# DESIGN OF EQUIPMENT

**Process Design of Distillation Column:**

The detailed process design of the Isoamyl Alcohol column is given below. The pictorial representation of the column is given in fig 6.1. The feed to the column is a mixture of Valeraldehyde and Isoamyl Alcohol. The compositions of the components are shown in the figure. The residue/bottom product is the required product consisting of mainly Isoamyl Alcohol.

**I. Thermodynamics:**

The primary requirement while designing mass transfer contact equipment is the thermodynamic equilibrium data. The data required is in the Vapor-Liquid Equilibrium (VLE) data for the Valeraldehyde-Isoamyl alcohol system. The X-Y curve is shown in the fig 6.2. To develop the VLE data, a model was used.

$$y_i\, p_t = \gamma_i\, x_i\, P_i^{sat} \qquad \text{----------- (1)}$$

Where,

$y_i$ = mole fraction of component "i" in vapor.

$p_t$ = total system pressure.

$\gamma_i$ = activity coefficient of component "i" in liquid.

$x_i$ = mole fraction of component "i" in liquid.

$P_i^{sat}$ = saturation vapor pressure of component "i".

The equilibrium vapor pressure was evaluated using correlations given in literature. The correlation was based on the critical properties of the components. The two components Valeraldehyde and Isoamyl Alcohol form a highly non-ideal system. To accommodate this non-ideality, an activity coefficient term was used for the liquid phase. The activity coefficient was evaluated using the UNIFAC model. Since the evaluation of the VLE data is highly iterative, an algorithm was developed which was solved using a computer program. The gas phase was assumed to be ideal. This is a valid assumption since the column is at 1 atmosphere pressure (760 mm Hg. abs.). The boiling points of the two components requires the column to be operated at 1 atmosphere. The operating pressure was chosen to be 760 mm Hg (abs).

**I.A Vapour-Liquid Equilibrium Data:**

| Temperature ( $^{0}$C ) | Mole fraction of Valeraldehyde in liquid phase, x | Mole fraction of Valeraldehyde in vapour phase, y |
|---|---|---|
| 130.62 | 0.00000 | 0.00000 |
| 128.33 | 0.05000 | 0.1191 |
| 126.14 | 0.10000 | 0.22507 |
| 124.04 | 0.15000 | 0.31787 |
| 122.09 | 0.20000 | 0.39969 |
| 120.22 | 0.25000 | 0.47192 |
| 118.45 | 0.30000 | 0.53579 |
| 116.79 | 0.35000 | 0.59238 |
| 115.22 | 0.40000 | 0.64264 |
| 113.74 | 0.45000 | 0.68738 |
| 112.36 | 0.50000 | 0.72734 |
| 111.07 | 0.55000 | 0.76319 |
| 109.87 | 0.60000 | 0.79549 |
| 108.76 | 0.65000 | 0.82481 |
| 107.73 | 0.70000 | 0.85166 |
| 106.78 | 0.75000 | 0.87656 |
| 105.90 | 0.80000 | 0.90008 |
| 105.09 | 0.85000 | 0.92291 |
| 104.34 | 0.90000 | 0.94600 |
| 103.65 | 0.95000 | 0.97081 |
| 103.02 | 1.00000 | 1.00000 |

Table 6.1 Vapor-Liquid equilibrium data

**Glossary of notations used:**

F = molar flow rate of Feed, kmol/hr.

D = molar flow rate of Distillate, kmol/hr.

W = molar flow rate of Residue, kmol/hr.

$x_F$ = mole fraction of Valeraldehyde in liquid/Feed.

$y_D$ = mole fraction of Valeraldehyde in Distillate.

$x_W$ = mole fraction of Valeraldehyde in Residue.

$M_F$ = Average Molecular weight of Feed, kg/kmol

$M_D$ = Average Molecular weight of Distillate, kg/kmol

$M_W$ = Average Molecular weight of Residue, kg/kmol

$R_m$ = Minimum Reflux ratio

R = Actual Reflux ratio

L = Molar flow rate of Liquid in the Enriching Section, kmol/hr.

G = Molar flow rate of Vapor in the Enriching Section, kmol/hr.

$\overline{L}$ = Molar flow rate of Liquid in Stripping Section, kmol/hr.

$\overline{G}$ = Molar flow rate of Vapor in Stripping Section, kmol/hr.

q = Thermal condition of Feed

$\rho_L$ = Density of Liquid, kg/m$^3$.

$\rho_V$ = Density of Vapor, kg/m$^3$.

$q_L$ = Volumetric flow rate of Liquid, m$^3$/s

$q_V$ = Volumetric flow rate of Vapor, m$^3$/s

$\mu_L$ = Viscosity of Liquid, cP.

$T_L$ = Temperature of Liquid, $^0$K.

$T_V$ = Temperature of Vapor, $^0$K.

## Preliminary calculations:

F = 56.1306 kmol/hr, $x_F$ = 0.12, $M_F$ = 87.9016 kg/kmol.

D = 8.3852 kmol/hr, $x_D$ = 0.7465, $M_D$ = 86.6048 kg/kmol.

W = 47.7454 kmol/hr, $x_W$ = 0.01, $M_W$ = 88.1293 kg/kmol.

Basis: 1 Hour Operation.

From the graph (Fig 6.3 and Fig 6.4)

$x_D / (R_m+1) = 0.135$

⇨ $R_m+1= x_D/ 0.135 = 0.7465/ 0.135 = 5.5556$

⇨ $R_m = 5.5556-1 = 4.5556$

Thus, $R_m$ = <u>4.5556</u>

Let $R= 1.5\times R_m$

Therefore, R= 1.5×4.5556= <u>6.8334</u>

Thus, $x_D/ (R+1) = 0.7465/ (6.8334+1)$

i.e., $x_D/ (R+1)$ = <u>0.0957</u>

Number of Ideal trays = <u>10</u> (including the reboiler).

Reboiler is the last tray.

Number of Ideal trays in Enriching Section = <u>4</u>

Number of Ideal trays in Stripping Section = <u>5</u>

Now, we know that,

$R = L_o/ D$

=> Lo = R×D

i.e., $L_o$= 6.8334×8.3852

i.e., $L_o$ =57.2858 kmol/hr.

Therefore, Lo = <u>57.2858</u> kmol/hr.

L= Liquid flow rate on the Top tray = <u>57.2858</u> kmol/hr.

Since feed is Liquid, entering at bubble point,

⇨ $q = (H_V - H_F) / (H_V - H_L) = \underline{1}$

Now,

Slope of q-line = q/ (q-1)

= 1/ (1-1) = 1/0 = $\underline{\infty}$

Now we know that,

$$\frac{(\bar{L} - L)}{F} = q = 1$$

⇨ $(\bar{L} - L) = F$

⇨ $\bar{L} = F + L$

i.e., $\bar{L} = 56.1306 + 57.2858$

i.e., $\bar{L} = 113.4164$ kmol/hr.

Therefore, liquid flow rate in the Stripping Section = $\underline{113.4146}$ kmol/hr.

Also, we know that,

$\bar{G} = [(q-1) \times F] + G$

i.e., $\bar{G} = [(1-1) \times F] + G$

i.e., $\bar{G} = [0 \times F] + G$

i.e., $\bar{G} = 0 + G$

⇨ $\underline{\bar{G} = G}$

Now, we know that,

G = L + D

i.e., $G = L_o + D$

i.e., G = 57.2858 + 8.3852

i.e., G = 65.669 kmol/hr.

Thus, the flow rate of Vapor in the Enriching Section = 65.6710 kmol/hr.

Since $\bar{G} = G$

⇨ $\bar{G} = G = 65.6710$ kmol/hr.

Therefore, the flow rate of Vapor in the Stripping Section = 65.6710 kmol/hr.

## III. List of parameters used in calculation:

| | ENRICHING SECTION | | STRIPPING SECTION | |
|---|---|---|---|---|
| PROPERTY | TOP | BOTTOM | TOP | BOTTOM |
| x | 0.7465 | 0.12 | 0.12 | 0.01 |
| y | 0.7465 | 0.195 | 0.195 | 0.01 |
| Liquid, L kmol/hr. | 57.2858 | 57.2858 | 113.4164 | 113.4164 |
| Vapor, G kmol/hr. | 65.6710 | 65.6710 | 65.6710 | 65.6710 |
| $T_{liquid}$, $^0C$ | 108.75 | 127.50 | 127.50 | 130.60 |
| $T_{vapor}$, $^0C$ | 114.25 | 129.25 | 129.25 | 130.60 |
| $M_{avg.\ liquid}$ kg/kmol | 86.6048 | 87.9016 | 87.9106 | 88.1293 |
| $M_{avg.\ Vapor}$ kmol/hr | 86.6048 | 87.7464 | 87.7464 | 88.1293 |

| | | | | |
|---|---|---|---|---|
| Liquid, L kg/hr. | 4961.2253 | 5035.5135 | 9970.5038 | 9995.3079 |
| Vapor, G kg/hr | 5687.4238 | 5762.3938 | 5762.3938 | 5787.5393 |
| Density, $\rho_l$ kg/m$^3$ | 750.65 | 733.80 | 733.80 | 727.68 |
| Density, $\rho_g$ kg/m$^3$ | 2.9150 | 2.7550 | 2.7550 | 2.6672 |
| $(L/G)(\rho_g/\rho_l)^{0.5}$ | 0.0544 | 0.0535 | 0.1060 | 0.1046 |

Table 6.2 Parameters used in calculations.

## IV. Design Specification:

### a). Design of Enriching Section:

Tray Hydraulics

The design of a sieve plate tower is described below. The equations and correlations are borrowed from the 6th and 7th editions of Perry's Chemical Engineers' Handbook. The procedure for the evaluation of the tray parameters is iterative in nature. Several iterations were performed to optimize the design. The final iteration is presented here.

1. **Tray Spacing, ($t_s$) :**

   Let $t_s$ = 500 mm.

2. **Hole Diameter, ($d_h$):**

   Let $d_h$ = 5 mm.

3. **Hole Pitch ($l_p$):**

   Let $l_p = 3\times d_h$

   i.e., $l_p = 3\times5 = 15$ mm.

4. **Tray thickness ($t_T$):**

Let $t_T = 0.6\times d_h$

i.e., $t_T = 0.6\times 5 = \underline{3}$ mm.

**5. Ratio of hole area to perforated area ($A_h/A_p$):**

Refer fig 6.3

Now, for a triangular pitch, we know that,

Ratio of hole area to perforated area $(A_h/A_p) = ½\ (\pi/4\times d_h^2)/\ [(\sqrt{3}/4)\ \times l_p^2]$

i.e., $(A_h/A_p) = 0.90\times\ (d_h/l_p)^2$

i.e., $(A_h/A_p) = 0.90\times\ (5/15)^2$

i.e., $(A_h/A_p) = 0.1$

Thus,

$(A_h/A_p) = \underline{0.1}$

**6. Plate Diameter ($D_c$):**

The plate diameter is calculated based on the flooding considerations.

$L/G\ \{\rho_g/\rho_l\}^{0.5} = \underline{0.0544}$ ---------- (maximum value)

Now for,

$L/G\ \{\rho_g/\rho_l\}^{0.5} = \underline{0.0544}$ and for a tray spacing of $\underline{500}$ mm.

We have,

from the flooding curve, ---------- (fig.18.10, page 18.7, 6th edition Perry.)

Flooding parameter, $C_{sb,\ flood} = \underline{0.28}$ ft/s = $\underline{0.0853}$ m/s.

Now,

$U_{nf} = C_{sb,\ flood} \times (\sigma / 20)^{0.2}\ [(\rho_l - \rho_g) / \rho_g]^{0.5}$

---- {eq$^{\underline{n}}$. 18.2, page 18.6, 6th edition Perry.}

where,

$U_{nf}$ = gas velocity through the net area at flood, m/s (ft/s)

$C_{sb,\ flood}$ = capacity parameter, m/s (ft/s, as in fig.18.10)

$\sigma$ = liquid surface tension, mN/m (dyne/cm.)

$\rho_l$ = liquid density, kg/m$^3$ (lb/ft$^3$)

$\rho_g$ = gas density, kg/m$^3$ (lb/ft$^3$)

Now, we have,

$\sigma$ = 17.465 mN/m = 17.465 dyne/cm.

$\rho_l$ = 733.80 kg/m$^3$.

$\rho_g$ = 2.7550 kg/m$^3$.

Therefore,

$U_{nf} = 0.28\times (17.465/20)^{0.2}\times [(733.80-2.7550)/ 2.7550]^{0.5}$

i.e., $U_{nf}$ = 4.4767 ft/s = 1.3645 m/s.

Let

Actual velocity, $U_n = 0.8\times U_{nf}$

i.e., $U_n = 0.8\times 4.4767$

i.e., $U_n$ = 3.5814 ft/s

$U_n$ = 1.0916 m/s

Now,

Volumetric flow rate of Vapor at the bottom of the Enriching Section

$= q_o = 5762.3938 / (3600\times 2.7550)$ = 0.5917 m$^3$/s.

Now,

Net area available for gas flow ($A_n$)

Net area = (Column cross sectional area) – (Downcomer area.)

$A_n = A_c – A_d$

Thus,

Net Active area, $A_n = q_o/ U_n = 0.5917/ 1.0196$ = 0.5421 m$^2$.

Let $L_w / D_c$ = 0.75

Where, $L_w$ = weir length, m

$D_c$ = Column diameter, m

Now,

$$\Theta_c = 2\times\sin^{-1}(L_w / D_c) = 2\times\sin^{-1}(0.75) = \underline{97.18^0}$$

Now,

$$A_c = (\pi/4) \times D_c^2 = \underline{0.7854}\times D_c^2,\ m^2$$

$$A_d = [(\pi/4) \times Dc^2 \times (\theta c/360^0)] - [(Lw/2) \times (Dc/2) \times \cos(\theta c/2)]$$

i.e., $A_d = [0.7854\times Dc^2 \times (97.18^0/360^0)]-[(1/4) \times (L_w / D_c) \times D_c^2 \times \cos(97.18^0)]$

i.e., $A_d = (0.2120\times D_c^2) - (0.1241\times D_c^2)$

i.e., $A_d = \underline{0.0879}\times D_c^2$, $m^2$

Since An = Ac -Ad

$$0.5421 = (0.7854\times Dc^2) - (0.0879\times Dc^2)$$

i.e., $0.6975\times D_c^2 = 0.5421$

$\Rightarrow$ $D_c^2 = 0.5421/ 0.6975 = 0.7772$

$\Rightarrow$ $D_c = \sqrt{0.7772}$

$\Rightarrow$ $D_c = \underline{0.8816}$ m

Take $D_c = \underline{0.90}$ m

Since $L_w / D_c = 0.75$,

$\Rightarrow$ $L_w = 0.75\times D_c = 0.75\times0.90 = 0.675$ m.

Therefore, $L_w = \underline{0.675}$ m.

