6.1. Distillation design:

6.1.1. Introduction:

Distillation is the most common class of separation processes and properly of the better-understand unit operation that uses the difference in relative volatilities, or differences in boiling of the component to be separated, it is the most widely used method of separation in the process industries.

-Types of distillation column:

1- Single flash vaporization.
2- Packed towers.
3- Plates towers.
   a) Bubble cap towers.
   b) Sieve plates.
   c) Valve plates towers.

-Sieve trays: Sieve trays offer several advantage over bubble-cap trays, and their simpler and cheaper construction has led to their increasing use. The general form of the flow on a sieve tray is typical of a cross flow system with perforation in the tray taking the place of the more complex bubble caps. The key differences in operation between these two types of tray should be noted. With the sieve tray the vapor passes vertically through the holes into the liquid on the tray, where as with the bubble cap the vapor issues in an approximately horizontal direction from the slots. With the sieve plate the vapor velocity through the perforation must be greater than a certain minimum value in order to prevent the weeping of the liquid stream down through the holes. At the other extreme, a very high vapor velocity leads to excessive entrainment and loss off tray efficiency.

6.1.2. Collect the data of fluid to be distilled and distilled fluids:

-Feed stream:
At 403° K, 2000 KPa.

Table (6.1) feed stream composition.

<table>
<thead>
<tr>
<th>Component</th>
<th>Mole flow (kmol/h)</th>
<th>Mole%</th>
<th>Mass flow (kg/h)</th>
<th>Wt%</th>
</tr>
</thead>
<tbody>
<tr>
<td>methanol</td>
<td>2516.10</td>
<td>0.217</td>
<td>80615.844</td>
<td>0.125</td>
</tr>
<tr>
<td>isobutylene</td>
<td>428.05</td>
<td>0.037</td>
<td>24017.8855</td>
<td>0.037</td>
</tr>
<tr>
<td>1-butene</td>
<td>1817.511622</td>
<td>0.157</td>
<td>101977.3431</td>
<td>0.158</td>
</tr>
<tr>
<td>2-butene</td>
<td>5172.917692</td>
<td>0.446</td>
<td>290236.8929</td>
<td>0.451</td>
</tr>
<tr>
<td>MTBE</td>
<td>1660.00</td>
<td>0.143</td>
<td>146329</td>
<td>0.227</td>
</tr>
<tr>
<td>water</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Total</td>
<td>11594.58</td>
<td>1</td>
<td>643176.9655</td>
<td>1</td>
</tr>
</tbody>
</table>

-Top product stream:

At 400° K, 1900KPa.

Table (6.2) top stream composition

<table>
<thead>
<tr>
<th>Component</th>
<th>Mole flow (kmol/h)</th>
<th>Mole%</th>
<th>Mass flow (kg/h)</th>
<th>Wt%</th>
</tr>
</thead>
<tbody>
<tr>
<td>methanol</td>
<td>2428.7308</td>
<td>0.246</td>
<td>77816.57994</td>
<td>0.157</td>
</tr>
<tr>
<td>isobutylene</td>
<td>428.0505</td>
<td>0.043</td>
<td>24017.914</td>
<td>0.049</td>
</tr>
<tr>
<td>1-butene</td>
<td>1817.512</td>
<td>0.185</td>
<td>101975.46</td>
<td>0.206</td>
</tr>
<tr>
<td>2-butene</td>
<td>5172.912</td>
<td>0.525</td>
<td>290236.83</td>
<td>0.587</td>
</tr>
<tr>
<td>MTBEs</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>water</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Total</td>
<td>9847.236</td>
<td>1</td>
<td>494046.06</td>
<td>1</td>
</tr>
</tbody>
</table>

-Bottom product stream:

At 440° K, 1925.175 KPa

Table (6.3) bottom stream composition

<table>
<thead>
<tr>
<th>Component</th>
<th>Mole flow (kmol/h)</th>
<th>Mole%</th>
<th>Mass flow (kg/h)</th>
<th>Wt%</th>
</tr>
</thead>
<tbody>
<tr>
<td>methanol</td>
<td>87.36842105</td>
<td>0.05</td>
<td>2799.284211</td>
<td>0.018</td>
</tr>
<tr>
<td>isobutylene</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1-butene</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2-butene</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>MTBE</td>
<td>1660</td>
<td>0.95</td>
<td>146329</td>
<td>0.981</td>
</tr>
<tr>
<td>water</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Total</td>
<td>1747.368421</td>
<td>1</td>
<td>149128.2842</td>
<td>1</td>
</tr>
</tbody>
</table>

-36-
Relative volatility:

Table (6.4) average relative volatility of composition.

