**PROCESS DESIGN OF ACID TOWER (Major equipment)**

(Vacuum distillation Tower)

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

= 130.38 kmol/ hr.

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

Feed:

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

Distillate:

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

Residue:

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

VLE data:

<table>
<thead>
<tr>
<th>Liquid molefrac of acetic acid. x</th>
<th>0.0</th>
<th>0.1</th>
<th>0.2</th>
<th>0.3</th>
<th>0.4</th>
<th>0.5</th>
<th>0.6</th>
<th>0.7</th>
<th>0.8</th>
<th>0.9</th>
<th>1.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vapor molefrac of acetic acid. y</td>
<td>0.0</td>
<td>0.21</td>
<td>0.37</td>
<td>0.51</td>
<td>0.63</td>
<td>0.715</td>
<td>0.795</td>
<td>0.86</td>
<td>0.92</td>
<td>0.96</td>
<td>1.0</td>
</tr>
<tr>
<td>T °C</td>
<td>74.22</td>
<td>72.22</td>
<td>69.46</td>
<td>67.13</td>
<td>64.83</td>
<td>62.57</td>
<td>60.33</td>
<td>58.12</td>
<td>57.32</td>
<td>55.94</td>
<td>53.79</td>
</tr>
</tbody>
</table>

Feed is a liquid at its boiling point
q=1; i.e. q line is vertical line passing through x=y=x_F.

From x-y plot,

\[
x_D / (R_m + 1) = 0.13
\]

\[
R_m = 6.369
\]

Optimum reflux ratio  R= 15
Number of ideal stages in enriching section = 7  
Number of ideal stages in stripping section = 4+1(reboiler)

### Average Conditions and Properties

<table>
<thead>
<tr>
<th></th>
<th>Enriching Section</th>
<th>Stripping Section</th>
</tr>
</thead>
<tbody>
<tr>
<td>Liquid flow kmol/hr</td>
<td>225.43</td>
<td>355.81</td>
</tr>
<tr>
<td></td>
<td>14751.0</td>
<td>25314.05</td>
</tr>
<tr>
<td>Vapor flow kmol/hr</td>
<td>240.46</td>
<td>240.46</td>
</tr>
<tr>
<td></td>
<td>16938.0</td>
<td>17293.88</td>
</tr>
<tr>
<td>$M_{\text{avg}}$ $\text{liq}$ kg/kmol</td>
<td>60.5</td>
<td>70.37</td>
</tr>
<tr>
<td></td>
<td>70.37</td>
<td>71.92</td>
</tr>
<tr>
<td>$M_{\text{avg}}$ $\text{vap}$ kg/kmol</td>
<td>60.5</td>
<td>68.96</td>
</tr>
<tr>
<td></td>
<td>68.96</td>
<td>71.92</td>
</tr>
<tr>
<td>$x$</td>
<td>0.958</td>
<td>0.1156</td>
</tr>
<tr>
<td></td>
<td>0.1156</td>
<td>0.006</td>
</tr>
<tr>
<td>$y$</td>
<td>0.958</td>
<td>0.22</td>
</tr>
<tr>
<td></td>
<td>0.22</td>
<td>0.006</td>
</tr>
<tr>
<td>$T_{\text{liq}} \degree \text{C}$</td>
<td>54.4</td>
<td>72</td>
</tr>
<tr>
<td></td>
<td>72</td>
<td>74.1</td>
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<tr>
<td>$T_{\text{vap}} \degree \text{C}$</td>
<td>55.8</td>
<td>72.2</td>
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<td></td>
<td>72.2</td>
<td>74.2</td>
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<tr>
<td>$\text{Liq kg/hr}$</td>
<td>13638.5</td>
<td>25038.3</td>
</tr>
<tr>
<td></td>
<td>15863.5</td>
<td>25589.8</td>
</tr>
<tr>
<td>$\text{Vap kg/hr}$</td>
<td>14547.8</td>
<td>16582.12</td>
</tr>
<tr>
<td></td>
<td>16582.12</td>
<td>17293.88</td>
</tr>
<tr>
<td>Liquid density kg/m$^3$</td>
<td>1083.94</td>
<td>1074.8</td>
</tr>
<tr>
<td></td>
<td>1074.8</td>
<td>1078.32</td>
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<tr>
<td>Vap density kg/m$^3$</td>
<td>0.1569</td>
<td>0.1704</td>
</tr>
<tr>
<td></td>
<td>0.1704</td>
<td>0.1767</td>
</tr>
<tr>
<td>$(\text{L/G})(\rho_l/\rho_g)^{0.5}$</td>
<td>0.0113</td>
<td>0.012</td>
</tr>
<tr>
<td></td>
<td>0.018</td>
<td>0.01894</td>
</tr>
</tbody>
</table>