Now,

$$A_c = 0.7854\times0.9^2 = \underline{0.6362}\ m^2$$

$$A_d = 0.0879\times D_c^2 = 0.0879\times0.9^2 = \underline{0.0712}\ m^2$$

$$A_n = A_c - A_d$$

i.e., $A_n = 0.6362- 0.0712$

$\Rightarrow$ $A_n = 0.5650\ m^2$

**7. Perforated plate area ($A_p$):**

$$A_a = Ac - (2\times A_d)$$

i.e., $A_a = 0.6362- (2\times0.0712)$

$\Rightarrow$ $A_a = \underline{0.4938}\ m^2$

Now,

$L_w / D_c = 0.675/ 0.9 = \underline{0.75}$

$\Theta_c = \underline{97.18}\ ^0$

$\alpha = 180\ ^0 - \Theta_c$

i.e., $\alpha = 180\ ^0 - 97.18\ ^0$

$\Rightarrow\ \alpha = \underline{82.82}\ ^0$

Now,

$A_{cz} = 2\times L_w\times$ (thickness of distribution)

where $A_{cz}$ = area of calming zone, $m^2$

$A_{cz} = 2\times0.675\times (50\times10^{-3}) = \underline{0.0675}\ m^2$ -------- (which is 10.61% of $A_c$)

Also,

$A_{wz} = \{(\pi/4) \times D_c^2\times (\alpha/360\ ^0)\} - \{(\pi/4) \times (D_c -0.05)^2\times (\alpha/360\ ^0)\}$

Where $A_{wz}$ = area of waste periphery, $m^2$

i.e., $A_{wz} = \{(\pi/4) \times0.90^2 \times (82.82\ ^0/360\ ^0)\}$

$- \{(\pi/4) \times (0.90-0.05)^2 \times (82.82\ ^0/360\ ^0)\}$

i.e., $A_{wz} = \underline{0.0316}\ m^2$ --------- (which is 4.97% of $A_c$)

Now,

$A_p = A_c - (2\times A_d) - A_{cz} - A_{wz}$

i.e., $A_p = 0.6362- (2\times0.0712) - 0.0675 - 0.0316$

Thus, $A_p = \underline{0.3947}\ m^2$

**8. Total Hole Area ($A_h$):**

Since,

$A_h / A_p = 0.1$

$\Rightarrow A_h = 0.1\times A_p$

i.e., $A_h = 0.1\times0.3947$

$\Rightarrow A_h = \underline{0.03947}\ m^2$

Thus, Total Hole Area = $\underline{0.03947}\ m^2$

Now we know that,

$A_h = n_h \times (\pi/4) \times d_h^2$

Where $n_h$ = number of holes.

$\Rightarrow$ $n_h = (4 \times A_h)/ (\pi \times d_h^2)$

i.e., $n_h = (4 \times 0.03947)/ (\pi \times 0.005^2)$

$\Rightarrow$ $n_h$ = 2010.19 ≈ 2010

Therefore, Number of holes = 2010.

**9. Weir Height ($h_w$):**

Let $h_w$ = 50 mm.

**10. Weeping Check**

All the pressure drops calculated in this section are represented as mm head of liquid on the plate. This serves as a common basis for evaluating the pressure drops.

**Notations used and their units:**

$h_d$ = Pressure drop through the dry plate, mm of liquid on the plate

$u_h$ = Vapor velocity based on the hole area, m/s

$h_{ow}$ = Height of liquid over weir, mm of liquid on the plate

$h_\sigma$ = Pressure drop due to bubble formation, mm of liquid

$h_{ds}$= Dynamic seal of liquid, mm of liquid

$h_l$ = Pressure drop due to foaming, mm of liquid

$h_f$ = Pressure drop due to foaming, actual, mm of liquid

$D_f$ = Average flow length of the liquid, m

$R_h$ = Hydraulic radius of liquid flow, m

$u_f$ = Velocity of foam, m/s

$(N_{Re})$ = Reynolds number of flow

f = Friction factor

$h_{hg}$ = Hydraulic gradient, mm of liquid

$h_{da}$ = Loss under downcomer apron, mm of liquid

$A_{da}$ = Area under the downcomer apron, $m^2$

c = Downcomer clearance, m

$h_{dc}$ = Downcomer backup, mm of liquid

Calculations:

**Head loss through dry hole**

$h_d$ = head loss across the dry hole

$h_d = k_1 + [k_2 \times (\rho_g/\rho_l) \times U_h^2]$ --------- ($eq^{n.}$ 18.6, page 18.9, 6th edition Perry)

where $U_h$ =gas velocity through hole area

$k_1$, $k_2$ are constants

For sieve plates

$k_1$ = 0 and

$k_2 = 50.8 / (C_v)^2$

where $C_v$ = discharge coefficient, taken from fig. edition 18.14, page 18.9 6th Perry).

Now,

$(A_h/A_a)$ = 0.03947/ 0.4938 = 0.07993

also $t_T/d_h$ = 3/5 = 0.60

Thus for $(A_h/A_a)$ = 0.07993 and $t_T/d_h$ = 0.60

We have from fig. edition 18.14, page 18.9 6th Perry.

$C_v$ = 0.730

⇒ $k_2 = 50.8 / 0.730^2$ = 95.3275

Volumetric flow rate of Vapor at the top of the Enriching Section

$= q_t$ = 5687.4238/ (3600×2.9150) = 0.5632 $m^3/s$ -------- (minimum at top)

Volumetric flow rate of Vapor at the bottom of the Enriching Section

$= q_o$ = 5762.3938 / (3600×2.7550) = 0.5917 $m^3/s$. ---- (maximum at bottom)

Velocity through the hole area ($U_h$):

Now,

Velocity through the hole area at the top = $U_{h, top} = q_t / A_h$

= 0.5632/0.03947

= 14.2691 m/s

also, Velocity through the hole area at the bottom= $U_{h, bottom} = q_o / A_h$

= 0.5917/0.03947

$= \underline{14.9911}$ m/s

Now,

$h_{d,\,top} = k_2\,[\rho_g/\rho_l]\,(U_{h,top})^2$

$= 95.3275\times(2.915/750.65)\times14.2691^2$

$\Rightarrow h_{d,\,top} = \underline{72.7803}$ mm clear liquid. -------- (minimum at top)

also

$h_{d,\,bottom} = k_2\,[\rho_g/\rho_l]\,(U_{h,\,bottom})^2$

$= 95.3275\times(2.755/733.80)\times14.9911^2$

$\Rightarrow h_{d,\,bottom} = \underline{79.0909}$ mm clear liquid ----- (maximum at bottom)

**Head Loss Due to Bubble Formation**

$h_\sigma = 409\,[\sigma / (\rho_{L\times}d_h)]$

where $\sigma$ =surface tension, mN/m (dyne/cm)

$d_h$ =Hole diameter, mm

$\rho_l$ = average density of liquid in the section, kg/m$^3$

= (750.65 + 733.80)/2

= $\underline{742.2250}$ kg/m$^3$

$h_\sigma = 409\,[17.4565 / (742.2250 \times 5)]$

$h_\sigma = \underline{1.9296}$ mm clear liquid

**Height of Liquid Crest over Weir:**

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

q = liquid flow rate at top, m$^3$/s

= 4961.2253/ (3600×750.65)

$q = \underline{1.8423\times10^{-3}}$ m$^3$/s

Thus, q' = $\underline{29.2011}$ gal/min.

$L_w$ = weir length = $\underline{0.675}$ m = $\underline{2.2146}$ ft

Now,

$q'/L_w^{2.5} = 29.2011/(2.2146)^{2.5} = \underline{4.0009}$

now for $q'/L_w^{2.5} = 4.0009$ and $L_w/D_c = 0.75$

we have from fig.18.16, page 18.11, 6th edition Perry

$F_w$= correction factor =1.035

Thus, $h_{ow} = 1.035\times664\times [(1.8423\times10^{-3})/0.675]^{2/3}$

$\Rightarrow$ $h_{ow}$ = 13.4219 mm clear liquid.

Now,

$(h_d + h_\sigma)$ = 72.7803 + 1.9296 = 74.7099 mm ------ Design value

$(h_w + h_{ow})$ = 50 + 13.4219 = 63.4219 mm

Also, $A_h/A_a$ = 0.07993 and $(h_w + h_{ow})$ =50 +13.4219 = 63.4219 mm

The minimum value of $(h_d + h_\sigma)$ required is calculated from a graph given in Perry, plotted against $A_h/A_a$.

i.e., we have from fig. 18.11, page 18.7, 6th edition Perry

$(h_d + h_\sigma)_{min}$ = 18.5 mm ------- Theoretical value.

The minimum value as found is 18.50 mm.

Since the design value is greater than the minimum value**, there is no problem of weeping.**

**Downcomer Flooding:**

$h_{ds} = h_w + h_{ow} + (h_{hg}/2)$ ------- (eqn 18.10, page 18.10, 6th edition Perry)

where,

$h_w$ = weir height, mm

$h_{ds}$ = static slot seal (weir height minus height of top of slot above plate floor, height equivalent clear liquid, mm)

$h_{ow}$ = height of crest over weir, equivalent clear liquid, mm

$h_{hg}$ = hydraulic gradient across the plate, height of equivalent clear liquid, mm.

In the above equation $h_{ow}$ is calculated at bottom of the section and since the tower is operating at atmospheric pressure, $h_{hg}$ is very small for sieve plate and hence neglected.

**Calculation of $h_{ow}$ at bottom conditions of the section:**

q = liquid rate at the bottom of the section, $m^3/s$

= 5035.5135/ (3600×733.8) = $1.9090\times10^{-3}$ $m^3/s$

Thus, $q' = (1.9090\times10^{-3}\times60)/ (3.785412\times10^{-3}) = \underline{30.3583}$ gal/min

$L_w$ = weir length = $\underline{0.675}$ m = $\underline{2.2146}$ ft.

$q'/L_w^{2.5} = 30.3583/ (2.2146)^{2.5} = \underline{4.1458}$

now for $q'/L_w^{2.5} = 4.1458$ and $L_w/D_c = 0.75$

we have from fig.18.16, page 18.11, 6th edition Perry

$F_w$= correction factor =$\underline{1.036}$

Thus, $h_{ow} = 1.0356\times664\times [(1.9090\times10^{-3})/0.675]^{2/3}$

$\Rightarrow$ $h_{ow} = \underline{13.7572}$ mm clear liquid. ----- (maximum at the bottom of section).

Therefore, $h_{ds} = 50 + 13.7572 = 63.7572$ mm.

Now, $F_{ga} = U_a \times \rho_g^{0.5}$

Where $F_{ga}$ = gas-phase kinetic energy factor,

$U_a$ = superficial gas velocity, m/s (ft/s),

$\rho_g$ = gas density, kg/m$^3$ (lb/ft$^3$)

Here $U_a$ is calculated at the bottom of the section.

Thus, $U_a = (G_b/\rho_g)/ A_a = (5762.3938/2.7550) / (0.4938\times3600) = \underline{1.1983}$ m/s

Thus, $U_a = \underline{3.9314}$ ft/s

$\rho_g = 2.7550$ kg/m$^3$ = $2.7550/ (1.601846\times10^{-1}) = \underline{0.1689}$ lb/ft$^3$

therefore, $F_{ga} = 3.9314\times (0.1689)^{0.5}$

$\Rightarrow$ $F_{ga} = \underline{1.6148}$

Now for $F_{ga} = 1.6148$, we have from fig. 18.15, page 18.10 6th edition Perry)

Aeration factor = $\beta = \underline{0.58}$

Relative Froth Density = $\phi_t = \underline{0.21}$

Now $h_l' = \beta\times h_{ds}$ ---- (eq$^{n.}$ 18.8, page 18.10, 6th edition Perry)

Where, $h_l'$ = pressure drop through the aerated mass over and around the disperser, mm liquid,

$\Rightarrow h_l' = 0.58\times 63.7572 = \underline{36.9792}$ mm.

Now,

$h_f = h_l'/\phi_t$ ------- (eq$^{n.}$ 18.9, page 18.10, 6th edition Perry)

$\Rightarrow h_f = 36.9792/ 0.21 = \underline{176.0914}$ mm.

**Head loss over downcomer apron:**

$h_{da} = 165.2\ \{q/\ A_{da}\}^2$ ----- (eq$^{n.}$ 18.19, page 18.10, 6$^{th}$ edition Perry)

where, $h_{da}$ = head loss under the downcomer apron, as millimeters of liquid,

q = liquid flow rate calculated at the bottom of section, $m^3/s$

and $A_{da}$ = minimum area of flow under the downcomer apron, $m^2$

Now,

$q = 5035.5135/\ (3600\times733.80) = \underline{1.9090\times10^{-3}}\ m^3/s$

Take clearance, C = $\underline{1}$" = $\underline{25.4}$ mm

$h_{ap} = h_{ds} - C = 63.7572 – 25.4 = \underline{38.3572}$ mm

$A_{da} = L_w \text{ x } h_{ap} = 0.675\times 38.3572\times10^{-3} = \underline{26.1611\times10^{-3}}\ m^2$

$\therefore\ h_{da} = 165.2[(1.9090\text{x } 10^{-3})/\ (26.1611\times10^{-3})]^{\ 2}$

$\therefore\ h_{da} = \underline{0.8797}$ mm

Now

$h_t = h_d + h_l`$

Here $h_d$ and $h_l'$ are calculated at bottom of the enriching section.

Now we have,

$h_{d,\ bottom} = \underline{79.0909}$ mm

$h_{l,\ bottom} = \underline{36.9792}$ mm

$\therefore\ h_t = h_d + h_l`$

$= 79.0909+36.9792$

$\therefore\ h_t\ \ = \underline{116.0701}$ mm

**Downcomer Backup:**

$h_{dc} = h_t + h_w + h_{ow} + h_{da} + h_{hg}$ ---- (eq$^n$ 18.3, page 18.7, 6$^{th}$ edition Perry)

$h_t$ = total pressure drop across the plate (mm liquid)

$= h_d + h_l`$

$h_{dc}$ = height in downcomer, mm liquid,

$h_w$ = height of weir at the plate outlet, mm liquid,

$h_{ow}$ =height of crest over the weir, mm liquid,

$h_{da}$ = head loss due to liquid flow under the downcomer apron, mm liquid,

$h_{hg}$ = liquid gradient across the plate, mm liquid.

$\therefore\ h_{dc} = 116.0701 + 50 + 13.7572 + 0.8797 + 0$

$\therefore\ h_{dc} = \underline{180.7070}$ mm.

Let $\phi_{dc}$ = average relative froth density (ratio of froth density to liquid density) = 0.5

$h`_{dc} = h_{dc} / \phi_{dc} = 180.7070/ 0.5$

$\therefore\ h`_{dc} = \underline{361.4140}$ mm.

which is less than the tray spacing, $t_s = \underline{500}$ mm.

Hence no flooding in the enriching section and hence the design calculations are acceptable.

**b). Design of Stripping Section:**

Tray Hydraulics

The design of a sieve plate tower is described below. The equations and correlations are borrowed from the 6th and 7th editions of Perry's Chemical Engineers' Handbook. The procedure for the evaluation of the tray parameters is iterative in nature. Several iterations were performed to optimize the design. The final iteration is presented here.

1. **Tray Spacing, ($t_s$) :**

   Let $t_s = \underline{500}$ mm.

2. **Hole Diameter, ($d_h$):**

   Let $d_h = \underline{5}$ mm.

3. **Hole Pitch ($l_p$):**

   Let $l_p = 3\times d_h$

   i.e., $l_p = 3\times5 = \underline{15}$ mm.

4. **Tray thickness ($t_T$):**

   Let $t_T = 0.6\times d_h$

   i.e., $t_T = 0.6\times5 = \underline{3}$ mm.

5. **Ratio of hole area to perforated area ($A_h/A_p$):**

   Refer fig 6.3

   Now, for a triangular pitch, we know that,

   Ratio of hole area to perforated area $(A_h/A_p) = \frac{1}{2} (\pi/4\times d_h^2)/ [(\sqrt{3}/4) \times l_p^2]$

i.e., $(A_h/A_p) = 0.90\times (d_h/l_p)^2$

i.e., $(A_h/A_p) = 0.90\times (5/15)^2$

i.e., $(A_h/A_p) = 0.1$

Thus,

$(A_h/A_p) = \underline{0.1}$

**6. Plate Diameter ($D_c$):**

The plate diameter is calculated based on the flooding considerations

$L/G \{\rho_g/\rho_l\}^{0.5} = \underline{0.1060}$ ---------- (maximum value)

Now for,

$L/G \{\rho_g/\rho_l\}^{0.5} = \underline{0.1060}$ and for a tray spacing of $\underline{500}$ mm.

we have,

from the flooding curve, ---------- (fig.18.10, page 18.7, 6th edition Perry.)