<table>
<thead>
<tr>
<th>Component</th>
<th>$\alpha_{feed}$</th>
<th>$\alpha_{top}$</th>
<th>$\alpha_{bottom}$</th>
<th>$A_{av}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>methanol</td>
<td>1.186110097</td>
<td>1.162297499</td>
<td>1.448866438</td>
<td>1.265758</td>
</tr>
<tr>
<td>isobutylene</td>
<td>4.214615978</td>
<td>4.270349142</td>
<td>3.743897719</td>
<td>4.076288</td>
</tr>
<tr>
<td>1-butene</td>
<td>4.281515808</td>
<td>4.345063797</td>
<td>3.73236071</td>
<td>4.119647</td>
</tr>
<tr>
<td>2-butene</td>
<td>3.479708054</td>
<td>3.515657126</td>
<td>3.194453855</td>
<td>3.396606</td>
</tr>
<tr>
<td>MTBE</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>water</td>
<td>0.381770611</td>
<td>0.369823631</td>
<td>0.51937441</td>
<td>0.423656</td>
</tr>
</tbody>
</table>

6.1.3. Heavy and light key:

- Heavy key: MTBE
- Light key: methanol.

6.1.4. Type of tray:

Sieve tray.

6.1.5. Determination of minimum reflux ratio:

$$\sum \frac{\alpha x}{\alpha - \Theta} = R_m + 1$$  \hspace{2cm} (1)

$\alpha$ = average Relative volatility of any component.
$X$ = mole faction of component in Distillate.
$\Theta$ = Constant.
$R_m$ = Minimum reflux ratio.

$$\sum \frac{\alpha z_f}{\alpha - \Theta} = 1 - q$$ \hspace{2cm} (2)

Where:

- $Z_f$ = mole faction of component in feed stream.
- $q$ = feed quality
  - $q = \frac{H_G - H_F}{H_G - H_L}$

Where:

- $H_G$ = Enthalpy of gas at the feed dew point (KJ/Kmol)
HL=Enthalpy of liquid at the feed bubble point (KJ/Kmol)
HF=Enthalpy of feed at 403 °K.

\[ q = \frac{1.91827-1.4672}{1.91827-1.67614} = 1.86 \]

Substitute in equation (2) to find(∅)

\[ \sum \frac{\alpha zf}{\alpha-\emptyset} = 1-1.86 \]
\[ \sum \frac{\alpha zf}{\alpha-\emptyset} = -0.86 \]
\[ \frac{1.265758 \times 0.217007}{1.265758 - \emptyset} + \frac{4.076288 \times 0.036918}{4.076288 - \emptyset} + \frac{4.119647 \times 0.156755}{4.119647 - \emptyset} + \frac{3.396606 \times 0.44615}{3.966606 - \emptyset} + \frac{1 \times 0.14317}{1 - \emptyset} + \frac{423656 \times 0}{0.423656 - \emptyset} = 0 \]

Solving ∅ By try & error:
\[ ∅ = 1.047365 \]

Substitute in equation (1) to find Rm:

\[ \frac{1.265758 \times 24664163}{1.265758 - \emptyset} + \frac{4.076288 \times 0.04346918}{4.076288 - \emptyset} + \frac{4.119647 \times 1.84571192}{4.119647 - \emptyset} + \frac{3.396606 \times 5.25318007}{3.966606 - \emptyset} + \frac{1 \times 0}{1 - \emptyset} + \frac{423656 \times 0}{0.423656 - \emptyset} = Rm + 1 \]

