s

Assuming counter current operation $\Delta T_{ln} = 57.17^0C$

Assuming U heat transfer coefficient = 800 W/m^2K

$A = Q / (\Delta T_{ln}) = 261.65\ m^2$.

Assuming, length of pipe is 12 ft.

Tube for the heat transfer purpose is selected:

Tube OD = ¾" , 12 BWG

∴OD : ID= 1.41:1

∴ The total no of tube is calculated= $N_t = 1204$

From Perry, for 1-2 STHE TEMA P for ¾ in. OD on 1-inch Δ^{lar} pitch

$N_t = 1378$ for Shell diameter = 1.067 m.

$U_{corrected}$= 700 W/m^2K

FILM COEFFICIENT

Shell side - Condensate

The heat transfer coefficient for the shell side given as:

$h_s = 1.51*[k^3*\rho^2*g/\mu^2]^{1/3} *N_{re}^{-1/3}$

Reynolds number (N_{Re})= $4*\Gamma/\mu$

Where, $\Gamma= W/(N^{1/3}*L)$

W= condensation rate

N= total no of tubes

L= length of each tubes

∴, Γ= 0.02062

Again, μ= 0.347 cp

N.B., all the properties been evaluated at the condensate average temperature.i.e, at 75.62°C.

Therefore, the Reynolds no is calculated= 237.72

Properties are evaluated at 75.62°C.

K = Thermal conductivity = 0.398 w/m.K.

μ = Viscosity = 0.347 x 10^{-3} cp.

ρ = Density = 892 kg/m^3.

h_s= 3897 W/m^2.K.

TUBE SIDE

N_{re}= v*ρ*d/μ

ρ = 994 kg/m^3

Therefore, velocity of the fluid on the tube side=1.948 m/s

diameter of each tube= 13.51 mm

Reynold's number (N_{Re}) = 33438

k = 0.61 W/mK

μ = 0.78 cp

c_p = 4.184 KJ/kgK

Prandtl number (N_{Pr}) = 5.35

For turbulent condition Dittus Bolter equation.

$$\frac{h_i d_e}{k} = 0.023\,(N_{Re})^{0.8}\,(N_{Pr})^{0.33}\,(\phi)^{0.14}$$

$\phi = \mu_l/\mu_w$

$\therefore$, ϕ= 1.0, since the liquid used is water.

h_i = 5996 W/m^2K

Calculated U_d = 926.61 W/m^2K assuming h_d = 1892 W/m^2K

$\therefore$, $U_d > U_{corrected}$

$\therefore$ Design is okay.

PRESSURE DROP CALCULATION

SHELL SIDE

Let us assume, no of baffles(B)=0

$a_s = 0.9683\ m^2$

$G_s = 9.57\ kg/m^2s$.

$d_e = 18.29\ mm$

$N_{Re} = 21887$

From Perry graph of f v/s/ N_{Re} on log log sheet

f = 0.2452

$$\Delta P_s = \left[\frac{2f(N_b+1)D_s G_s}{g\rho_g d_e}\right] \text{ x } 0.5 = 1.369 \text{ kPa.(KERN's method)}$$

since the shell side pressure drop is less than 14 kPa , the design is satisfactory.

TUBE SIDE

$N_{Re} = 33438$

$F = 0.0791\ (N_{Re})^{-1/4} = 0.00584$

$\Delta P_l = 4*f*L*v^2*\rho l/2d_i = 11.82$ kPa

$\Delta P_e = 2.5*v^2*\rho l/2 = 4.700$kPa

$\Delta P_{Total} = 2*(\Delta P_l + \Delta P_e) = 33.04$ kPa.

which is very less than permissible value(70 kPa), therefore design is satisfies all the necessary condition.