Flooding parameter, $C_{sb,\ flood} = \underline{0.265}$ ft/s = $\underline{0.08077}$ m/s.

Now,

$U_{nf} = C_{sb,\ flood} \times (\sigma / 20)^{0.2} [(\rho_l - \rho_g) / \rho_g]^{0.5}$

---- {eq$^{\underline{n}}$. 18.2, page 18.6, 6th edition Perry.}

where,

$U_{nf}$ = gas velocity through the net area at flood, m/s (ft/s)

$C_{sb,\ flood}$ = capacity parameter, m/s (ft/s, as in fig.18.10)

$\sigma$ = liquid surface tension, mN/m (dyne/cm.)

$\rho_l$ = liquid density, kg/m$^3$ (lb/ft$^3$)

$\rho_g$ = gas density, kg/m$^3$ (lb/ft$^3$)

Now, we have,

$\sigma = \underline{17.1830}$ mN/m = $\underline{17.1830}$ dyne/cm.

$\rho_l = \underline{727.68}$ kg/m$^3$.

$\rho_g = \underline{2.6672}$ kg/m$^3$.

Therefore,

$U_{nf} = 0.265\times (17.183/20)^{0.2}\times [(727.68-2.6672)/ 2.7550]^{0.5}$

i.e., $U_{nf} = \underline{4.2475}$ ft/s = $\underline{1.2946}$ m/s.

Let

Actual velocity, $U_n = 0.8\times U_{nf}$

i.e., $U_n = 0.8 \times 4.2475$

i.e., $U_n = \underline{3.3980}$ ft/s

$U_n = \underline{1.0357}$ m/s

Now,

Volumetric flow rate of Vapor at the bottom of the Stripping Section

$= q_o = 5787.5393/(3600 \times 2.6672) = \underline{0.6060}\ m^3/s.$

Now,

Net area available for gas flow ($A_n$)

Net area = (Column cross sectional area) – (Downcomer area.)

$A_n = A_c - A_d$

Thus,

Net Active area, $A_n = q_o / U_n = 0.6060/1.0357 = \underline{0.5851}\ m^2$.

Let $L_w / D_c = 0.75$

Where, $L_w$ = weir length, m

$D_c$ = Column diameter, m

Now,

$\Theta_c = 2 \times \sin^{-1}(L_w / D_c) = 2 \times \sin^{-1}(0.75) = \underline{97.18^0}$

Now,

$A_c = (\pi/4) \times D_c^2 = \underline{0.7854} \times D_c^2,\ m^2$

$A_d = [(\pi/4) \times Dc^2 \times (\theta c/360^0)] - [(Lw/2) \times (Dc/2) \times \cos(\theta c/2)]$

i.e., $A_d = [0.7854 \times Dc^2 \times (97.18^0/360^0)] - [(1/4) \times (L_w / D_c) \times D_c^2 \times \cos(97.18^0)]$

i.e., $A_d = (0.2120 \times D_c^2) - (0.1241 \times D_c^2)$

i.e., $A_d = \underline{0.0879} \times D_c^2,\ m^2$

Since An = Ac -Ad

$0.5851 = (0.7854 \times Dc^2) - (0.0879 \times Dc^2)$

i.e., $0.6975 \times D_c^2 = 0.5851$

$\Rightarrow\ D_c^2 = 0.5851/0.6975 = 0.8389$

$\Rightarrow\ D_c = \sqrt{0.8389}$

$\Rightarrow\ D_c = \underline{0.9159}$ m

Take $D_c = \underline{0.92}$ m

Since $L_w / D_c = 0.75$,

$\Rightarrow \quad L_w = 0.75\times D_c = 0.75\times0.92 = 0.690$ m.

Therefore, $L_w = \underline{0.690}$ m.

Now,

$A_c = 0.7854\times0.92^2 = \underline{0.6648}\ m^2$

$A_d = 0.0879\times D_c^2 = 0.0879\times0.92^2 = \underline{0.0744}\ m^2$

$A_n = A_c - A_d$

i.e., $A_n = 0.6648 - 0.0744$

$\Rightarrow \quad A_n = \underline{0.5904}\ m^2$

**7. Perforated plate area ($A_p$):**

$A_a = Ac - (2\times A_d)$

i.e., $A_a = 0.6648- (2\times0.0744)$

$\Rightarrow \quad A_a = \underline{0.5160}\ m^2$

Now,

$L_w / D_c = 0.690/ 0.92 = \underline{0.75}$

$\Theta_c = \underline{97.18}\ ^0$

$\alpha = 180\ ^0 - \Theta_c$

i.e., $\alpha = 180\ ^0 - 97.18\ ^0$

$\Rightarrow \quad \alpha = \underline{82.82}\ ^0$

Now,

$A_{cz} = 2\times L_w\times$ (thickness of distribution)

Where $A_{cz}$ = area of calming zone, $m^2$

$A_{cz} = 2\times0.690\times (50\times10^{-3}) = \underline{0.0690}\ m^2$ -------- (which is 10.37% of $A_c$)

Also,

$A_{wz} = \{(\pi/4) \times D_c^2\times (\alpha/360\ ^0)\} - \{(\pi/4) \times (D_c -0.05)^2\times (\alpha/360\ ^0)\}$

Where $A_{wz}$ = area of waste periphery, $m^2$

i.e., $A_{wz} = \{(\pi/4) \times0.92^2 \times (82.82\ ^0/360\ ^0)\}$

$- \{(\pi/4) \times (0.92-0.05)^2 \times (82.82\ ^0/360\ ^0)\}$

i.e., $A_{wz} = \underline{0.0323}\ m^2$ --------- (which is 4.86% of $A_c$)

Now,

$A_p = A_c – (2×A_d) - A_{cz} - A_{wz}$

i.e., $A_p = 0.6648- (2×0.0744) – 0.0690 – 0.0323$

Thus, $A_p = \underline{0.4147} m^2$

**8. Total Hole Area ($A_h$):**

Since,

$A_h / A_p = 0.1$

$\Rightarrow A_h = 0.1× A_p$

i.e., $A_h = 0.1×0.4147$

$\Rightarrow A_h = \underline{0.04147}\ m^2$

Thus, Total Hole Area = $\underline{0.04147}\ m^2$

Now we know that,

$A_h = n_h × (\pi/4) ×d_h^2$

Where $n_h$ = number of holes.

$\Rightarrow\ n_h = (4×A_h )/ ( \pi × d_h^2 )$

i.e., $n_h = (4×0.04147)/ (\pi ×0.005^2)$

$\Rightarrow\ n_h = \underline{2112.05} \approx \underline{2112}$

Therefore, Number of holes = $\underline{2112.}$

**9. Weir Height ($h_w$):**

Let $h_w = \underline{50}$ mm.

**10. Weeping Check**

All the pressure drops calculated in this section are represented as mm head of liquid on the plate. This serves as a common basis for evaluating the pressure drops.

**Notations used and their units:**

$h_d$ = Pressure drop through the dry plate, mm of liquid on the plate

$u_h$ = Vapor velocity based on the hole area, m/s

$h_{ow}$ = Height of liquid over weir, mm of liquid on the plate

$h_\sigma$ = Pressure drop due to bubble formation, mm of liquid

$h_{ds}$= Dynamic seal of liquid, mm of liquid

$h_l$ = Pressure drop due to foaming, mm of liquid

$h_f$ = Pressure drop due to foaming, actual, mm of liquid

$D_f$ = Average flow length of the liquid, m

$R_h$ = Hydraulic radius of liquid flow, m

$u_f$ = Velocity of foam, m/s

$(N_{Re})$ = Reynolds number of flow

f = Friction factor

$h_{hg}$ = Hydraulic gradient, mm of liquid

$h_{da}$ = Loss under downcomer apron, mm of liquid

$A_{da}$ = Area under the downcomer apron, $m^2$

c = Downcomer clearance, m

$h_{dc}$ = Downcomer backup, mm of liquid

Calculations:

**Head loss through dry hole:**

$h_d$ = head loss across the dry hole

$h_d = k_1 + [k_2\times (\rho_g/\rho_l) \times U_h^2]$ --------- (eq$^{n.}$ 18.6, page 18.9, 6$^{th}$ edition Perry)

where $U_h$ =gas velocity through hole area

$k_1$, $k_2$ are constants

For sieve plates

$k_1$ = 0 and

$k_2 = 50.8 / (C_v)^2$

where

$C_v$ = discharge coefficient, taken from fig. edition 18.14, page 18.9 6$^{th}$ Perry).

Now,

$(A_h/A_a)$ = 0.04147/ 0.5160 = 0.0804

also $t_T/d_h$ = 3/5 = 0.60

Thus for $(A_h/A_a)$ = 0.0804 and $t_T/d_h$ = 0.60

We have from fig. edition 18.14, page 18.9 6$^{th}$ Perry.

$C_v$ = 0.735

$\Rightarrow$ $k_2 = 50.8 / 0.735^2$ = 94.0349

Volumetric flow rate of Vapor at the top of the Stripping Section

$= q_t = 5762.3938/(3600\times2.7550) = \underline{0.5917} m^3/s$ -------- (minimum at top)

Volumetric flow rate of Vapor at the bottom of the Stripping Section

$= q_o = 5787.5393/(3600\times2.6672) = \underline{0.6060}\ m^3/s$. ------- (maximum at bottom).

Velocity through the hole area ($U_h$):

Now,

Velocity through the hole area at the top $= U_{h,\,top} = q_t/A_h$

$= 0.5917/0.04147$

$= \underline{14.2682}$ m/s

also, Velocity through the hole area at the bottom$= U_{h,\,bottom} = q_o/A_h$

$= 0.6060/0.04147$

$= \underline{14.6130}$ m/s

Now,

$$h_{d,\,top} = k_2\,[\rho_g/\rho_l]\,(U_{h,top})^2$$

$$= 94.0349\times(2.7550/733.80)\times14.2682^2$$

$\Rightarrow h_{d,\,top} = \underline{70.6754}$ mm clear liquid. -------- (minimum at top)

also

$$h_{d,\,bottom} = k_2\,[\rho_g/\rho_l]\,(U_{h,\,bottom})^2$$

$$= 94.0349\times(2.6672/727.68)\times14.6130^2$$

$\Rightarrow h_{d,\,bottom} = \underline{73.2876}$ mm clear liquid ----- (maximum at bottom)

**Head Loss Due to Bubble Formation**

$$h_\sigma = 409\,[\sigma / (\rho_{L\times}d_h)\,]$$

where $\sigma$ =surface tension, mN/m (dyne/cm)

$d_h$ = Hole diameter, mm

$\rho_l$ = average density of liquid in the section, $kg/m^3$

$= (733.80 + 727.68)/2$

$= \underline{730.74}\ kg/m^3$

$$h_\sigma = 409\,[17.1830 / (730.740 \times 5)]$$

$h_\sigma$ = 1.9260 mm clear liquid

**Height of Liquid Crest over Weir:**

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

Where q = liquid flow rate at top, $m^3/s$

= 9970.5038/ (3600×733.80)

= $3.7796 \times 10^{-3}$ $m^3/s$

Thus, q' = 59.9079 gal/min.

$L_w$ = weir length = 0.690 m = 2.2638 ft

Now,

$q'/L_w^{2.5} = 59.9079/ (2.2638)^{2.5} = 7.7694$

Now for $q'/L_w^{2.5} = 7.7694$ and $L_w/D_c = 0.75$

We have from fig.18.16, page 18.11, 6th edition Perry

$F_w$= correction factor =1.06

Thus, $h_{ow} = 1.06 \times 664 \times [(3.7796 \times 10^{-3})/0.690]^{2/3}$

⇒ $h_{ow}$ = 21.8712 mm clear liquid.

Now,

$(h_d + h_\sigma)$ = 70.6754 + 1.9260 = 72.6014 mm ------ Design value

$(h_w + h_{ow})$ = 50 + 21.8712 = 71.8712 mm

Also, $A_h/A_a$ = 0.0804 and $(h_w + h_{ow})$ =50 +21.8712 = 71.8712 mm

The minimum value of $(h_d + h_\sigma)$ required is calculated from a graph given in Perry, plotted against $A_h/A_a$.

i.e., we have from fig. 18.11, page 18.7, 6th edition Perry

$(h_d + h_\sigma)_{min}$ = 19.00 mm ------- Theoretical value.

The minimum value as found is 19.00 mm.

Since the design value is greater than the minimum value**, there is no problem of weeping.**

**Downcomer Flooding:**

$h_{ds} = h_w + h_{ow} + (h_{hg}/2)$ ------- (eqn 18.10, page 18.10, 6th edition Perry)

Where,

$h_w$ = weir height, mm

$h_{ds}$ = static slot seal (weir height minus height of top of slot above plate floor, height equivalent clear liquid, mm)

$h_{ow}$ = height of crest over weir, equivalent clear liquid, mm

$h_{hg}$ = hydraulic gradient across the plate, height of equivalent clear liquid, mm.

In the above equation $h_{ow}$ is calculated at bottom of the section and since the tower is operating at atmospheric pressure, $h_{hg}$ is very small for sieve plate and hence neglected.

**Calculation of $h_{ow}$ at bottom conditions of the section:**

q = liquid rate at the bottom of the section, $m^3/s$

= 9995.3079/ (3600×727.68) = $\underline{3.8196\times10^{-3}}$ $m^3/s$

Thus, $q' = (3.8196\times10^{-3}\times60)/ (3.785412\times10^{-3}) = \underline{61.0174}$ gal/min

$L_w$ = weir length = $\underline{0.690}$ m = $\underline{2.2638}$ ft.

$q'/L_w^{2.5} = 61.0174/ (2.2638)^{2.5} = \underline{7.9133}$

Now for $q'/L_w^{2.5}$ = 7.9133 and $L_w/D_c$ =0.75

We have from fig.18.16, page 18.11, 6th edition Perry

$F_w$= correction factor =$\underline{1.065}$

Thus, $h_{ow} = 1.0650\times664\times [(3.8176\times10^{-3})/0.690]^{2/3}$

⇒ $h_{ow}$ = $\underline{22.1291}$ mm clear liquid. ----- (maximum at the bottom of section).

Therefore, $h_{ds}$ = 50 +22.1291 = 72.1291 mm.

Now, $F_{ga} = U_a \times\rho_g^{0.5}$

Where $F_{ga}$ = gas-phase kinetic energy factor,

$U_a$ = superficial gas velocity, m/s (ft/s),

$\rho_g$ = gas density, $kg/m^3$ ($lb/ft^3$)

Here $U_a$ is calculated at the bottom of the section.

Thus, $U_a = (G_b/\rho_g)/ A_a$ = (5787.5393/2.6672) / (0.5160×3600) = $\underline{1.1743}$ m/s

Thus, $U_a$ = $\underline{3.8527}$ ft/s

$\rho_g = 2.6672\ kg/m^3 = 2.6672/ (1.601846\times10^{-1}) = \underline{0.1656}\ lb/ft^3$

Therefore, $F_{ga} = 3.8527\times (0.1656)^{0.5}$

⇒ $F_{ga}$ = $\underline{1.5678}$

Now for $F_{ga}$ = 1.5678, we have from fig. 18.15, page 18.10 6th edition Perry)

Aeration factor = $\beta$ = <u>0.60</u>

Relative Froth Density = $\phi_t$ = <u>0.20</u>

Now $h_l' = \beta \times h_{ds}$ ---- (eq$^{n.}$ 18.8, page 18.10, 6th edition Perry)

Where, $h_l'$ = pressure drop through the aerated mass over and around the disperser, mm liquid,

$\Rightarrow h_l' = 0.60 \times 72.1291 = \underline{43.2775}$ mm.