Rm = 1.494995

6.1.6. Calculation of the actual ratio(R)

The rule of thumb is:
\[ R = (1.2 \text{ ------ } 1.5) R_{\text{min}} \]

R = 1.2Rm = 1.2 \times 1.5 = 1.8

6.1.7. Calculation of the minimum number of theoretical stages:

\[ N_{\text{min}} = \frac{\ln \left( \frac{X_{lk}}{X_{hk}} \right)}{\ln \alpha_{lk}} \times \frac{X_{hk}}{X_{lk}} R \]

Where:
\[ X_{lk} = \text{mole fraction of light key.} \]
\[ X_{hk} = \text{mole fraction of heavy key.} \]
\[ \alpha_{lk} = \text{average relative volatility of light key.} \]
Nmin = 26 stages
6.1.8. Calculation of the number of theoretical stages:

\[ N - N_{\text{min}} \frac{R - R_{\text{min}}}{N + 1} = 0.75 \left[ 1 - \left( \frac{R - R_{\text{min}}}{R + 1} \right)^{0.566} \right] \]

\[ \frac{R - R_{\text{min}}}{R + 1} = 1.8 - 1.5 \]

From Gilland relation.

\[ \frac{N - N_{\text{min}}}{N + 1} = 0.54 \]

\[ N = 57.695 \text{ stages} \]

6.1.9. Calculation of the column efficiency (E₀):

\[ E_0 = 0.5278 - 0.27511 \log(\alpha_{lk} \mu F) + 0.04493(\log(\alpha_{lk} \mu F))^2 \]

\[ \mu F = 0.2161 \]

\[ E_0 = 69.29\% \]

6.1.10. Calculation of the number of actual stages (Na):

\[ Na = \frac{N}{E_0} = \frac{57.695}{0.6929} = 83.265 \text{ stages} \]

6.1.11. Calculation of the height of the column (Ht):

\[ Ht = N \times C + \frac{(N - 1) \times C}{10} + 0.2 \times Ht \]

C: tray spacing = 0.609 (so as to ensue accessibility for cleaning)

\[ 0.8Ht = 84 \times 0.3 + \frac{(84 - 1) \times 0.3}{10} = 27.69 \]

\[ Ht = 34.6 \text{ m} \]

6.1.12. Determination of the feed plate location (m):

\[ \frac{n}{m} = \left[ \left( \frac{zhk}{zlk} \right) f \times \left( \frac{x_{lk}}{x_{hk}} \right)^2 \times \left( \frac{B}{D} \right) \right]^{0.206} \]

\[ D = 9847.2118 \text{ Kmol/h} \]

\[ B = 1747.368 \text{ Kmol/h} \]

\[ \frac{n}{m} = \left[ \left( \frac{0.14317034}{0.217006616} \right) f \times \left( \frac{0.2396416 \times 0.007}{9847.2118} \right)^2 \right]^{0.206} = 2.7561 \]

\[ \frac{N}{1 + \frac{B}{m}} = \frac{84}{1 + 2.7561} = 22.36 \text{ stages} \approx 22 \]

\[ m = 22 \text{ stage} \]
the feed enter the column at tray no 22 from the Bottom.

6.1.13. Calculation of the tower diameter(D):

The following areas terms are used in the plate design procedure:
- \( A_t = \) Total column cross-sectional area,
- \( A_d = \) cross-sectional area of down comer,
- \( A_n = \) Net area available for vapor-liquid disengement, normally equal to \( A_c - A_d \) for a single pass plate,
- \( A_a = \) Active or bubbling area, equal to \( A_c - 2A_d \) for single-pass plates,
- \( A_o = \) Hole area, the total area of all the active holes,
- \( A_p = \) perforated area (including blanked areas),
- \( A_{ap} = \) The clearance area under the down comer apron.