MECHANICAL DESIGN OF
DISTILLATION COLUMN
(REF: BROWNELL & YOUNG,CH:10)

a) **SPECIFICATION**:

1. inside diameter : 4.65 m (design with the maximum dia for safety)
2. height of disengaging section: 40 cm
3. design pressure: 50 mmHg
4. (since the vessel operated under vacuum, subjected to external pressure)external pressure: 0.965 kgf/cm^2
5. design pressure: 1.033 kgf/cm^2
6. design temperature: 70^oC
7. shell material: carbon steel(sp. Gr.=7.7) (IS:2002-1962, GRADE I)
8. permissible tensile stress: 950 kgf/cm^2
9. insulation material: asbestos
10. density of insulation: 2700 kg/m^3
11. insulation thickness: 50 mm
12. tray spacing: 500 mm
13. down comer plate material: stainless steel(sp. Gr.: 7.8)

SHELL THICKNESS CALCULATION:

Let the thickness of the shell= 10 mm

Using stiffener channels of C-60, 18x4, of CSA=18 in2

Wt =51.9 lb/ft

At a distance of 500 mm, (below each tray)

$\therefore$, D_o = 4.67 m

L = 0.5 m

$\therefore$, **L/D_o** = 0.11

&, **D_o/t** = 467 $\therefore$, B= 12000

$\therefore$, **$p_{allowable}$= B/(14.22*(D_o/t)),** t= 5.71 mm ≈ 6 mm

Which, suggest the thickness is allowable under the operating condition.

Therefore, allowing corrosion correction, thickness choose= 12 mm

HEAD:

Design for torrispherical head.

The head is under external pressure.

Let, t_h = 10 mm

R_c = D_o = 4.67 m

$\therefore$, **$R_c/(100*t_h)$** = 4.67

$\therefore$, B= 4000

$\therefore$,**$p_{allowable}$= B/(14.22*R_c/t_h),** $\therefore$, t_h= 17.15 mm(> 10 mm)

Hence, 10 mm thickness is not satisfactory.

Further, iteration suggest the design thickness with a corrosion allowance :t_h= 15 mm

The approximate weight of the head is calculated= 3000 kg

CHECK FOR SHELL THICKNESS:

Material specification:

Carbon steel (sp. Gr. =7.7) (IS: 2002-1962, GRADE I)

Tensile strength(R_{20})= 37 kgf/mm^2

Yield stress (E_{20})= $0.55R_{20}$

Since, the vessel operated under vacuum, compressive axial stress:

$\mathbf{f_{ap}= pd/(4*(t_s-c))}$ = 120.6 kgf/cm^2

i) Dead wt calculation:

Total dead load can be calculated as:

$\sum$W = head wt+ liquid wt(X)+ wt of the attachment(X)

head wt= 3000 kg

liquid hold up in each tray= $\boldsymbol{\rho l*(A_a*h_l + A_d*h_{dc})}$

= 571 kg $\approx$ 600 kg

wt of attachment per plate= 1100 kg (approx.)

$\therefore$,$\sum$W= (3000+ 3400X) kg

Where, X is the distance in meter from the top tangent.

Further, the wt of the insulation and shell also exerts a compressive stress:

$\boldsymbol{\pi*d_i*X*t*\rho_s + \pi/4*(D_{0,ins}^2 - d_0^2)*X*\rho_{ins}}$ = 3126.8X kg

$\therefore$, total compressive stress on the shell due to dead wt:

$\mathbf{f_{dsx} = \sum W/(\pi * d_i * (t_s - c))}$ = (2.055+4.47X) kg/cm^2

ii) Wind pressure calculation:

Wind load: $P_w = 0.0025\ V_w^2$

Where, $\mathbf{P_w}$= wind pr on the column (lb/ft^2)

$\mathbf{V_w}$= wind velocity in miles per hour

Let the design wind velocity= 90 mi/hr

P_w = 20.25 lb/ft^2 = 98.67 kg/m^2

∴Moment at a distance X from the top tangent:

$\mathbf{M_{wx} = ½ * P_w * X^2 * d_{eff}}$ = 235.35X^2 kg-m

Where, d_{eff}= effective outer diameter of the vessel including insulation= 4.77 m