Now,

$h_f = h_l'/\phi_t$ ------- (eq$^{n.}$ 18.9, page 18.10, 6th edition Perry)

$\Rightarrow h_f = 43.2775/ 0.20 = \underline{216.3875}$ mm.

**Head loss over downcomer apron:**

$h_{da} = 165.2 \{q/ A_{da}\}^2$ ----- (eq$^{n.}$ 18.19, page 18.10, 6th edition Perry)

Where, $h_{da}$ = head loss under the downcomer apron, as millimeters of liquid,

q = liquid flow rate calculated at the bottom of section, $m^3/s$

and $A_{da}$ = minimum area of flow under the downcomer apron, $m^2$

Now,

$q = 9995.3079/ (3600 \times 727.68) = \underline{3.8196 \times 10^{-3}}\ m^3/s$

Take clearance, C = <u>1</u>" = <u>25.4</u> mm

$h_{ap} = h_{ds} - C = 72.1291 – 25.4 = \underline{46.7291}$ mm

$A_{da} = L_w \times h_{ap} = 0.690 \times 46.7291 \times 10^{-3} = \underline{32.2431 \times 10^{-3}}\ m^2$

$\therefore h_{da} = 165.2[(3.8196 \times 10^{-3})/ (32.2431 \times 10^{-3})]^2$

$\therefore h_{da} = \underline{2.2818}$ mm

Now

$h_t = h_d + h_l`$

Here $h_d$ and $h_l'$ are calculated at bottom of the Stripping section.

Now we have,

$h_{d,\ bottom} = \underline{73.2876}$ mm

$h_{l,\ bottom} = \underline{43.2775}$ mm

$\therefore h_t = h_d + h_l`$

$= 73.2876+43.2775$

$\therefore h_t = \underline{116.5651}$ mm

**Downcomer Backup:**

$h_{dc} = h_t + h_w + h_{ow} + h_{da} + h_{hg}$ ---- (eq$^n$ 18.3, page 18.7, 6$^{th}$ edition Perry)

$h_t$ = total pressure drop across the plate (mm liquid)

$= h_d + h_l$`

$h_{dc}$ = height in downcomer, mm liquid,

$h_w$ = height of weir at the plate outlet, mm liquid,

$h_{ow}$ =height of crest over the weir, mm liquid,

$h_{da}$ = head loss due to liquid flow under the downcomer apron, mm liquid,

$h_{hg}$ = liquid gradient across the plate, mm liquid.

$\therefore h_{dc} = 116.5651 + 50 + 21.8712 + 21.2818 + 0$

$\therefore h_{dc} = \underline{190.7181}$ mm.

Let $\phi_{dc}$ = average relative froth density (ratio of froth density to liquid density) = 0.5

$h`_{dc} = h_{dc} / \phi_{dc} = 190.7181/ 0.5$

$\therefore h`_{dc} = \underline{381.4362}$ mm.

which is less than the tray spacing, $t_s = \underline{500}$ mm.

Hence no flooding in the Stripping Section and hence the design calculations are acceptable.

**Formulas used in calculation of properties:**

1. **VISCOSITY:**

(i). Average Liquid Viscosity:

$$(\mu_{liq})^{1/3} = [x_1 \times (\mu_1)^{1/3}] + [x_2 \times (\mu_2)^{1/3}]$$

(ii). Average Gas Viscosity:

$$\mu_g = \sum (y_i \times \mu_i \times M_i^{1/2}) / \sum (y_i \times M_i^{1/2})$$

2. **DIFFUSIVITIES:**

**(i). Liquid Phase Diffusivity:**

For the case of Organic solutes diffusing in Organic solvents

$D_{AB} = (K \times T) / [\eta_B \times (V_A)^{1/3}]$ ----- (eq$^{n.}$ 3.140, page 3-287, 6$^{th}$ edition Perry)

Where,

$K = (8.2 \times 10^{-8}) \times [1 + (3 \times V_B / V_A)^{2/3}]$,

$T$ = absolute temperature, $^0K$,

$\eta_B$ = viscosity of solvent B, cP,

$V_A$ =molar volume of solute A at its normal boiling temperature, $cm^3$/g-mol.

$D_{AB}$ =mutual diffusivity coefficient of solute A at very low concentration in solvent B, $cm^2/s$

**(ii). Gas Phase Diffusivity:**

$D_{AB} = 10^{-3} \times T^{1.75} \times [(M_A + M_B) / (M_A \times M_B)]^{1/2}\} / \{P \times [(\sum v_A)^{1/3} + (\sum v_B)^{1/3}]^2$

------ (eq$^{n.}$ 3.133, page 3-281, 6$^{th}$ edition Perry)

Where P = Pressure in atmospheres,

T = Temperature in $^0K$

$D_{AB}$ = Diffusivity, $cm^2/s$

$\sum v_A$ and $\sum v_B$ = summation of atomic diffusion volumes for components A and B respectively.

$M_A$ and $M_B$ = Molecular weights of components A and B respectively.

**3. SURFACE TENSION:**

$\sigma = [P_{ch} \times (\rho_l - \rho_g)/M]^4 \times 10^{-12}$ ----- (eq$^{n.}$ 8.23, page 293, Coulson and Richardson vol.6)

Where $\sigma$ = surface tension, dyne/cm

$P_{ch}$ =Sugden's Parachor,

$\rho_l$ = liquid density, kg/m$^3$

$\rho_g$ = density of saturated vapor, kg/m$^3$

M = Molecular weight

$\sigma$, $\rho_l$, and $\rho_g$ are evaluated at system temperature.

Also,

$\sigma_{mix} = \sum (x_i \times \sigma_i)$ where i=1,2,3 …n.

4. **DENSITY:**

**(i). Liquid Density:**

$\rho^{sat} = P_c / (R \times T_c \times Z_c^{[1+(1-Tr)\ 2/7]})$

Where, $\rho^{sat}$ = saturated liquid molar density,

$P_c$ = critical pressure,

R = gas constant,

$T_c$ = absolute critical temperature,

$Z_c$ = critical compressibility factor,

$T_r$ = reduced temperature = $T/T_c$

**(ii). Vapor density:**

Vapor density is calculated assuming ideal gas law holds good.

i.e. $P \times V = R \times T$

Where, R = universal gas constant

**Average Properties:**

| | Enriching Section | Stripping Section |
|---|---|---|
| **Liquid Flow Rate (L)** | | |
| kmol/hr | 57.2858 | 113.4164 |
| kg/hr | 4998.37 | 9982.395 |
| **Vapor Flow Rate (G)** | | |
| kmol/hr. | 65.6690 | 65.6690 |
| kg/hr. | 5724.735 | 5724.735 |
| **Temperature (T)** | | |
| $T_{avg.,liquid}$ ($^0$ C) | 118.125 | 129.05 |
| $T_{avg., vapor}$ ($^0$ C) | 121.75 | 129.925 |
| **Viscosity (μ)** | | |
| $\mu_{avg., liquid}$ (cP) | 0.3229 | 0.3546 |
| $\mu_{avg., vapor}$ (cP) | 0.0234 | 0.009 |
| **Density (ρ)** | | |
| $\rho_{avg., liquid}$ (kg/m$^3$) | 742.1650 | 730.7400 |
| $P_{avg., vapor}$ (kg/m$^3$) | 2.835 | 2.7111 |
| **Surface Tension (σ)** | | |
| $\sigma_{mix}$ (dyne/cm) | 17.453 | 17.124 |
| **Diffusivities (D)** | | |
| Liquid Diffusivity, $D_L$ cm$^2$/s | $4.237\times10^{-5}$ | $3.97\times10^{-5}$ |
| Vapor Diffusivity, $D_V$ cm$^2$/s | 0.05691 | 0.05979 |
| **Schimid number, $S_c$=μ/(ρ× D)** | | |
| Gas $N_{Sc, g}$ | 1.4925 | 0.5619 |
| Liquid $N_{Sc, l}$ | 102.9338 | 122.3896 |

Table 6.3 Average Properties

## V. EFFICENCIES: (AIChE Method)

## A) Enriching Section:

1. **Point Efficiency, ($E_{og}$):**

$E_{og} = 1\text{-}e^{-Nog} = 1\text{-exp}(-N_{og})$ ----- (eq$^{n.}$ 18.33, page 18.15, 6$^{th}$ edition Perry)

Where $N_{og}$ = Overall transfer units

$N_{og} = 1/ [(1/N_g) + (\lambda/N_l)]$ ---- (eq$^{n.}$ 18.34, page 18.15, 6$^{th}$ edition Perry)

Where $N_l$ = Liquid phase transfer units,

$N_g$ = Gas phase transfer units,

$\lambda = (m\times G_m)/ L_m$ = Stripping factor,

m = slope of Equilibrium Curve,

$G_m$ = Gas flow rate, mol/s

$L_m$ = Liquid flow rate, mol/s

$N_g= (0.776 + (0.00457\times h_w) – (0.238\times U_a\times \rho_g^{0.5}) + (104.6\times W))/ (N_{Sc,\,g})^{0.5}$

----- (eq$^{n.}$ 18.36, page 18.15, 6$^{th}$ edition Perry)

Where $h_w$ = weir height = <u>50.00</u> mm

$U_a$ = Gas velocity through active area, m/s

= (Avg. vapor flow rate in kg/hr)/ (3600×Avg. vapor density ×active area)

= 5724.735/ (3600×2.835×0.4938)

⇨ $U_a$ = <u>1.1689</u> m/s

$D_f = (L_w + D_c)/2 = (0.675 + 0.9)/2$ = <u>0.7875</u> m

Average Liquid rate = <u>4998.37</u> kg/hr

Average Liquid Density =<u>742.1650</u> kg/m$^3$

q = 4998.37/ (3600×742.1650) =<u>$1.8753 \times 10^{-3}$</u> m$^3$/s

W = Liquid flow rate, m$^3$/ (s.m) of width of flow path on the plate,

$= q/D_f = 1.8753\times10^{-3}/0.7875$ = <u>$2.8313\times10^{-3}$</u> m$^3$/ (s.m)

$N_{Sc,\,g}$ = Schmidt number $=\mu_g/ (\rho_g\times D_g)$ = <u>1.4925</u>

Now,

<u>Number of gas phase transfer units</u>

$N_g=(0.776+(0.00457\times 50)–(0.238\times 1.1689\times 2.835^{0.5}) + (104.6\times 2.8313\times 10^{-3}))/ (1.4925)^{0.5}$

⇨ $N_g$ = <u>0.6482</u>

Also, Number of liquid phase transfer units

$N_l = k_l \times a \times \theta_l$ ----- (eq$^n$ 18.36a, page 18.15, 6$^{th}$ edition Perry)

Where $k_l$ = Liquid phase transfer coefficient kmol/ (sm$^2$ kmol/m$^3$) or m/s

a = effective interfacial area for mass transfer m$^2$/m$^3$ froth or spray on the plate,

$\theta_l$ = residence time of liquid in the froth or spray, s

$\theta_l = (h_l \times A_a)/ (1000 \times q)$ ---- (eq$^{n.}$ 18.38, page 18.16, 6$^{th}$ edition Perry)

Now, q = liquid flow rate, m$^3$/s

q = 4998.37/ (3600×742.1650) = <u>1.8753x10 $^{-3}$</u> m$^3$/s

$h_l = h_l'$ = <u>36.9792</u> mm

$A_a$ = <u>0.4938</u> m$^2$

$\therefore \theta_l$ = 36.9792×0.4938/ (1000×1.8753×10$^{-3}$) = <u>9.7373</u> s

$k_l \times a = (3.875\times10^8\times D_L)^{0.5}\times ((0.40\times U_a\times\rho_g^{0.5}) + 0.17)$

--- (eq$^{n.}$ 18.40a, page 18.16, 6$^{th}$ edition Perry)

$D_L$= liquid phase diffusion coefficient, m$^2$/s

$k_l \times a = (3.875\times10^8\times4.237\times10^{-9})^{0.5}\times ((0.40\times1.1689\times2.8350^{0.5}) + 0.17)$

$\therefore k_l \times a$ = <u>1.2122</u> m/s

$\therefore N_l = k_l \times a \times \theta_l$

i.e., $N_l$ = 1.2122×9.7373 = <u>11.8036</u> m

<u>Slope of equilibrium Curve</u>

$m_{top}$ = <u>0.8329</u>

$m_{bottom}$ = <u>0.9192</u>

$G_m/L_m$ = 65.6690/57.2858

$\lambda t = m_t \times G_m/L_m$ = <u>0.9548</u>

$\lambda b = m_b \times G_m/L_m$ = <u>1.0537</u> $\Rightarrow \bar{\lambda}$ = <u>1.0043</u>

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

= 1/ [(1/0.6456) + (1.0043/11.8036)]

$N_{og}$ = <u>0.6120</u>

$E_{og} = 1-e^{-Nog}$ = 1-exp (-$N_{og}$)

= $1-e^{-0.6120}$ = 1-exp (-0.6120)

$E_{og}$ = <u>0.4577</u>

$\therefore$ Point Efficiency = $E_{og}$ = <u>0.4577</u>

2. **Murphree Plate Efficiency ($E_{mv}$):**

Now, Pelect number $= N_{Pe} = Z_l^2 / (D_E \times \theta_l)$

$Z_l$ = length of liquid travel, m

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

----- (eq$^{n.}$ 18.45, page 18.17, 6$^{th}$ edition Perry)

Where $D_E$ = Eddy diffusion coefficient, $m^2/s$

$D_E = (6.675 \times 10^{-3} \times (1.1689)^{1.44}) + (0.922 \times 10^{-4} \times 36.9792) - 0.00562$

$D_E = \underline{6.1465 \times 10^{-3}}\ m^2/s$

Also,

$Z_l = D_c \times \cos(\theta_c/2) = 0.90 \times \cos(97.18^0/2) = \underline{0.5952}$ m

$N_{Pe} = Z_l^2 / (D_E \times \theta_l)$

$= 0.5952^2 / (6.1465 \times 10^{-3} \times 9.7373)$

$N_{Pe} = \underline{5.9192}$

$\bar{\lambda} \times E_{og} = 1.0043 \times 0.4577 = \underline{0.4597}$

Now for $\lambda \times E_{og} = 0.4545$ and $N_{Pe} = 5.9192$

We have from fig.18.29a, page 18.18, 6$^{th}$ edition Perry

$E_{mv}/ E_{og} = \underline{1.2}$

$\therefore E_{mv} = 1.2 \times E_{og} = 1.2 \times 0.4577 = \underline{0.5492}$

$\therefore$ Murphree Plate Efficiency $= E_{mv} = \underline{0.5492}$

3. **Overall Efficiency ( $E_{OC}$):**

$$\text{Overall Efficiency} = E_{OC} = \frac{\log[1 + E_\alpha(\lambda - 1)]}{\log \lambda}$$

----- (eq$^{n.}$ 18.46, page 18.17, 6$^{th}$ edition Perry)

where $$E_\alpha / E_{mv} = \frac{1}{1 + E_{MV}[\psi/(1-\psi)]}$$

----- (eq$^{n.}$ 18.27, page 18.13, 6$^{th}$ edition Perry)

$E_{mv}$ = Murphee Vapor efficiency,

$E_\alpha$ = Murphee Vapor efficiency, corrected for recycle effect of liquid entrainment.