- Top diameter calculation:

\[
U_F = K \frac{\rho_L - \rho_V}{\rho_V}
\]

Where:
- \( U_F = \) flooding vapor velocity (m/s) based on the net column cross sectional area \( A_n \).
- \( K = \) constant obtained from figure(1) appendix (A)

\[
F_{LV} = \frac{L}{V} \sqrt{\frac{\rho_V}{\rho_L}}
\]

Where:
- \( F_{LV} = \) The vapor liquid flow factor in figure (1) appendix
- \( L = \) Liquid mass flow rate kg/s
- \( V = \) Vapor mass flow rate kg/s

Top Diameter calculations:

\[
\frac{L}{V} = \frac{R}{R + 1} = \frac{1.8}{1.8 + 1} = 0.64
\]

From ideal gas law:

\[
PV = nRT
\]

\[
\rho_V = \frac{T_p P_{out}}{T_p V_0} \frac{273.5 \times 19 \times 50.17}{400 \times 1 \times 22.4} = 29.09 \text{ Kg/m}^3
\]

\[
F_{LV} = 0.64 \sqrt{\frac{29.09}{467.37}} = 0.160
\]

From figure (1) appendix (A)
K=0.05

\[ U_F = 0.05 \times \sqrt{\frac{467.37 - 29.09}{29.09}} = 0.753 \]

Design velocity (U) = 80% of (U_F)

\[ U = 0.8 \times 0.753 = 0.602 \text{ m/s} \]

\[ A_n = \frac{V}{\rho \nu U \times 3600} = \frac{(1 + R)D}{\rho \nu U \times 3600} = \frac{(1 + 1.8) \times 9847.2118}{29.09 \times 0.602 \times 3600} = 0.437 \text{ m}^2 \]

\[ A_d = 0.12 A_t \]

\[ A_n = A_t - 0.12 A_t = 0.88 A_t \]

\[ A_t = \frac{A_n}{0.88} = \frac{0.437}{0.88} = 0.496 \text{ m}^2 \]

\[ D = \left( \frac{4A_t}{\pi} \right)^{0.5} = 0.79 \text{ m} \]

**Bottom diameter calculations:**

\[ \bar{L} = (q \times F) + L \]

From Ideal gas law:

\[ PV = nRT \]

\[ \rho_v = \frac{T_v P_{\text{atm}}}{T P_v V_0} = \frac{273.15 \times 19.252 \times 85.34}{440 \times 1 \times 22.4} = 45.53 \]

\[ F_{LV} = 1.046 \sqrt{\frac{45.53}{728.228}} = 0.261 \]

From figure (1) appendix (A) at FLV = 0.261 and spacing 60 mm

K=0.046

\[ U_F = 0.046 \times \sqrt{\frac{728.228 - 45.53}{45.53}} = 0.178 \text{ m/s} \]

Design velocity (U) = 80% of flooding velocity (U_F)

\[ 0.8 \times 0.178 = 0.1424 \text{ m/s} \]

\[ A_n = \frac{V}{\rho v U \times 3600} = \frac{27572.19}{45.53 \times 0.1424 \times 3600} = 1.198 \text{ m}^2 \]

Downcomer area = 12% from total area = 0.88A_t

\[ A_t = \frac{A_n}{0.88} = \frac{1.198}{0.88} = 1.36 \text{ m}^2 \]

\[ D = \left( \frac{4A_t}{\pi} \right)^{0.5} = \left( \frac{4 \times 1.36}{3.14} \right)^{0.5} = 1.3172 \text{ m} \]

Taking the bottom diameter for the entire tower since it is the greatest diameter.

\[ A_t = 1.36 \text{ m}^2 \]

\[ A_d = 0.12 A_t \]

\[ = 0.12 \times 1.36 = 0.1632 \text{ m}^2 \]
\[ A_u = A_t - 2A_d \]
\[ = 1.36 - 2(0.1632) = 1.0336 \text{m}^2. \]

\[ A_o = 0.1 \times A_u = 0.10336 \text{m}^2. \]

\[ A_c = 0.07 \times A_t = 0.07 \times 1.36 = 0.0952 \text{m}^2. \]