∴, f_{wx}= tensile stress on the upwind side

$\mathbf{= M_{wx}/(\pi * r_o^2 * (t_s - c))}$ = 0.1386 kg/cm^2

<u>STRESS BALANCE FOR THE UPWIND SIDE:</u>

$\mathbf{F_{t,max} = f_{wx} - f_{dsx} - f_{ap}}$

Where, $F_{t,max}$= 50% of the maximum allowable stress

= 475 kg/cm^2

There for upwind side solution gives: X= 69.1 m (>14m)

<u>STRESS BALANCE FOR THE DOWNWIND SIDE:</u>

$\mathbf{F_{C,max} = f_{wx} + f_{dsx} + f_{ap}}$

Where, $F_{C,max}$= maximum allowable compressive stress.

= 1/3* yield stress

= 1/3* 20.25 kgf/mm^2

Therefore, the solution to the quadratic equation:

X= 49.27 m (> 14m)

N.B. the wind moment on the downwind side act as a compressive force on the tower.

Since, the thickness of 12 mm with corrosion allowance is enough to with stand the load of the tower of 14 m height, the thickness of the shell is maintained 12 mm through out the entire tower length.

SKIRT SUPPORT DESIGN:

Let, we assume skirt material: carbon steel;

IS:2002-1962,GRADE1

Yield stress= 20.35 kgf/mm^2

Allowable compressive stress: 9660.31 lb/in^2

We design for cylindrical skirt support.

Moreover, it is been attached to the shell at a height of 50 cm from the bottom tangent.

Skirt height selected= 2.0 m

Where, the tangent to tangent distance= 13.5 m

Let, t= thickness of the skirt.

For, X= 13.5 m

$\mathbf{F_{wb} = 24599/t}$

Further for seismic load: $\mathbf{f_{sb} = 8CWH/(\pi r^2 t)}$

Where, for safe design, C=0.1

W= weight of the tower = 20300 lb

&, r= 92 in

∴, f_{sb}= 3226/t

Again, f_{db} = stress due to dead load at the bottom

= 35.12/t

Therefore the force balance at the bottom of the tower gives: $f_{t,max}$=(f_{wb} or f_{sb}) - f_{db} (upwind side)

$f_{c,max}$=(f_{wb} or f_{sb}) + f_{db} (downwind side)

since, $f_{wb} > f_{sb}$, for safe design we will consider f_{wb} in consideration.

Therefore, the minimum allowable thickness calculated= 2.3 in = 58 mm

SKIRT BEARING PLATE:

$\eta = E_S/E_C$

where, E_s= modulus of steel

E_c= modulus of concrete

Let, η= 10.

∴, let, f_s= 20000 psi

f_c= 1200 psi (from table: 10.1, BROWNELL & YOUNG)

$$\therefore, k = \frac{1}{1 + f_s/(\eta f_c)} = 0.375$$

Let, width of the bearing plate, t_3= 1 ft

$$\therefore, f_{c,max} = f_{c,bolt\ circle} * \left(\frac{2kd + t_3}{2kd}\right)$$

Where, d= 184 in

$f_{c,bolt}$= 1104 psi

Again (from table 10.2, BROWNELL & YOUNG)

At k= 0.375 C_c= 1.7025

C_t= 2.2785

Z= 0.4215

J= 0.7835

$\therefore$, $\mathbf{t_1 = A/\pi d}$; A= bolt area

let assume the circle in which 24 bolts of $2^1/_2$ in diameter.

$\therefore$, area per bolt = 3.72 sq in

$\therefore$, t_1= 0.154 in

$\therefore$, $\mathbf{F_t = f_s * t_1 * r * C_t}$

$\Rightarrow$ 30700 = f_s*0.154*92*2.2785

$\Rightarrow$ f_s= 951 psi

$\therefore$, $\mathbf{F_c = F_t + W}$ = 51000 lb.

Again t_2= 11.846 in

$\mathbf{F_c = (t_2 + \eta t_1) * r * f_c * C_c}$ $\Rightarrow$ f_c = 24.324 psi

$\therefore$,k= 0.2036

thus iterating with new values finally we get,

k= 0.269

C_c= 1.340

C_t= 2.571

Z= 0.450

J= 0.778

∴, the max compressive stress in bolt & concrete

$\mathbf{f_{s,compression}} = \boldsymbol{\eta} * \mathbf{f_c}$ = 305.8 psi

Where, $f_{c,max\ induced}$= 34.286 psi

This is a safe value.