$(L/G) \times \{\rho_g/\rho_l\}^{0.5} = (4998.37/5724.736) \times \{2.835/742.1650\}^{0.5} = \underline{0.0533}$

Thus, for $(L/G) \times \{\rho_g/\rho_l\}^{0.5} = 0.0533$ and at 80 % of the flooding value,

we have from fig.18.22, page 18.14, 6th edition Perry

$\psi$ = fractional entrainment, moles/mole gross down flow = $\underline{0.052}$

$$\Rightarrow E_\alpha / E_{mv} = \frac{1}{1 + E_{mv}\,[\psi/(1-\psi)]}$$

$$\Rightarrow E_\alpha = \frac{E_{mv}}{1 + E_{mv}\,[\psi/(1-\psi)]}$$

$$= 0.5492/\,(1+0.5492[0.052/\,(1-0.052)])$$

$\Rightarrow E_\alpha = \underline{0.5331}$

$$\text{Overall Efficiency} = E_{OC} = \frac{\log\,[1 + E_\alpha(\lambda - 1)]}{\log \lambda}$$

$E_{OC} = \log\,[1+ 0.5331(1.0043-1)]/ \log 1.0043$

Overall Efficiency = $E_{OC} = \underline{0.5335}$

Actual trays = $N_{act} = N_T/E_{OC}$ = (ideal trays)/ (overall efficiency)

Where $N_T$ = Theoretical plates,

$N_{act}$ = actual trays

$N_{act} = 4/0.5335 = \underline{7.4977} \approx \underline{8}$

Thus, Actual trays in the Enriching Section = $\underline{8}$

Thus $\underline{8^{th}}$ tray is the feed tray.

Total Height of Enriching section = $8 \times t_s = 8 \times 500 = \underline{4000}$ mm = $\underline{4}$ m

**B) Stripping Section:**

**1. Point Efficiency, ($E_{og}$):**

$E_{og} = 1-e^{-N_{og}} = 1-\exp(-N_{og})$ ----- (eqn. 18.33, page 18.15, 6th edition Perry)

Where $N_{og}$ = Overall transfer units

$N_{og} = 1/\,[(1/N_g) + (\lambda/N_l)]$ ---- (eqn. 18.34, page 18.15, 6th edition Perry)

Where $N_l$ = Liquid phase transfer units,

$N_g$ = Gas phase transfer units,

$\lambda = (m\times G_m)/ L_m$ = Stripping factor,

m = slope of Equilibrium Curve,

$G_m$ = Gas flow rate, mol/s

$L_m$ = Liquid flow rate, mol/s

$N_g = (0.776 + (0.00457\times h_w) - (0.238\times U_a\times \rho_g^{0.5}) + (104.6\times W))/ (N_{Sc, g})^{0.5}$

----- (eq$^{n.}$ 18.36, page 18.15, 6$^{th}$ edition Perry)

Where $h_w$ = weir height = 50.00 mm

$U_a$ = Gas velocity through active area, m/s

= (Avg. vapor flow rate in kg/hr)/ (3600×Avg. vapor density ×active area)

= 5774.79/ (3600×2.7111×0.5160)

⇨ $U_a$ = 1.1604 m/s

$D_f = (L_w + D_c)/2 = (0.690 + 0.92)/2$ = 0.8050 m

Average Liquid rate = 9982.395 kg/hr

Average Liquid Density =730.7400 $kg/m^3$

q = 9982.395/ (3600×730.7400) =$3.7995 \times 10^{-3}$ $m^3/s$

W = Liquid flow rate, $m^3$/ (s.m) of width of flow path on the plate,

= $q/D_f = 3.7995\times10^{-3}/0.8050 = 4.7199\times10^{-3}$ $m^3$/ (s.m)

$N_{Sc, g}$ = Schmidt number $=\mu_g/ (\rho_g\times D_g)$ = 0.5619

Now,

Number of gas phase transfer units

$N_g = (0.776 + (0.00457\times50) - (0.238\times1.1604\times2.7111^{0.5}) + (104.6\times4.7199\times10^{-3}))/ (0.5619)^{0.5}$

⇨ $N_g$ = 1.3956

Also,

Number of liquid phase transfer units

$N_l = k_l\times a\times\theta_l$ ----- (eq$^n$ 18.36a, page 18.15, 6$^{th}$ edition Perry)

Where $k_l$ = Liquid phase transfer coefficient kmol/ (sm$^2$ kmol/m$^3$) or m/s

a = effective interfacial area for mass transfer $m^2/m^3$ froth or spray on the plate,

$\theta_l$ = residence time of liquid in the froth or spray, s

$\theta_l = (h_l \times A_a)/ (1000 \times q)$ ---- (eq$^{n.}$ 18.38, page 18.16, 6$^{th}$ edition Perry)

Now, q = liquid flow rate, $m^3/s$

q = 9982.735/ (3600×730.7400) = $\underline{3.7995 \times 10^{-3}}$ $m^3/s$

$h_l = h_l' = \underline{43.2775}$ mm

$A_a = \underline{0.5160}\ m^2$

$\therefore \theta_l = 43.2775 \times 0.5160/ (1000 \times 3.7995 \times 10^{-3}) = \underline{5.8774}$ s

$k_l \times a = (3.875 \times 10^8 \times D_L)^{0.5} \times ((0.40 \times U_a \times \rho_g{}^{0.5}) + 0.17)$

--- (eq$^{n.}$ 18.40a, page 18.16, 6$^{th}$ edition Perry)

$D_L$= liquid phase diffusion coefficient, $m^2/s$

$k_l \times a = (3.875 \times 10^8 \times 3.97 \times 10^{-9})^{0.5} \times ((0.40 \times 1.1604 \times 2.7111^{0.5}) + 0.17)$

$\therefore k_l \times a = \underline{1.4303}$ m/s

$\therefore N_l = k_l \times a \times \theta_l$

i.e., $N_l = 1.4303 \times 5.8774 = \underline{8.4065}$ m

Slope of equilibrium Curve

$m_{top} = \underline{0.9192}$

$m_{bottom} = \underline{2.4875}$

$G_m/L_m = 65.6690/113.4164$

$\lambda t = m_t \times G_m/L_m = \underline{0.5322}$

$\lambda b = m_b \times G_m/L_m = \underline{1.4403} \quad \Rightarrow \quad \bar{\lambda} = \underline{0.9863}$

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

$= 1/ [(1/1.3956) + (0.9863/8.4065)]$

$N_{og} = \underline{1.1988}$

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

$= 1-e^{-1.1988} = 1-\exp(-1.1988)$

$E_{og} = \underline{0.6985}$

$\therefore$ Point Efficiency = $E_{og} = \underline{0.6985}$

1. **Murphree Plate Efficiency ($E_{mv}$):**

Now, Pelect number = $N_{Pe} = Z_l / (D_E \times \theta_l)$

$Z_l$ = length of liquid travel, m

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

----- (eq$^{n.}$ 18.45, page 18.17, 6$^{th}$ edition Perry)

Where $D_E$ = Eddy diffusion coefficient, $m^2/s$

$D_E = (6.675 \text{ x } 10^{-3} \times (1.1604)^{1.44}) + (0.922 \times 10^{-4} \times 43.2775) - 0.00562$

$D_E = \underline{6.6398 \times 10^{-3}}\ m^2/s$

Also,

$Z_l = D_c \times \cos(\theta_c/2) = 0.92 \times \cos(97.18^0/2) = \underline{0.6085}$ m

$N_{Pe} = Z_l^2 / (D_E \times \theta_l)$

$= 0.6085^2 / (6.6398 \times 10^{-3} \times 5.8774)$

$N_{Pe} = \underline{9.4881}$

$\bar{\lambda} \times E_{og} = 0.9863 \text{ x } 0.6985 = \underline{0.6889}$

Now for $\lambda \times E_{og} = 0.6889$ and $N_{Pe} = 9.4881$

We have from fig.18.29a, page 18.18, 6$^{th}$ edition Perry

$E_{mv}/E_{og} = \underline{1.32}$

$\therefore E_{mv} = 1.32 \times E_{og} = 1.32 \times 0.6985 = \underline{0.9220}$

$\therefore$ Murphree Plate Efficiency = $E_{mv} = \underline{0.5492}$

2. **Overall Efficiency ( $E_{OC}$):**

$$\text{Overall Efficiency} = E_{OC} = \frac{\log[1 + E_\alpha(\lambda - 1)]}{\log \lambda}$$

----- (eq$^{n.}$ 18.46, page 18.17, 6$^{th}$ edition Perry)

$$\text{where } E_\alpha / E_{mv} = \frac{1}{1 + E_{MV}[\psi/(1-\psi)]}$$

----- (eq$^{n.}$ 18.27, page 18.13, 6$^{th}$ edition Perry)

$E_{mv}$ = Murphee Vapor efficiency,

$E_\alpha$ = Murphee Vapor efficiency, corrected for recycle effect of liquid entrainment.

$(L/G) \times \{\rho_g/\rho_l\}^{0.5} = (9982.395/5774.79) \times \{2.7111/730.7400\}^{0.5} = \underline{0.1047}$

Thus, for $(L/G) \times \{\rho_g/\rho_l\}^{0.5} = 0.1047$ and at 80 % of the flooding value,

We have from fig.18.22, page 18.14, 6$^{th}$ edition Perry

$\psi$ = fractional entrainment, moles/mole gross down flow = 0.027

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

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

$= 0.9220/ (1+0.9220[0.027/ (1-0.027)])$

$\Rightarrow E_\alpha$ = 0.8990

$$\text{Overall Efficiency} = E_{OC} = \frac{\log[1 + E_\alpha(\lambda - 1)]}{\log \lambda}$$

$E_{OC} = \log[1+ 0.8990(0.9863-1)]/ \log 0.9863$

Overall Efficiency = $E_{OC}$ = 0.8984

Actual trays = $N_{act} = N_T/E_{OC}$ = (ideal trays)/ (overall efficiency)

Where $N_T$ = Theoretical plates,

$N_{act}$ = actual trays

$N_{act}$ = 5/0.8984 = 5.5655 ≈ 6

Thus, Actual trays in the Stripping Section = 6

Total Height of Stripping section = $6\times t_s$ = 6×500 = 3000 mm = 3 m

Total Height of Column:

$=H_C$ = Height of Enriching section + Height of Stripping section

= 4000 + 3000 = 7000 mm = 7 m

**SUMMARY OF THE DISTILLATION COLUMN:**

**A) Enriching section**

Tray spacing = 500 mm

Column diameter = 900 mm = 0.90 m

Weir length = 0.675 m

Weir height = 50 mm

Hole diameter = 5 mm

Hole pitch = 15 mm, triangular

Tray thickness = 3 mm

Number of holes = 2010

Flooding % = 80

**B) Stripping section**

Tray spacing = 500 mm

Column diameter = 920 mm = 0.92 m

Weir length = 0.690 m

Weir height = 50 mm

Hole diameter = 5 mm

Hole pitch = 15 mm, triangular

Tray thickness = 3 mm

Number of holes = 2112

Flooding % = 80

**VI. Mechanical Design of Distillation Column**

**a) SHELL:**

Diameter of the tower = $D_i$ = 910 mm = 0.910 m

Working/Operating Pressure = 1 atmosphere = 1.0329 $kg/cm^2$

Design pressure = 1.1×Operating Pressure = 1.1×1.0329 = 1.1362 $kg/cm^2$

Working temperature = 130.6 $^0C$ = 403.75 $^0K$

Design temperature = 145 $^0C$ = 418.15 $^0K$

Shell material – IS: 2002-1962 Grade I Plain Carbon steel

Permissible tensile stress ($f_t$) = 93.195 $MN/m^2$ = 950 $kg/cm^2$

Elastic Modulus (E) = $1.88\times10^5$ $MN/m^2$ = $1.9164\times10^6$ $kg/cm^2$

Insulation material - asbestos

Insulation thickness = 2”= 50.8 mm

Density of insulation = 2700 $kg/m^3$

Top disengaging space = 0.5 m

Bottom separator space = 1.0 m

Weir height = 50 mm

Downcomer clearance = 1” = 25.4 mm

**b) HEAD - TORISPHERICAL DISHED HEAD:**

Material - IS: 2002-1962 Grade I Plain Carbon steel

Allowable tensile stress = 93.195 $MN/m^2$ = 950 $kg/cm^2$

**c) SUPPORT SKIRT:**

Height of support = 1600 mm = 1.6 m

Material – Carbon Steel

**d) TRAYS-SIEVE TYPE:**

Number of trays = 14

Hole Diameter = 5 mm

Number of holes:

Enriching section = 2010

Stripping section = 2112

Tray spacing:

Enriching section: 19.6850” = 500 mm

Stripping section: 19.6850” = 500 mm

Thickness = 3 mm

**e) SUPPORT FOR TRAY:**

Purlins – Channels and Angles

Material – Carbon Steel

Permissible Stress = 1275 $kg/cm^2$

**1. Shell minimum thickness:**

Considering the vessel as an internal pressure vessel.

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

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, $t_s$ = ((1.1362×910)/ ((2×950×0.85) - 1.1362)) + 3 = 0.6407 + 3 = 3.6407 mm

Taking the thickness of the shell = 6 mm (standard)

**Check for Plastic deformation**

P = 2×$f_t$× (t/D) × (1+1.5U(1-0.2D/L))/ (100t/D)

U = 1.5% (for new equipment)

P = 2×93.195× (6/910) ×(1+(1.5×0.015)(1-(0.2×(910/10000)))/(100×6/910)

P = 1.9051 MN/m$^2$ = 19.42 kg/cm$^2$

$P_{(allowable)}$ = 1.9051 MN/m$^2$ = 19.42 kg/cm$^2$

The allowable pressure is greater than the design pressure. Hence, the thickness is satisfactory with respect to plastic deformation.

**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

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, mm

Now, $R_c$ = 910 mm

⇨ $R_k$ = 6% × $R_c$ = 0.06×910 = 540 mm

W= ¼ × (3 + ($R_c$/$R_k$)$^{0.5}$) = ¼ × (3 + (910/540)$^{0.5}$) = 1.7706 mm

$t_h$ = (1.1362×910×1.7706)/ (2×950×0.85) = 1.1336 mm

Including corrosion allowance take the thickness of head = 6 mm

**Pressure at which elastic deformation occurs**

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

$= 0.366 \times 1.88 \times 10^5 \times (6/910)^2$

$= \underline{2.9913}$ MN/ $m^2$ = $\underline{30.4924}$ 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) + $(2 \times s_f)$ + $(2 \times i_{cr}/3)$ --- ($eq^{n.}$ 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

$s_f$ = <u>1”</u>

$i_{cr}$ = <u>1¼”</u>

Also, O.D. = <u>910</u> mm = <u>32.8268”</u>

Diameter = 32.8268 + (32.8268/24) + (2×1) + (2×1¼/3) =

d = 32.8268 + 1.4928 +2+ 0.8333 = <u>40.1529”</u> = <u>1019.8837</u> mm

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

$= ((\pi \times 40.1529^2 \times 0.2362)/4) \times (590/1728)$ = <u>102.1335</u> lb

= <u>46.3269</u> kg

**3. Shell thickness at different heights**

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

**3.1 Axial Tensile Stress due to Pressure:**

$$f_{ap} = \frac{P \times D_i}{4(t_s - c)} = \frac{1.1362 \times 910}{4(6-3)} = \underline{86.1618} \text{ kg/cm}^2$$

This is the same through out the column height.

**3.2 Compressive stress due Dead Loads:**

3.2a Compressive stress due to Weight of shell up to a distance ‘X’ meter from top.