**-A_p=Preformatted area:**

When down comer area = 0.12 \( \times A_t \)

\[ \frac{LW}{D} = 0.75 \text{(From figure (4) appendix (A) & } \Theta_C = 98^\circ \text{(from figure(5) appendix (A))} \]

Where \( L_W \) : Weir length.

\[ L_W = 0.75 \times D = 0.75 \times 1.3172 = 0.9879 \text{ m} \]

Angle subtended at plate edge by imperforated strip = 180 - 98 = 82°

Calming zones width = 50 mm

Mean length, imperforated edge strips

\[ = (1.3172 - 50 \times 10^{-3} \) \( \pi \times \left( \frac{82}{180} \right) = 1.813 \text{ m}. \]

Area of imperforated edge strips = 50 \( \times 10^{-3} \) \( \times 1.813 = 0.0906 \text{ m}^2. \]

Mean length of calming zone = (1.3172 - 50 \( \times 10^{-3} \) \( \sin\left( \frac{98}{2} \right) = 0.9563 \text{ m} \)

Area of calming zone = 2(0.9563 \( \times 50 \times 10^{-3} \) ) = 0.09563 \( \text{m}^2 \)

Total area for perforations, \( A_p = 1.336 - 0.0906 - 0.09563 = 0.8473 \text{m}^2 \)

\[ \frac{A_o}{A_p} = 0.1 \left( \frac{A_u}{A_p} \right) = 0.1 \left( \frac{1.0336}{0.8473} \right) = 0.12198. \]

\[ \frac{A_o}{A_p} = 0.9 \left( \frac{d_o}{L_p} \right)^2 \]

Where \( L_p \) : hole pitch.

\[ 0.12198 = 0.9 \left( \frac{d_o}{L_p} \right)^2 \]

\[ \left( \frac{d_o}{L_p} \right)^2 = 0.1355 \]

\[ \left( \frac{L_p}{d_o} \right) = 2.716. \]

2.716 are satisfactory, within 2.5 to 4.0.
6.1.14. Determination of fractional entrainment ($\phi$):

From figure (2) appendix (A)

At $F_{LV}=0.261$ and 80% flooding $\phi=0.09$(well below 0.1).

$$e=\frac{\phi \times L}{1-\phi} = \frac{0.009 \times 17724.98}{1-0.009} = 160.973 \text{kg/h}.$$ 

6.1.15. Weeping point:

Weeping will occur when $U_o(\text{min}) < U_o(\text{min})$ calculated.

$$U_o = \frac{V}{\rho \times A_o} = \frac{37543.53194}{45.53 \times 0.10336 \times 3600} = 2.3175 \text{m/s}$$

Taking 70% turn down.

$$U_o(\text{min}) = 0.7 \times U_o = 0.7 \times 2.3175 = 1.624 \text{m/s}.$$ 

$U_o(\text{min})$ calculated $= \frac{k_2 - 0.9(25.4-d_o)}{\rho_v^{0.5}}$

d_o=5 mm 

$k_2$ is a function of $(h_w + h_{ow}(\text{min}))$

$h_w$: weir height $= 23$ mm

$h_{ow}(\text{min})$: minimum weir crest $= 750 \times \frac{(L_{\text{min}})}{\rho_l L_w}$

$L_{\text{min}} = 0.7 \times 17724.98 = 12407.486 \text{kg/h}.$

$$h_{ow}(\text{min}) = 750 \times \left(\frac{12407.486}{728.228 \times 0.9879 \times 3600}\right)^{2/3} = 21.31$$

$$h_w + h_{ow}(\text{min}) = 23 + 21.31 = 44.31 \text{mm}.$$ 

From figure (3) appendix (A)

$k_2=30$

$$U_o(\text{min})\text{calculated}=\frac{30-0.9(25.4-5)}{(45.53)^{0.5}} = 1.5 \text{m/s}.$$ 

∴ Weeping will not occur.