Therefore, the thickness of the bearing plate,

$\Rightarrow \quad t_4 = l*\sqrt{(3*f_{c,max}/f_{allowable})} = 1$ in

where, l= outer radius of bearing plate

<u>MECHANICAL DESIGN OF CONDENSER</u>

SHELL SIDE:

MATERIAL :

Carbon steel (corrosion allowance= 3 mm)

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

Number of shell= 1

Number of tube passes= 2

Condensing fluid type: Mixed vapor

Working pressure= 1 atm

= 0.101 N/mm^2

Design pressure= 0.11 N/mm^2

Temperature of inlet= 100^{0}C

Temperature of outlet= 90^{0}C

Design temperature= 95^{0}C

TUBE SIDE:

Number of tubes= 1378

Out side diameter= 19.05 mm

Inside diameter= 13.51 mm

Length of each pipe= 3.63 m

Pitch Δ^{lar} = 1"

Feed= water

Working pressure= 1 atm

Design pressure= 0.11 N/mm^2

Inlet temperature= 25^{0}C

Outlet temperature= 40^{0}C

SHELL SIDE DESIGN:

$$\text{Shell thickness } (t_s) = \frac{\mathbf{P*D_i}}{\mathbf{2*f*J - P}} + \mathbf{c}$$

P = design pressure = 1.1 kg/cm^2.

D = diameter of shell = 1.067 m

F = 95 N/mm^2.

J= joint efficiencies= 0.85

c = corrosion allowance = 3 mm.

t_s = 10 mm.

Take shell thickness as 10 mm.

Head thickness:

Assume torrispherical head.

$$T_h = \frac{P*R_C*W}{2*f*J}$$

R_C = crown radius = D_C

Where,

$W = ¼*(3+\sqrt{(R_c/R_k)})$= 1.77

R_k= knuckle radius (6% of R_c)

∴; T_h= 1.28 mm

Standard minimum thickness =6 mm

Let, T_h= 10mm (with corrosion allowance)

SINCE THERE IS NO BAFFLE IS USED TIE RODS AND SPACERS ARE NOT REQUIRED.

FLANGES:

Loose type except lap joint flange is designed.

Design pressure= 10N/mm^2

Flange material: IS:2004-1962 class2

Bolting steel= 5% Cr Mo steel

Gasket material= asbestos composition

Shell inside diameter=1067 mm

Shell thickness =10 mm

Shell outside diameter= 1087 mm

Determination of gasket thickness:

$D_0/D_i = \sqrt{((y - p*m)/(y - p(m+1))}$

Where,

m→ gasket factor

$y \rightarrow$ minimum design seating stress

Assuming gasket thickness of 10 mm (from IS:2825-1969)

$y = 25.50\ MN/m^2$

$m = 2.75$

$\therefore$, $D_o = 1094$ mm

$\therefore$, minimum gasket width= 1mm

a gasket width of 6 mm is selected.

$\therefore$, diameter at the location of gasket load:

$\mathbf{G = d_i + N}$

$= 1104$ mm

Estimation of bolt load:

Load due to design pressure

$\mathbf{H = (\pi * G^2/4) * p} = 0.1053$ MN

Load to keep the joint tight under operation:

$\mathbf{H_p = \pi * G * N * m * p} = 12.5*10^{-3}$ MN

Total operating load:

$\mathbf{W_o = H_p + H} = 0.1179$ MN

Load to seat under bolting condition:

$\mathbf{W_g = \pi * G * b * y} = 0.5306$ MN

$\therefore$, $W_g > W_o$ **, therefore W_g is the controlling load.**

Calculation of minimum bolting area:

$\mathbf{A_m = A_g = W_g/S_g}$

For 5% Cr Mo steel at the design pressure $S_g = 138\ MN/m^2$

$\therefore$, $A_m = 3.84*10^{-3}\ m^2$

Calculation for optimum bolt size.