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

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

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

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

$\rho_s$ = density of shell material, $kg/m^3$

$D_m$ = mean diameter of shell,

$t_s$ = thickness of shell,

c = corrosion allowance

Now, $\rho_s = \underline{8500}\ kg/m^3$

$f_{ds} = \rho_s \times X = \underline{(8500 \times X)}\ kg/m^2 = \underline{(0.0085 \times X)}\ kg/cm^2$

3.2b Compressive stress due to weight of insulation at a height X meter

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

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

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

$D_{ins} = D_c + 2t_s + 2t_{ins} = 91 + (2 \times 0.6) + (2 \times 5.08) = \underline{102.36}$ cm.

$D_m = (91 + (91 + (2 \times 0.6)))/2 = \underline{91.60}$ cm.

$$f_{d(ins)} = \frac{\pi \times 102.36 \times 5.08 \times 2700 \times X}{\pi \times 91.6 \times (0.6 - 0.3)} = \underline{51090.6026 \times X}\ kg/m^2$$

$$= \underline{5.1091 \times X}\ kg/cm^2$$

3.2c Stress due to the weight of the liquid and tray in the column up to a height X meter.

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

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 = 736.4525 $kg/m^3$

Liquid and tray weight for X meter

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

$= [(X-0.3)/ 0.5 + 1] \times (\pi \times 0.91^2/4) \times 736.4525$

$= \underline{[2X + 0.4] \times 478.0353}$ kg

$f_{d\,(liq)} = F_{liq-tray} \times 10/ (\pi \times D_m \times (t_s - c))$

$= [2X + 0.4] \times 478.0353 \times 10/ (\pi \times 916 \times (6 - 3))$

$= [2X + 0.4] \times 0.5537$

$= \underline{1.1074X + 0.2215}$ kg/cm$^2$

3.2d Compressive stress due to attachments such as internals, top head, platforms and ladder up to height X meter.

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

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 = $\underline{(46.3269+25X)}$ kg

$f_{d\,(attch.)} = (46.3269+25X) \times 10/ \pi \times 91 \times (6 - 3) = \underline{0.4486 + 0.2915X}$ kg/cm$^2$

Total compressive dead weight stress:

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

$= 0.85X + 5.1091X + [1.1074X+0.2215] + [0.4486 +0.2915X]$

$f_{dx} = \underline{7.3580X + 0.6701}$ 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

$= 0.7 \times P_w \times D \times X^2/2$

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

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

Now $P_w = \underline{35}$ lb/ft$^2$ --- (from table 9.1 Brownell and Young)

$= \underline{189.631}$ kg/m$^2$

Bending moment due to wind load

$= M_{wx} = 0.7\times189.631\times0.916\times X^2/2 = \underline{121.591}$ kg-m

$f_{wx} = 1.4\times189.631\times X^2/\ \pi\ \times0.916\times(6\text{-}3) = \underline{3.075X^2}$ kg/cm$^2$

**5. Stresses due to Seismic load:**

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

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

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

Where C = seismic coefficient,

W= total weight of column, kg

H = height of column

Total weight of column = W= $C_v\times\pi\times\rho_m\times D_m\times g\times(H_v+(0.8\times D_m))\times t_s\times10^{-3}$

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

$\rho_m$ = density of vessel material, kg/m$^3$

$D_m$ = mean diameter of vessel = $D_i + (t\times10^{-3})$

$= 0.91+(6\times10^{-3}) = \underline{0.916}$ m

$W=1.5\times\pi\times8500\times0.916\times9.81\times(8.5+(0.8\times0.916))\times6\times10^{-3}=\underline{1993926.83}N=\underline{203254.52}$ kg

Weight of plates: ------- (Coulson and Richardson 6$^{th}$ volume)

Plate area = $\pi\times0.91^2/4 = \underline{0.6504}$ m$^2$

Weight of each plate = $1.2\times0.6504 = \underline{0.7805}$ kN

Weight of 14 plates = $14\times0.7805 = \underline{10.927}$ kN = $\underline{10.927\times10^3}$ N = $\underline{1113.86}$ kg.

Total weight of column = 203254.52 + 1113.86 = $\underline{204368.38}$ kg

Let C = seismic coefficient = 0.08

$M_{sx} = [0.08\times204368.38\times X^2/3] \times [((3\times10)-X)/10^2]$

$= 16349.47X^2 \times [0.3-0.01X]$ kg-m

$f_{sx} = M_{sx}\times10^3/\pi\times D_m^2\times (t_s-c)/4 = 16349.47X^2 \times [0.3-0.01X \times10^3/\pi\times91.6^2\times (6-3)/4$

$= [1.4664X^2- 0.0489X^3]$, kg/cm$^2$

On the up wind side:

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

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 either is therefore accepted and considered for evaluation of combined stresses.

Thus,

$3.075X^2 + 86.1618- [7.3580X + 0.6701] = f_{t, max}$

i.e., $3.075X^2- 7.3580X + 86.1618 - 0.6701- (0.85\times950) = 0$

$3.075X^2- 7.3580X – 722.0083 =0$

=> X = 16.5670 m

On the down side:

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

$3.075X^2 - 86.1618+ [7.3580X + 0.6701] = f_{c,max}$

The column height is 10 m, for which the maximum value is

$f_{c,max} = 3.075(10)^2 - 86.1618+ [7.3580(10) + 0.6701]$

$= 295.5883$ kg/cm$^2$

This shows that the stress on the down wind side is compressive.

If the column is considered without internal pressure operating then the compressive stress will be

$f_c = 3.075(10)^2 + [7.3580(10) + 0.6701] = 381.7501$ kg/cm$^2$

Elastic stability:

$f_c' = 0.105\times E\times (t_s- c)/D$

E- Modulus of elasticity

$f_c' = 0.105\times1.9164\times10^6\times (6- 3)/916 = 659.0240$ kg/cm$^2$

⇨ $f_c' > f_c$

Thus the compressive stress is well within the permissible stress for elasticity.

Since X= 16.567 m

Hence we see that the design value of the column height is more than 10 m, which is the actual column height. So we conclude that the design is safe and thus the design calculations are acceptable.

Hence a thickness of 6 mm is taken throughout the length of shell.

Height of the head = $D_c/4 = 0.91/4 = 0.2275$ m

Skirt support Height = 1.6 m

Total actual height = 7 + (2×0.2275) + 1.6 = 9.0550 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 = 910 mm.

(ii) Height = 7000 mm = 7 m

(iii) Weight of vessel, attachment = 204368.38 kg.

(iv) Diameter of skirt (straight) = 910 mm

(v) Height of skirt = 1.6 m

(vi) Wind pressure = 189.631 $kg/m^2$

**1. Stresses due to dead Weight:**

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

$f_d$ = stress,

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

$D_{ok}$ = outside diameter of skirt,

$t_{sk}$ = thickness of skirt,

$f_d = 204368.38 / (\pi \times 91.6 \times t_{sk}) = 710.1799 / t_{sk}$ $kg/cm^2$

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

$p_w = k \times p_1 \times h_1 \times D_o$

$p_1 =$ 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

$M_w = p_w \times H/2$

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

Z- Modulus of section of skirt cross-section

$p_w = 0.7 \times 189.631 \times 1.6 \times 0.91 = \underline{191.1481}$ kg

$M_w = p_w \times H/2 = 191.1481 \times 7/2 = \underline{669.0184}$ kg-m

Substituting the values we get,

$f_{wb} = \underline{250.4579/t_{sk}}$ kg/cm$^2$

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

Load = C×W

C = seismic coefficient,

W= total weight of column.

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

C=0.08

$f_{sb} = (2/3) \times (0.08 \times 1000 \times 204368.38)/(\pi \times (91.6/2)^2 \times t_{sk} = \underline{29.3278/ t_{sk}}$ kg/cm$^2$

Maximum tensile stress:

$f_{t,\, max} = (710.1799/ t_{sk}) – (250.4549/ t_{sk}) = \underline{(459.725/ t_{sk})}$ kg/cm$^2$

Permissible tensile stress = $\underline{925}$ kg/cm$^2$

Thus, 925 = $(459.725/ t_{sk})$

=> $t_{sk} = 459.725/925 = \underline{0.497}$ cm = $\underline{4.97}$ mm

As per IS 2825-1969, minimum corroded skirt thickness = $\underline{7}$ mm

Thus use a thickness of $\underline{7}$ mm for the skirt.

**Design of skirt bearing plate:**

Assume both circle diameter = skirt diameter + 32.5 = 91+ 32.5 = 123.5 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,

$f_c$ = (204386.38×4)/ (π × (123.5$^2$- 91$^2$)) + (0.7× 189.631× 3 ×42.3$^2$×/(2× π×(123.5$^4$ - 91$^4$)/(32×123.5))

= 264.76 + 2.732

$f_c$ = 267.492 kg/cm$^2$

This is less than the permissible value for concrete.

Maximum bending moment in bearing plate

$M_{max}$ = (0.9351×16.25$^2$/2) = 123.4624 kg-cm

Stress, f = (6×0.9351× 16.25$^2$)/ (2 ×$t_B^2$) = 740.7744/ $t_B^2$

Permissible stress in bending is 1000 kg/cm$^2$

Thus, $t_B^2$ = 740.7744/1000 => $t_B$ = 0.8607 cm = 8.6070 mm

Therefore a bolted chair has to be used.

**Anchor Bolts:**

Minimum weight of Vessel = $W_{min}$ = 1400 kg. ------ (assumed value)

$f_{c,min} = ( W_{min}/A) – (M_w/Z)$

= [(4×1400)/ (π × (123.5$^2$ – 91$^2$))] - (0.7× 189.631× 3 ×42.3$^2$×/ (2× π×(123.5$^4$91$^4$)/(32×123.5))

= 2.557 – 2.732 = - 0.175 kg/cm$^2$

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

Assuming there are 40 bolts,

$P_{bolts} = (0.175/40) \times ((\pi \times (123.5^2 - 91^2))/4) = \underline{11.9770}$ kg

**Trays:**

The trays are standard sieve plates throughout the column. The plates have 2010 holes in Enriching section and 2112 holes in the Stripping section of 5mm diameter arranged on a 15mm triangular pitch. The trays are supported on purloins. The details of the trays are shown in fig 6.3

**Nozzle Design:**

Nozzles are required for compensation where a hole is made in the shell. The following nozzles are required:

**1. Feed Nozzle:**

Liquid Velocity = $V_L = \underline{2}$ m/s

Area of Nozzle = (Mass of liquid in)/ $(\rho_L \times V_L)$

Mass of liquid in = [(molar flow rate) × (molecular weight of liquid)]/3600

= [57.2858 × 87.9016]/3600 = $\underline{1.3988}$ kg/s

Thus, Area of Nozzle = (1.3988)/ (733.80 × 2) = $\underline{9.5455 \times 10^{-4}}$ $m^2$

Now, Area of Nozzle = $\pi \times d_N^2/4 = \underline{9.5455 \times 10^{-4}}$ $m^2$

⇨ $d_N^2 = (4 \times 9.5455 \times 10^{-4}/\pi)$

⇨ $d_N = \underline{0.03486}$ m = $\underline{34.86}$ mm.

t = $\underline{10}$ mm

**2. Liquid Outlet Nozzel:**

Liquid Velocity = $V_L = \underline{2}$ m/s

Area of Nozzle = (Mass of liquid in)/ $(\rho_L \times V_L)$

Mass of liquid in = [(molar flow rate) × (molecular weight of liquid)]/3600

= [113.4164 ×88.1293]/3600 = $\underline{2.7765}$ kg/s

Thus, Area of Nozzle = (2.7765)/ (727.68 × 2) = $\underline{1.9078 \times 10^{-3}}$ $m^2$

Now, Area of Nozzle = $\pi \times d_N^2/4$ = $\underline{1.9078 \times 10^{-3}}$ $m^2$

⇨ $d_N^2 = (4 \times 1.9078 \times 10^{-3}/\pi)$

⇨ $d_N$ = $\underline{0.04931}$ m = $\underline{49.31}$ mm.

t = $\underline{10}$ mm

**3. Vapor Outlet Nozzel:**

Vapor Velocity = $V_G$= $\underline{1.2180}$ m/s

Area of Nozzle = (Mass of liquid in)/ ($\rho_G \times V_G$)

Mass of liquid in = [(molar flow rate) × (molecular weight of vapor)]/3600

= [65.6690 ×86.6048]/3600 = $\underline{1.5798}$ kg/s

Thus, Area of Nozzle = (1.5798)/ (2.9150 × 1.2180) = $\underline{0.4450}$ $m^2$

Now, Area of Nozzle = $\pi \times d_N^2/4$ = $\underline{0.4450}$ $m^2$

⇨ $d_N^2 = (4 \times 0.4450/\pi)$

⇨ $d_N$ = $\underline{0.7527}$ m = $\underline{752.7}$ mm.

t = $\underline{10}$ mm

**4. Reboiler Vapor Outlet:**

Vapor Velocity = $V_G$= $\underline{1.2637}$ m/s

Area of Nozzle = (Mass of liquid in)/ ($\rho_G \times V_G$)

Mass of liquid in = [(molar flow rate) × (molecular weight of vapor)]/3600

= [65.6690 ×88.1293]/3600 = $\underline{1.6076}$ kg/s

Thus, Area of Nozzle = (1.60760)/ (2.6672 × 1.2637) = $\underline{0.4770}$ $m^2$

Now, Area of Nozzle = $\pi \times d_N^2/4$ = $\underline{0.4770}$ $m^2$

⇨ $d_N^2 = (4 \times 0.4770/\pi)$

⇨ $d_N$ = $\underline{0.7793}$ m = $\underline{779.3}$ mm.

t = $\underline{10}$ mm

**5. Reflux Liquid Inlet:**

Liquid Velocity = $V_L$= $\underline{2}$ m/s

Area of Nozzle = (Mass of liquid in)/ ($\rho_L \times V_L$)

Mass of liquid in = [(molar flow rate) × (molecular weight of liquid)]/3600

= [57.2858 ×86.6048]/3600 = $\underline{1.3781}$ kg/s

Thus, Area of Nozzle = (1.3781)/ (750.65 × 2) = $\underline{9.2113 \times 10^{-4}}$ $m^2$

Now, Area of Nozzle = $\pi \times d_N^2/4$ = $\underline{9.2113 \times 10^{-4}}$ $m^2$

⇨ $d_N^2 = (4\times\underline{9.2113 \times 10^{-4}} /\pi)$

⇨ $d_N$ = $\underline{0.0343}$ m = $\underline{34.3}$ mm.

t = $\underline{10}$ mm

All nozzles are provided with a standard compensation pad of $\underline{36}$ mm thickness. This small compensation is sufficient as the design pressure is $\underline{1.1362}$ kg/cm$^2$

## VII. Process Design of Condenser:

The following is the detailed design of the total condenser for the Distillation column. The condenser is operated at the same pressure as that of the column. The vapor from the column is condensed and sent as reflux and product. Any changes in compensation are neglected. The optimization of the condenser is done in several iterative steps. The final trial is presented here. The design methods used here are from Chemical Engineering by Coulson and Richardson, vol.6

5687.25 kg/hr. of Vapor enters the condenser at 114.25 $^0$C. The complete condensation takes place at 108.75 $^0$C. Pressure is 1 atmosphere.

**Cooling Medium:**

Cold water is used as a cooling medium. It is available at 25 $^0$C and is to be heated to 40 $^0$C, i.e., water enters the condenser at 25 $^0$C and it leaves the condenser at 40 $^0$C.

**Tubes choosen:**

(¾)" O.D. 16 BWG, 16 feet length, 1" square pitch.

**Data available:**

Average Molecular weight of Vapor/Feed = (0.7465×86.08) + ((1-0.7465) ×88.15)

$= \underline{86.6048}$ kg/kmol. $= \underline{86.6048}$ g/g-mol.