6.1.16. Pressure drop calculation:

$$\Delta P = 9.81 \times h_t \times 10^{-3} \times \rho_l$$

$$h_t = h_d + (h_w + h_{ow}) + h_r$$

$$h_d = 51 \left(\frac{U_o}{C_o}\right)^2 \frac{\rho_v}{\rho_l}$$

From figure (6) appendix (A)

$$A_o\frac{A_o}{A_P} = 12.198 \% \& \frac{\text{plate thickness}}{\text{hole thickness}} = 1$$
Design

Chapter 6

\( C_0 = 0.859 \)

\[ h_d = 51 \left( \frac{2.3175}{0.859} \right)^2 \frac{45.53}{728.228} = 23.208 \text{mm.} \]

\( h_{ow} \text{(min)} = 750 \times \left( \frac{27503.63}{728.228 \times 0.9879 \times 3600} \right)^{2/3} = 36.23 \text{mm.} \)

\( h_w = 23 \text{mm} \)

\( h_r = \frac{12.5 \times 10^3}{728.228} = 17.16 \)

\( h_t = 21.31 + 36.23 + 23 + 17.16 = 97.7 \text{mm} \)

\( \Delta P = 9.81 \times 97.7 \times 10^{-3} \times 728.228 = 0.007 \text{ bar/tray.} \)

6.1.17. Down comer liquid back up:

For safe design and to avoid flooding

\( h_b < \frac{1}{2}(C + h_w) \)

\( h_b = h_t + h_d + h_w + h_{ow} + h_r + h_{dc} \)

\( h_{dc} = 166 \left( \frac{L}{\rho_l A_{ap}} \right)^2 \)

\( A_{ap} = h_{ap} \times L_w \)

\( h_{ap} = h_w - 10 \text{mm} \)

23 - 10 = 13 \text{mm} \)

\( A_{ap} = 0.9879 \times 10^{-3} \times 13 = 0.013 \text{mm} \)

\( h_{dc} = 166 \left( \frac{17724.98}{728.228 \times 0.013 \times 3600} \right)^2 = 4.64 \text{mm} \)

\( h_b = 97.7 + 36.23 + 23 + 4.67 = 201.83 \text{mm} \)

\( \frac{1}{2}(C + h_w) \approx \frac{1}{2}(0.3 + 23 \times 10^{-3}) = 0.323 \text{m.} \)

\( h_b < \frac{1}{2}(C + h_w) \) no flooding will occure.

6.1.18. Down comer residence time:

\[ t_r = \frac{A_d h_b \rho_l}{L} = \frac{0.1632 \times 0.2018 \times 728.228}{(17724.98 / 3600)} = 4.8 \text{ sec.} \]

4.8 > 3 so it is acceptable.

6.1.19, Thickness calculation:

- columnar thickness:
Highest operating temperature is 166.85°C.

Design stress at 166.85°C = 111 N/mm².

Joint efficiency = 0.85.

\[ e = \frac{P_iD_i}{2Jf - P_i} \]

\[ = \frac{1925175 \times 1.3172}{2 \times 111 \times 10^6 \times 0.85 - 1925175} = 0.01357 \text{mm.} \]

Corrosion allowance 2mm.

\[ \therefore \text{column thickness} = 2.01357 \text{mm.} \]

**Head thickness:**

- Ellipsoidal heads:

\[ e = \frac{P_iD_i}{2Jf - 0.2P_i} \]

\[ = \frac{1925175 \times 1.3172}{2 \times 111 \times 10^6 \times 0.85 - 1925175} = 0.011 \text{m.} \]

- Tori spherical head

\[ e = \frac{P_iC_sR_c}{2Jf -(C_s-0.2)} \]

\[ C_s \equiv \text{stress concentration factor for torispherical head.} \]

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

\[ R_c \equiv \text{crown radius.} \]

\[ \frac{R_c}{R_k} = \text{no less than 0.6.} \]

\[ R_k \equiv \text{knuckle radius.} \]

\[ R_c \equiv D_i \]

\[ R_k \equiv 0.6D_i. \]

\[ C_s = \frac{1}{4} (3 + \sqrt{1/0.6}) = 1.072. \]

\[ J = 1 \text{(No joint in head).} \]

\[ E = \frac{1925175 \times 1.072 \times 1.3172}{2 	imes 111 \times 10^6 + (1.072 - 0.2)} = 0.01224 \text{mm.} \]