$g_1 = g_o/ (0.707)$ $= 1.415g_o$

Let we select the bolt size: M18*2 , R=0.027

Now**, $C= id+ 2*(1.415g_o + R)$**

$= 1156$ mm ≈ 1160 mm (where, $g_o = 12.5$ mm)

∴, 1.16m is the bolt circle diameter

Where, 18 mm is the bolt diameter

∴, flange outside diameter is calculated:

A= C + bolt diameter + 0.02m

= 1.20 m (SELECTED)

CHECK THE GASKERT WIDTH:

The total number of bolts on the flange= 44

And, the root area of each bolt = $1.54* 10^{-4}$ m^2

$A_b* S_g/ \pi*G*N = 22.46 < 2y$

Hence, the condition is satisfied.

- **FLANGE OPERATING CONDITIONS:**

A) for operating condition**: $W_o = W_1 + W_2 + W_3$**

Where **$W_1 = \pi*B2*p/4$** = 0.01021 MN

$W_2 = H – W_1$ = 0.0032 MN

$W_3 = W_o – H$ = 0.0125 MN

Total moment on flange,

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

Where, a_1 = (C-B)/2 =0.0365 m

a_3 = (C-G)/2 = 0.028 m

a_2 = $(a_1+a_3)/2$ =0.03225 m

∴, M_o = 4.18* 10^{-4} MJ

B) FOR BOLTING UP CONDITION:

(IS:2825- 1969)(EQN:4.6,P:56)

M_g =W*a_3

Where, **W=(A_m + A_b)*S_g/2 =** (5.308*10^{-3})*S_g =0.732 Nm

∴, M_g =0.0205 MJ

since, M_g>M_o , M_g is the moment under operating condition.

CALCULATION OF FLANGE THICKNESS:

t^2 = M*C_f*Y/(B*S_T)

Where, K= A/B =1.103

∴, Y=17

Let, C_F =1 (bolt pitch correction factor)

Again, S_F= allowable stress for flange material

= 100 MN

∴, t= 0.056 m

Actual bolt spacing,= π*1.16/44 = 0.082 m

Bolt pitch correction:

C_F= √(B_s/(2*D +t))= 0.944 ∴, t= 0.054 m ≈ 60 mm

TUBE SHEET THICKNESS CALCULATION:

Tube sheet thickness **(t) = $FG*(0.25*p/f)^{0.5}$**

= 0.0188 m

∴, considering corrosion allowance= (t) = 21 mm

CHANNEL DESIGN

Channel thickness:

$T_c = G_C (k*p/f)^{0.5}$ = 21 mm (k= 0.3 for ring type gasket)

Covers are assumed flat and welded to channel.

SUPPORT DESIGN

Material low carbon steel

Saddle type of support is designed.

Length= 3.63 m

Vessel diameter= 1.067 m

Knuckle radius= 64.02 mm

Total head depth **$= \sqrt{(D_o*r_0/2)}$**

= 185 mm

∴, A= 0.5*R = 267 mm

Maximum weight of shell, attachments and contents = 25543 kg.

A = 0.267 m

L = 3.36 m

H = 0

R = 0.5335 m

Q = W/2*(L + 4/3*H)= 49510.84 kg-m.

Longitudinal bending moment;

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

= 152.62 kg-m

Bending moment at the centre of the tubes:

M_2 = QL/4[(1+2(R2-H2)/L2)/(1+4*H/3L)- 4H/L]

= 345.12 kg-m

$$f_1 = \frac{M_1}{\pi R^2 t} = 1.7068 \text{ kg/cm}^2.$$

R = 0.5335 m

t = 0.010 m

$$f_2 = \frac{M_2}{\pi R^2 t} = 0.3849 \text{ kg/cm}^2.$$

f_{max} = 950 kg/cm^2.

f_p = (pD)/ 4t = 293.4 kg/cm^2.

All these values are less than 950.

∴ Design is satisfactory.