$\lambda_{Valeraldehyde} = \underline{8040}$ cal/g-mol $= \underline{390.7918}$ kJ/kg.

$\lambda_{Isoamyl\ alcohol} = \underline{10540}$ cal/g-mol $= \underline{500.2764}$ kJ/kg.

$\lambda_{Vapor} = (0.7465 \times 390.7918) + ((1-0.7465) \times 500.2764) = \underline{418.5462}$ kJ/kg.

$C_{p,\ Valeraldehyde}$ (g) $= 3.410 + (1.034 \times 10^{-1} \times T) - (5.033 \times 10^{-5} \times T^2)$, cal/mol.$^0$K

$C_{p,\ Isoamyl\ alcohol}$ (g) $= -2.279 + (1.357 \times 10^{-1} \times T) - (8.323 \times 10^{-5} \times T^2)$, cal/mol.$^0$K

Now, $T_{avg.} = (114.25 + 108.75)/2 = \underline{111.50}$ $^0$C

$C_{p,\ Valeraldehyde}$ (g) $= \underline{35.7272}$ cal/mol.$^0$K $= \underline{1.7366}$ kJ/kg.$^0$K

$C_{p,\ Isoamyl\ alcohol}$ (g) $= \underline{37.6037}$ cal/mol.$^0$K $= \underline{1.7848}$ kJ/kg.$^0$K

$C_{p,\ mix.} = \sum (x_i \times C_{p,\ i})$

$= (0.7465 \times 35.7272) + ((1-0.7465) \times 37.6037)$

$= \underline{36.2029}$ cal/mol.$^0$K

$C_{p,\ mix} = \underline{1.7490}$ kJ/kg.$^0$K.

**1. SHELL SIDE: (VAPOR)**

Feed = 5687.25 kg/hr

Average molecular weight $M_f = \underline{86.6048}$ kg/kmol

Heat Load:

$Q = q_{superheat} + q_{latent\ heat}$

$q_{superheat} = (m \times C_p \times \Delta T)$

$= (5687.25 \times 1.7490 \times (387.40 - 381.90)/3600)$

$q_{superheat} = \underline{15.1968}$ kW

$q_{latent\ heat} = (m \times \lambda)$

$= (5687.25 \times 418.5462/3600)$

$q_{latent\ heat} = \underline{661.2158}$ kJ/s $= \underline{661.2158}$ kW

Since $q_{superheat}$ is small as compared to $q_{latent\ heat}$ and hence neglected.

Thus, $Q \approx q_{latent\ heat} = \underline{661.2158}$ kJ/s $= \underline{661.2158}$ kW

**2. TUBE SIDE: (WATER)**

$Q = (m_w \times C_p \times \Delta T)$

=> $m_w = Q/(C_p \times \Delta T) = (661.2158\times10^3)/(4.187\times10^3\times(313.15-298.15))$ = <u>10.52</u> kg/s

Where $m_w$ is the cooling water flow rate.

**3. LMTD CALCULATIONS:**

Considering **Counter- Current Operation.**

| HOT SIDE (VAPOR) | COLD SIDE (WATER) | TEMPERATURE DIFFERENCE, ΔT |
|---|---|---|
| ↓ 114.25 $^0$C | 40 $^0$C ↑ | 74.25 $^0$C |
| 108.75 $^0$C | 25 $^0$C | 83.75 $^0$C |

$\Delta T_{lm}$ = ((114.25-40)-(108.75-25))/ln ((114.25-40)/ (108.75-25)) = <u>78.9047</u> $^0$C

Now,

$R = (T_1-T_2)/(t_2-t_1)$ = (114.25-108.75)/ (40 – 25) = <u>0.3667</u>

$S = (t_2-t_1)/(T_1-t_1)$ = (40 – 25)/ (114.25-25) = <u>0.1681</u>

Consider 1-2 exchanger.

Now for R= <u>0.3667</u> and S = <u>0.1681</u>,

We have from fig. 10.14a, page 10-27, 6$^{th}$ edition Perry

$F_T$ = <u>0.98</u>

Thus, corrected LMTD = $\Delta T_{lm,\ corrected}$ = 0.98 ×78.9047 = <u>77.7266</u> $^0$C

Let us assume $U_d$ = <u>700</u> W/m$^2$ $^0$K --- (from Table10.10, page10-44, 6$^{th}$ edition Perry)

Now $Q = U\times A\times \Delta T_{lm,\ corrected}$

- ⇨ $A = Q/(U\times \Delta T_{lm,\ corrected})$
- ⇨ A = (661.2158×10$^3$)/ (700× 77.3266)
- ⇨ A = <u>12.4964</u> m$^2$

Thus, trial Area = A = <u>12.4964</u> m$^2$

Now for (¾)” O.D., 16 BWG, 16 feet length, 1" square pitch.

Outer diameter = $d_o$= (¾)” = <u>0.01905</u> m

Inner diameter = $d_i$= 0.62" = <u>0.015748</u> m

Length = L= 16 ft. = <u>4.8768</u> m

Square pitch = $P_t$ = 1" = <u>0.0254</u> m

Flow Cross sectional area = $(\pi\times d_i^2/4) = (\pi\times0.015748^2/4)$ = <u>1.9478×10$^{-4}$</u> m$^2$

Surface area of one tube = $\pi \times 0.01905 \times 4.8768$ = <u>0.2919</u> $m^2$ (ignoring the tube sheet thickness)

Thus, number of tubes = 12.4964/ 0.2919 = <u>42.8119</u> ≈ <u>43</u>

From the tube Count Table11.3, page11-14, 6th edition Perry)

For TEMA (P) or (S) Type and 2 passes we have the nearest tube count = $N_T$ = <u>48</u>

Shell internal diameter = $D_s$ = <u>10”</u> = <u>0.254</u> m

Thus, corrected Area = 48×0.2919 = <u>14.0112</u> $m^2$

Thus, corrected $U_d$ = $(661.2158\times10^3)/(14.0112\times 77.3266)$ = <u>624.4622</u> $W/m^2\,^0K$

**Tube Bundle Diameter, ($D_b$):**

$D_b = d_o \times (N_T/k_1)^{(1/n1)}$ ---- (eq$^n$ 12.3b, page 577, Coulson and Richardson Vol.6)

Where $N_T$ = number of tubes,

$D_b$ = tube bundle diameter, mm

$d_o$ = tube outside diameter, mm

Now for 1” square pitch and 2 passes,

We have from Table 12.4, page 577, Coulson and Richardson Vol.6

$k_1$= <u>0.156</u>

$n_1$= <u>2.291</u>

Thus, $D_b = 19.05\times (48/0.156)^{(1/2.291)}$ = <u>232.2387</u> mm

Now number of tubes in central row = $N_r = D_b/P_t$ = 232.2387/25.4 = <u>9.1422</u> ≈ <u>9</u>

**4. SHELL SIDE HEAT TRANSFER COEFFICIENT:**

Estimate the wall temperature $T_w$. Assuming a condensing coefficient of <u>1400</u> $W/m^2\,^0K$

Mean Temperatures:

Shell side: $T_{avg.}$ = (114.25 + 108.75)/2 = <u>111.5</u> $^0C$

Tube side: $T_{avg.}$ = (25 + 40)/2 = <u>32.5</u> $^0C$

Thus,

$(111.5 - T_w)\times1400 = 624.4622\times(111.5 – 32.5)$

=> $(111.5 - T_w) = 624.4622\times(111.5 – 32.5)/1400$

=> $T_w$ = 111.5- 35.2375 = <u>76.2625</u> $^0C$

Mean temperature of Condensate = (111.5 +76.2625)/2 = <u>93.8813</u> $^0C$

Physical Properties at 93.8813 $^0$C

$\rho_L$ = 746.50 kg/m$^3$

$\mu_L$ = $0.3227\times10^{-3}$ N.s/m$^2$

g = 9.81 m/s$^2$

$k_L$= 0.149 W/m $^0$K

Vapor density at mean vapor temperature:

$\rho_v = (86.6048/22.4) \times (273.15/ (93.8813 + 273.15)) \times(1/1) = 2.8880$ kg/m$^3$

The shell side film transfer coefficient is calculated by using a modified Nusselt's equation:

Mass flow rate per unit length ($\Gamma_h$) = $W_c$/ ($L\times N_t$)

= 5687.25/ (3600×4.8768×48)

= $6.7488\times10^{-3}$ kg/ (m.s)

$N_r' = (2/3) \times N_r = (2/3) \times 9 = 6$

$h_c = 0.95\times k_L\times [(\rho_L\times (\rho_L- \rho_v) \times g)/(\mu_L\times\Gamma_h)]^{(1/3)} \times(N_r')^{(-1/6)}$

Where $h_c$ = mean coefficient for a tube bundle, W/m$^2$ $^0$C

$k_L$ = condensate thermal conductivity, W/m $^0$C

$\rho_L$ = condensate density, kg/m$^3$

$\rho_v$ = vapor density, kg/m$^3$

$\mu_L$ = condensate viscosity, Ns/m$^2$

g = acceleration due gravity, m/s$^2$

$\Gamma_h$ = the tube loading, the condensate flow per unit length of tube, kg/m.s

$W_c$ = total condensate flow,

$N_t$ = number of tubes in bundle,

$N_r'$ = average number of tubes in a vertical tube row

$N_r'$ can be taken as (2/3) of the number of tubes in central row.

Thus,

$h_c=0.95\times0.149\times[(746.50\times(746.50-2.8880)\times9.81)/(0.3227\times10^{-3}\times6.7488\times10^{-3})]^{(1/3)}\times(6)^{(-1/6)}$

⇨ $h_c$ = 1425.2506 W/m$^2$ $^0$K

Which is close enough to the assumed value of 1400 W/m$^2$ $^0$K, so there is no need of correction in the assumed/calculated value of $T_w$ = 76.2625 $^0$C

## 5. TUBE SIDE HEAT TRANSFER COEFFICIENT:

Tube cross-sectional area = $(\pi\times0.015748^2/4)\times(48/2) = \underline{4.6747\times10^{-3}}\ m^2$

$G_t = 10.77/(4.6747\times10^{-3}) = \underline{2303.8916}\ kg/m^2s$

$T_{avg.} = (25 + 40)/2 = \underline{32.5}\ ^0C$

Properties of water at 32.5 $^0C$

$\rho_L = \underline{994.865}\ kg/m^3$

$\mu_L = \underline{0.83\times10^{-3}}\ N.s/m^2$

$k_L = \underline{0.63}\ W/m\ ^0K$

$C_p = \underline{4.186\times10^3}\ J/kg^0K$

Now $N_{Re} = R_e = (d_i\times u\times\rho)/\mu = (G_t\times d_i)/\mu = (2303.8916\times0.015748)/(0.83\times10^{-3})$

$= \underline{43712.8734}$

$Pr = (\mu\times C_p)/k = (0.83\times10^{-3}\times 4.186\times10^3)/0.63 = \underline{5.5149}$

$(h_i\times d_i)/k = 0.023\times R_e^{0.8}\times Pr^{0.3}$

⇨ $h_i = 0.023\times R_e^{0.8}\times Pr^{0.3}\times k/d_i$

⇨ $h_i = 0.023\times(43712.8734)^{0.8}\times(5.5149)^{0.3}\times0.63/0.015748$

⇨ $h_i = \underline{7921.2142}\ W/m^2\ ^0K$

### 5.1 FOULING FACTORS:

As neither fluid is heavily fouling, use a fouling factor of $\underline{4000}$ $W/m^2\ ^0K$ for each side and assume $k_w = \underline{50}\ W/m.^0K$

$(1/U_o) = (1/h_o) + (1/h_{od}) + (d_o\times\ln(d_o/d_i)/(2\times k_w)) + [(d_o/d_i)\times(1/h_{id})] + [(d_o/d_i)\times(1/h_i)]$

Where $U_o$ =the overall coefficient based on the outside area, $W/m^2\ ^0C$

$h_o$ = outside fluid film coefficient, $W/m^2\ ^0C$

$h_i$ = inside fluid film coefficient, $W/m^2\ ^0C$

$h_{od}$ = outside dirt coefficient (fouling factor), $W/m^2\ ^0C$

$h_{id}$ = inside dirt coefficient (fouling factor), $W/m^2\ ^0C$

$k_w$ = thermal conductivity of the tube wall, $W/m.^0C$

$d_o$ = tube outside diameter, m

$d_i$ = tube inside diameter, m

$(1/U_o) = (1/1425.2506) + (1/4000) + (0.01905\times\ln(0.75/0.62)/(2\times50))$

$+ [(0.75/0.62)\times(1/4000)] + [(0.75/0.62)\times(1/7921.2142)]$

⇨ $(1/U_o) = 1.4430 \times 10^{-3}$ $m^2\ {}^0C/W$

⇨ $U_o$ = <u>693.0007</u> ≈ <u>693</u> $W/m^2\ {}^0C$

Which is close enough to the corrected value of $U_d$ = <u>624.4622</u> $W/m^2\ {}^0C$ and hence acceptable.

**6. PRESSURE DROP CALCULATIONS:**

**a) Pressure drop in tube side:**

Calculation of $u_t$:

Tube cross-sectional area == $(\pi \times 0.015748^2/4) \times (48/2)$ = <u>$4.6747\times10^{-3}$</u> $m^2$

At 32.5 $^0C$, we have

$\rho_w$ = <u>994.865</u> $kg/m^3$

Thus tube velocity ($u_t$):

$u_t = 10.77/(4.6747\times10^{-3}\times994.865)$ = <u>2.3158</u> m/s --- (< 4 m/s, max. limit)

$R_e = (d_i \times u_t \times \rho)/\mu = (0.015748\times2.3158\times994.865)/ (0.83 \times10^{-3})$ = <u>43713.1915</u>

$f = 0.079 \times (R_e)^{(-1/4)}$

$f = 0.079 \times (43713.1915)^{(-1/4)}$ = <u>$5.4636\times10^{-3}$</u>

Now,

$\Delta P = (4\times f\times L\times u_t^2)/ (2\times g\times d_i)] \times [\rho\times g]$

$= (4\times5.4636\times10^{-3}\times4.8768\times2.3158^2)/ (2\times9.81\times0.015748)] \times [994.865\times9.81]$

$\Delta P$ = <u>18054.4675</u> $N/m^2$ ≈ <u>18.0545</u> kPa.

$\Delta P_E = 2.5\times (\rho\times u_t^2/2)$

$\Delta P_E = 2.5\times (994.865\times2.3158^2/2)$

$\Delta P_E$ = <u>6669.2388</u> $N/m^2$ ≈ <u>6.6692</u> kPa

$\Delta P_T$ = (number of passes) × $(\Delta P + \Delta P_E)$

$\Delta P_T = 2 \times (18.0545 + 6.6692)$ = <u>49.4474</u> kPa ------- (<70 kPa)

Since the pressure drop on the tube side is less than 70 kPa and hence the calculations of pressure drop on the tube side are acceptable.

**b) Pressure drop in shell side:**

Use a pull-through floating head, hence no need of close clearance.