Ellipsoidal heads IS recommended since it has the smallest thickness

\[ \therefore \text{head thickness} = 0.011 \text{mm.} \]
Table (6.5) summary of design calculation.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tower diameter</td>
<td>1.3172M</td>
</tr>
<tr>
<td>Tray spacing</td>
<td>0.30</td>
</tr>
<tr>
<td>Tower Height</td>
<td>34.6M</td>
</tr>
<tr>
<td>Total area(cross sectional area)</td>
<td>$1.36m^2$</td>
</tr>
<tr>
<td>Down comer area</td>
<td>$0.1632m^2$</td>
</tr>
<tr>
<td>Net area</td>
<td>$1.19m^2$</td>
</tr>
<tr>
<td>Active area</td>
<td>$1.0336m^2$</td>
</tr>
<tr>
<td>Hole area</td>
<td>$0.10336m^2$</td>
</tr>
<tr>
<td>Number of theoretical stages</td>
<td>57.695 stages</td>
</tr>
<tr>
<td>Tower efficiency</td>
<td>69.29%</td>
</tr>
<tr>
<td>Plate thickness</td>
<td>0.005M</td>
</tr>
<tr>
<td>Weir height</td>
<td>0.005M</td>
</tr>
<tr>
<td>Weir length</td>
<td>0.987M</td>
</tr>
<tr>
<td>Hole diameter</td>
<td>0.005M</td>
</tr>
<tr>
<td>Fractional entrainment</td>
<td>0.09</td>
</tr>
<tr>
<td>Weeping velocity</td>
<td>1.5M/S</td>
</tr>
<tr>
<td>Total presser drop head</td>
<td>0.007 bar</td>
</tr>
<tr>
<td>thickness Of column</td>
<td>2.01357MM</td>
</tr>
<tr>
<td>thickness Of head</td>
<td>0.011MM</td>
</tr>
</tbody>
</table>

6.2. Reactor design:

-Type of reactor proposed:
A packed bed reactor, which is essentially a plug flow reactor packed of solid catalyst particles to speed up the reaction.

-Justification of selection:
  • Adiabatic packed bed reactor, is the cheapest type of reactors and simple to design and construction.
  • It give the highest conversion per weight of catalyst of any catalyst reactor.
  • Running the reactor adiabatically allows to recover heat from the high temperature product and reduce cost of energy.
“The process uses an acidic ion-exchange-resin catalyst.”

6.2.1. Design calculation:

$$(\text{CH}_3)_2\text{C} = \text{CH}_2 + \text{CH}_3\text{OH} \rightarrow (\text{CH}_3)_3\text{C}-\text{O-CH}_3$$

Conversion: 80% of isobutylene.

-Input and output stream:

Table (6.6) Summary of material balance around reactor.

<table>
<thead>
<tr>
<th>Component</th>
<th>Input (Kmol/h)</th>
<th>Output (Kmol/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Methanol</td>
<td>4176.10</td>
<td>2516.10</td>
</tr>
<tr>
<td>Isobutylene</td>
<td>2088.05</td>
<td>428.05</td>
</tr>
<tr>
<td>1-butene</td>
<td>1817.511622</td>
<td>1817.511622</td>
</tr>
<tr>
<td>2-butene</td>
<td>5172.917692</td>
<td>5172.917692</td>
</tr>
<tr>
<td>Mtbe</td>
<td>0.00</td>
<td>1660.00</td>
</tr>
<tr>
<td>Water</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Total</td>
<td>13254.58</td>
<td>11594.58</td>
</tr>
</tbody>
</table>

-Rate law:

$$-r_A = k_f \frac{C_{\text{isobutylene}}}{C_{\text{methanol}}} - k_r \frac{C_{\text{mtbe}}}{C^2_{\text{methanol}}}$$

Where:

$$k_f = 1.464 \times 10^{22} \exp\left(-\frac{129,600}{RT}\right)$$

$$k_r = 6.05 \times 10^{16} \exp\left(-\frac{85,400}{RT}\right)$$

$$C_{\text{isobutylene}} = C_A(1 - X_A)$$

$$C_{\text{methanol}} = C_A(\theta_{\text{meth}} - X_A)$$

$$C_{\text{mtbe}} = C_A(\theta_{\text{mtbe}} + X_A)$$

“The units of reaction rate, ri, are mol/m3h, and the activation energy is in J/mol.”