Select baffle spacing ($l_b$) = shell diameter, baffles 45% cut

From fig. 12.10(bundle diameter v/s (shell diameter – bundle diameter), page 577, Coulson and Richardson Vol.6

Clearance = 89.5 maintenance

Thus shell i.d. = 254 + 89.5 = 343.5 mm

Cross flow area:

$A_s = (P_t - d_o) \times D_s \times l_b / P_t$

Where $P_t$ = tube pitch

$D_s$ = shell i.d., m

$A_s = (25.4-19.05) \times 343.5\times10^{-3}\times343.5\times10^{-3} /25.4 = \underline{0.0295}\ m^2$

Mass flow rate based on inlet conditions,

$G_s = 5687.25/ (3600 \times0.0295) = \underline{53.5523}\ kg/s.m^2$

Equivalent diameter:

$d_{eq.} = (1.27/d_o) \times (P_t^2 - (0.785\times d_o^2))$

$d_{eq.} = (1.27/0.01905) \times (0.0254^2 - (0.785\times0.01905^2))$

$d_{eq.} = \underline{0.024}\ m$

Vapor viscosity = $\mu_v$ = $\underline{0.0027}\ mNs/m^2$

$R_e = (G_s\times d_{eq})/\mu_v = (53.5523\times0.024)/ (0.0027\times10^{-3}) = \underline{476020.45}$

From fig. 12.30, page 602, Coulson and Richardson Vol.6

Friction factor = $\underline{1.75 \times10^{-2}}$

$u_s = G_s/\rho_v = 53.5523/2.8880 = \underline{18.5430}\ m/s$

Taking the pressure drop as 50% of that calculated using the inlet flow; neglect viscosity correction.

Pressure drop:

$\Delta P_S = 0.5\times [8\times j_f\times (D_s/d_{eq}) \times (L/l_b) \times (\rho\times u_S^2/2)]$

$\Delta P_S = 0.5\times [8\times1.75\times10^{-2}\times (343.5/24) \times (4.8768/0.3435) \times (2.8880\times18.5430^2/2)]$

$\Delta P_S = \underline{7062.3451}\ N/m^2 = \underline{7.0624}\ kPa$ ----- (<14 kPa)

The maximum allowable pressure drop on the shell side for atmospheric operation is 14 kPa. Hence, the condenser pressure drop is within the limits.

**Summary of Condenser design**

Shell outer diameter = 254 mm

Bundle diameter = 232.2387 maintenance

Number of tubes = 48

Tube OD = (3/4)”

Pitch = 1”square pitch

Tube length = 16 ft

Shell side pressure drop = 7.0624 kPa

Tube side pressure drop = 49.4474 kPa

Condenser type: TEMA Pull-Through Floating Head 1-2 Heat Exchanger

## VIII. Mechanical design of Condenser

**(a) Shell side details**

Material of construction: Carbon steel

Permissible stress for carbon steel: 95 $N/mm^2$

Fluid: vapor mixture of valeraldehyde and Isoamyl alcohol

Working pressure: 0.101325 $N/mm^2$

Design pressure: 0.1115 $N/mm^2$

Inlet temperature: 114.25 $^0C$

Out let temperature: 108.75 $^0C$

Design temperature: 137.1 $^0C$

Number of shell passes: one

Number of shells: one

**(b) Tube side details**

Material of construction: Stainless Steel

IS- grade 10

Permissible stress for carbon steel: 10.06 $kg/mm^2$

Number tubes: 48

Number of passes: 2

Number of tubes per pass: 24

Outside diameter: 19.05 mm

Inside diameter: 15.75 mm

Length of each tube: 4.8768 m

Pitch square: 1 inch

Working pressure: 0.101325 $N/mm^2$

Design pressure: 0.1115 $N/mm^2$

Inlet temperature: 25 $^0C$

Outlet temperature: 40 $^0C$

**SHELL SIDE:**

**(1) Shell thickness:**

$$t_s = (P_d \times D_s) / ((2 \times f \times J) - P_d)$$

Where $P_d$ = design pressure

$D_s$ = shell diameter

f = allowable tensile stress

J = joint factor

$t_s = (0.1115 \times 254) / ((2 \times 95 \times 0.85) - 0.1115)$

= <u>0.176</u> mm

Minimum thickness of shell of 254 mm diameter, must be= <u>6.3</u> mm

------- (IS-4503, Table 4)

Including corrosion allowance of <u>3</u> mm, take shell thickness = <u>9.3</u> mm

**(2) Nozzles:**

Inlet and outlet diameter = <u>100</u> mm

Vent = <u>50</u> mm

Drain = <u>50</u> mm

Opening for relief valve = <u>75</u> mm

Material of construction: carbon steel

Permissible stress for Carbon steel = <u>950</u> $kg/cm^2$

Diameter = <u>100</u> mm = <u>10</u> cm

$t_n = (P_d \times D) / ((2 \times f \times J) - P_d)$

Let J= 1, seamless pipe

$t_n = (1.1362 \times 10) / ((2 \times 950 \times 1) - 1.1362)$

$t_n = \underline{5.9836 \times 10^{-3}}$ cm = $\underline{5.9836 \times 10^{-2}}$ mm

Including a corrosion allowance use thickness of <u>4</u> mm

**(3) Head thickness.**

Shallow dished and torispherical

$R_{(Crown\ radius)}$ = <u>254</u> mm

$R_{(knuckle\ radius)}$ = 6% $R_{(Crown\ radius)}$ = 0.06×254 = <u>15.24</u> mm

W= ¼ × $(3 + (R_c/R_k)^{0.5})$ = ¼ × $(3 + (910/540)^{0.5})$ = <u>1.7706</u> mm

$$t_h = (P \times Rc \times W) / (2 \times f \times J)$$

$= (0.1115\times254\times1.7706)/ (2\times95\times1)$

$= \underline{0.264}$ mm

Minimum shell thickness should be 10 mm including corrosion allowance.

**(4) Transverse Baffles**

Baffle spacing, $l_b = D_s$

$= \underline{254}$ mm

Number of baffles,

$N_b + 1 = L/l_b = 4.8768/0.254 = \underline{19.2} \approx \underline{19}$

$N_b = \underline{18}$

Use baffles of thickness= $t_b = \underline{6}$ mm

**(5) Tie Rods and spacers**

For shell diameter, 200-400mm

Diameter of Rod = 8 mm

Number of rods= 4

**(6) Flanges**

Design pressure= 0.1115 N/mm$^2$

Flange material IS: 2004-1962, class 2

Bolting steel: 5% Cr-Mo steel

Gasket material: Asbestos composition

Shell thickness: 9.3 mm=$g_o$

Outside diameter of shell: 254 mm

Allowable stress of flange material: 100 MN/m$^2$

Allowable stress of bolting material: 138 MN/m$^2$

**Determination of gasket width:**

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

Assume a gasket thickness of 1.6 mm

y = minimum design yield seating stress = 25.5 MN/m$^2$

m = gasket factor = 2.75

$d_O/d_i = [(25.5-(0.1115\times2.75))/(25.5-(0.1115\times (2.75+1)))]^{0.5}$

$d_O/d_i$ = $\underline{1.0022}$

let $d_i$ of gasket equal $\underline{254}$ mm

$d_o$= 1.0022×$d_i$ = 1.002×0.254

$d_o$= $\underline{0.2546}$ m

Minimum gasket width = N = 0.801(1.002-1)/2 = $\underline{0.00088}$ m

Taking gasket width of $\underline{0.010}$ m

i.e., N= $\underline{0.010}$ m

$d_o$= $\underline{0.2546}$ m

Basic gasket seating width, $b_o$= $\underline{6}$ mm

Diameter of location of gasket load reaction is

$G=d_i + N$

$=0.254+0.010$

$= \underline{0.264}$ m

**Estimation of Bolt loads:**

Load due to design pressure

$H= (\pi\times G^2\times P)/4$

$= (\pi\times 0.264^2\times 0.1115)/4 = \underline{6.1034\times 10^{-3}}$ MN

Load to keep joint tight under operation

$H_p=\pi\times G\times (2b)\times m\times p$

$= \pi\times 0.264\times (2\times 0.00612)\times 2.75\times 0.1115$

$= \underline{3.1127\times 10^{-3}}$ MN

Total operating load

$W_o = H+H_p$

$= (6.1034\times 10^{-3}) + (3.1127\times 10^{-3})$

$= \underline{9.2161\times 10^{-3}}$ MN

Load to seat gasket under bolting condition

$W_g = \pi\times G\times b\times y$

$= \pi\times 0.2640\times 0.00612\times 25.5$

= 0.1294 MN

$W_g > W_o$, => Controlling load= 0.1294 MN

**Calculation of optimum bolting area**

$A_m = A_o = W_o/S_o$

$S_o$ = allowable stress for bolting material at design pressure.

= $(9.2161\times10^{-3})/138$

= $6.6783\times10^{-05}$ $m^2$

Calculation of optimum bolt size

Bolt size, M18 X 2

Actual 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

$C = n\times B_s/\pi$ = 0.9243

C =ID + 2(1.415g + R)

= 0.254 +2[(1.415×0.008) +0.027]

= 0.3306 m

Choose C = 0.33 m

Bolt circle diameter = 0.33 m

Calculation of flange outside diameter

A=C+ bolt diameter +0.02

=0.33+0.018+0.02

= 0.368 m

Let A= 0.37 m

Check for gasket width

$(A_b S_G) / (\pi\times G\times N) = (2.5447\times10^{-4}\times138) / (\pi\times0.264\times0.010)$ = 4.2341 < 2y,

where $S_G$ is the Allowable stress for the gasket material

Hence condition satisfied.

**Flange moment computation**

**(a) For operating condition**

$W_o = W_1 + W_2 + W_3$

$W_1 = (\pi \times B^2 \times P)/4$

$= (\pi \times 0.254^2 \times 0.1115)/4$

$= \underline{5.6498 \times 10^{-3}}$ MN

$W_2 = H - W1$

$= (6.1034 \times 10^{-3}) - (5.6498 \times 10^{-3})$

$= \underline{4.5360 \times 10^{-4}}$ MN

$W_3 = W_o - H = H_p$

$= \underline{3.1127 \times 10^{-3}}$ MN

$M_o$=Total flange moment

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

$a_1 = (C-B)/2 = (0.33-0.254)/2$

$a_1 = \underline{0.038}$ m

$a_3 = (C-G)/2 = (0.33-0.264)/2$

$a_3 = \underline{0.033}$ m

$a_2 = (a_1 + a_3)/2 = (0.038+0.033)/2 = \underline{0.0355}$ m

$M_o = (0.038 \times 5.6498 \times 10^{-3}) + (0.0355 \times 4.46 \times 10^{-5}) + (0.033 \times 3.0066 \times 10^{-3})$

$M_o = \underline{3.1398 \times 10^{-4}}$ MN-m

**(b) For bolting condition**

$M_g = W \times a_3$

$W = (A_m + A_b) * S_g/2$

$A_b = 44 \times 2.5447 \times 10^{-4} = \underline{11.1967 \times 10^{-3}}\ m^2$

$A_m = \underline{6.3051 \times 10^{-5}}\ m^2$

$W = ((6.3051 \times 10^{-5}) + (11.1967 \times 10^{-3})) \times 138/2$

$W = \underline{0.7769}$ MN

$M_g = 0.7769 \times 0.0325$

$= \underline{0.0253}$ MN-m

$M_g > M_o$, hence moment under operating condition $M_g$ is controlling, $M_g = M$

**Calculation of flange thickness**

$t^2 = M\ C_F\ Y / (B\ S_F)$, $S_F$ is the allowable stress for the flange material

K =A/B = 0.37/0.254 = <u>1.4567</u>

For K = 1.15, Y = 14

Assuming $C_F$ =1

$t^2 = 0.0253\times1\times14/ (0.254\times100)$

t= <u>0.1181</u> m= <u>118.1</u> mm

Actual bolt spacing, $B_S = \pi\times C/n = (\pi\times0.33)/ 44 =$ <u>0.0236</u> m

**<u>Bolt Pitch Correction Factor</u>**

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

$= [0.0236/ ((2\times0.018)+0.1181)]^{1/2}$

= <u>0.3913</u>

$\sqrt{C_F}$ = <u>0.6256</u>

Actual flange thickness = $\sqrt{C_F}\times t$

= 0.6256×0.1181= <u>0.0739</u> m = <u>73.9</u> mm

Standard flange thickness available is <u>75</u> mm

**TUBE SIDE:**

**(1) Thickness of tube:**

$t_t = (P_d\times D_s)/ ((2\times f\times J) + P_d)$

$t_t = (0.1115\times19.05)/ ((2\times98.6886\times1) + 0.1115)$

$t_t$ = <u>0.01076</u> mm

Since the tube is a stainless steel tube there is no need of corrosion allowance, take the thickness of tube as <u>3</u> mm

**(2) Tube sheet thickness:**

$t_{ts} = F\times G\times(0.25\times P/f)^{0.5}$

$t_{ts} = 1\times0.265\times(0.25\times0.1115/98.6886)^{0.5}$

$t_{ts}$ = <u>$4.4537\times10^{-3}$</u> m

$t_{ts}$ = <u>4.4537</u> mm

Including the corrosion allowance take $t_{ts}$ = <u>8</u> mm

**(3) Channel and channel Cover:**

Since the pressure on the tube side is high and the velocity is well within the range, it is proposed to make the channel and cover out of a single plate.

$t_h = G_c\sqrt{(KP/f)}$

$= 0.265\times \sqrt{(0.3\times0.1115/98.6886)}$

$= \underline{4.8788\times10^{-3}}$ m ≈ $\underline{5}$ mm

$t_h = \underline{8}$ mm including corrosion allowance

**(4) Nozzles:**

Inlet and Outlet diameter = $\underline{100}$ mm

Thickness of nozzle,

$t_n = (P_d\times D)/ ((2\times f\times J)-P_d)$

Let J= 1, seamless pipe

$t_n = (5.088\times100)/ ((2\times93.175\times0.85)-5.088)$

$t_n = \underline{0.33186}$ cm = $\underline{3.3186}$ mm

Including a corrosion allowance use thickness of $\underline{8}$ mm.

Considering the size of nozzle and the pressure rating it is necessary to provide a reinforcing pad on the channel cover.

Area required to compensate for each nozzle is = $A= d\times t_h = 100 \times 8 = \underline{800}$ $mm^2$

Compensation will be available from the additional thickness of channel cover and nozzle. Hence it is proposed to use a $\underline{10}$ mm thick pad.

## Saddle support

Material: low carbon steel

Total length of shell: $\underline{5.3848}$ m

Diameter of shell: $\underline{254}$ mm

Knuckle radius: $\underline{15.24}$ mm

Shallow dished and torispherical head

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

$= \sqrt{(254\times15.24/2)}$

$= \underline{43.9941}$ mm

Weight of the shell and its contents = W = 11934 kg

R=D/2= 254/2 = 127 mm

Distance of saddle center line from shell end = A = 0.5×R= 0.5×127 = 63.5 mm

**Longitudinal Bending Moment**

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

$Q = W/2(L+4H_d/3)$

$= 11934\times (5.3848+ (4\times0.0439941/3))/2$

$=$ 32505.6063 kg-m

$M_1=32505.6063\times0.0635[1-(1-0.0635/5.3848+(0.127^2-0.0439931^2)/(2\times5.3848\times0.0635))/(1+4\times0.0439931/ (3\times5.3848))]$

$=$ 864.104 kg-m

Bending moment at center of the span

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

$M_2 =$ 71645.87 kg-m

**Stresses in shell at the saddle**

(a) At the topmost fiber of the cross section

$f_1 =M_1/(k_1\pi R^2 t)$ $\qquad k_1=k_2=1$

$=864.104/ (3.14\times0.127^2\times0.008)$

$=$ 213.1664 kg/cm$^2$

the stresses are well within the permissible values.

(b) Stress in the shell at mid point

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

$=$ 537.1579 kg/cm$^2$

(c) Axial stress in the shell due to internal pressure

$f_p= PD/4t$

$= 10.06\times254/4\times10$

$= \underline{63.8810}$ kg/cm$^2$

$f_2 + f_p = 537.1579 + 63.8810 = \underline{601.0389}$ kg/cm$^2$

The sum $f_2$ and $f_p$ is well within the permissible values.