Design equation:

$$\frac{dF_A}{dV} = F_A \left(\frac{dX_A}{dV}\right) = -r_A = k_f \frac{C_{\text{isobutylene}}}{C_{\text{methanol}}} - k_r \frac{C_{\text{mtbe}}}{C^2_{\text{methanol}}}$$
\[ dV = \frac{F_{AO}}{k_1 c_{\text{isobutylene}}} \left( \frac{c_{\text{methanol}}}{c_{\text{methanol}}} \right) dX_A \rightarrow (1) \]

\[ \int_0^V dV = F_{AO} \int_0^{0.8} \frac{dX_A}{k_1 c_{\text{isobutylene}}} \left( \frac{c_{\text{methanol}}}{c_{\text{methanol}}} \right) \rightarrow (2) \]

- Integration of right side of equation (2)

Since the reactor is adiabatic, temperature (T) and conversion (X) are related by the following equation:

\[ X_A = \frac{\sum \theta_i c_{pi} (T - T_0)}{-\Delta H_{RX}} \]

Calculations were made by using Excel, and data need is constructed with the aid of equation (2), and tabulated in table (6.7):

Table (6.7) relation between conversion & temperature

<table>
<thead>
<tr>
<th>T</th>
<th>X</th>
<th>F(x)</th>
</tr>
</thead>
<tbody>
<tr>
<td>358.0001</td>
<td>0</td>
<td>0.095535</td>
</tr>
<tr>
<td>362.5341</td>
<td>0.091711</td>
<td>0.070099</td>
</tr>
<tr>
<td>367.0681</td>
<td>0.180646</td>
<td>0.05221</td>
</tr>
<tr>
<td>371.6021</td>
<td>0.26688</td>
<td>0.039508</td>
</tr>
<tr>
<td>376.1361</td>
<td>0.350477</td>
<td>0.030415</td>
</tr>
<tr>
<td>380.6701</td>
<td>0.431E-01</td>
<td>0.023869</td>
</tr>
<tr>
<td>385.204</td>
<td>5.10E-01</td>
<td>0.019149</td>
</tr>
<tr>
<td>389.738</td>
<td>0.586016</td>
<td>0.015773</td>
</tr>
<tr>
<td>394.272</td>
<td>0.659605</td>
<td>0.013431</td>
</tr>
<tr>
<td>398.806</td>
<td>0.730798</td>
<td>0.011961</td>
</tr>
<tr>
<td>403.34</td>
<td>0.79963</td>
<td>0.011381</td>
</tr>
</tbody>
</table>

These data are plotted in figure (6.1) below:
The area under the curve $A = 0.031534679$

\[ \therefore \frac{V}{F_A} = A \]

\[ \rightarrow \quad V = F_A \times A \]

$V = 2088.05 \times 0.031534679 = 65 \, m^3$

\[ V = \frac{\pi D^2 L}{4} \]

Put $L = 13.8D$

\[ V = \frac{\pi D^2 \times 13.8D}{4} \]

\[ \rightarrow \quad D = \frac{3 \sqrt{V}}{10.8} = \frac{3 \sqrt{65}}{10.8} = 1.8 \, m. \]

$L = 13.8 \times 1.8 = 24.8 \, m$. 

- **Reactor thickness:**
  
  Highest operating temperature is $403^\circ K$

  Design stress at $403^\circ K = 70 \, N/mm^2$

  \[ e = \frac{P_i D_i}{2Jf - P_i} \]
\[
\frac{1925175 \times 1.8}{2 \times 70 \times 10^6 \times 0.85 - 1925175} = 29.59
\]

Corrosion allowance 2mm.
∴ Reactor thickness = 31.59mm.