### Liquid Flow kmol/hr kg/hr

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<td>73.05</td>
</tr>
<tr>
<td>$T_{\text{vap}} \degree \text{C}$</td>
<td>64</td>
<td>73.2</td>
</tr>
<tr>
<td>$\rho_{\text{liq}}$ kg/m$^3$</td>
<td>1079.37</td>
<td>1076.56</td>
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<tr>
<td>$\rho_{\text{vap}}$ kg/m$^3$</td>
<td>0.1636</td>
<td>0.1735</td>
</tr>
<tr>
<td>$\mu_{\text{liq}}$ cP</td>
<td>0.69</td>
<td>0.603</td>
</tr>
<tr>
<td>$\mu_{\text{vap}}$ cP</td>
<td>0.00937</td>
<td>0.009412</td>
</tr>
<tr>
<td>$\sigma_{\text{liq}}$ dyn/cm</td>
<td>28.985</td>
<td>28.208</td>
</tr>
<tr>
<td>$D_{\text{L cm}}^2$/sec</td>
<td>3.463 x $10^3$</td>
<td>3.343 x $10^3$</td>
</tr>
<tr>
<td>$D_{\text{V cm}}^2$/sec</td>
<td>1.082</td>
<td>1.134</td>
</tr>
</tbody>
</table>
ENRICHING SECTION

I Tray Hydraulics:

- Tray spacing $t_s = 500\text{mm}$
- Hole diameter $d_h = 5\text{mm}$
- Hole pitch $L_p = 15\text{mm}$
- Tray thickness $t_T = 3\text{mm}$
- $A_h / A_p = 0.10$

II Tower Diameter:

\[(L/G)(\rho_l/\rho_g)^{0.5} = 0.012\] (max at the bottom)

(From PERRY : fig 18-10 ; p.no. 18-7)

For $t_s = 18\text{ in}$,

- Capacity parameter, $C_{sb(\text{flood})} = 0.29\ \text{ft/s}$
- Gas velocity through net area at flood $U_{nf} = C_{sb(\text{flood})} \times \left[ \sigma / 20 \right] \times \frac{[(\rho_l - \rho_g)]^{0.5}}{\rho_g}$

\[\sigma = \text{liq surface tension} = 28.985\ \text{dyn/cm}\]
\[\rho_l = 1079.37\ \text{kg/m}^3\]
\[\rho_g = 0.1636\ \text{kg/m}^3\]

$U_{nf} = 25.36\ \text{ft/s} = 7.732\ \text{m/s}$

For 75% flooding condition, $U_n = 0.75 \times 7.732 = 5.799\ \text{m/s}$

Net area $A_N = \text{Max. vol. flow rate of vapor} / U_n$
\[= 16582.12 / (3600 \times 0.1636 \times 5.799) = 4.85\ \text{m}^2\]

Ratio of weir length to tower dia i.e. $L_W / D_C = 0.75$
\[\theta_c = 2 \sin^{-1}(L_W / D_C) = 97.2^\circ\]

Column C.S.area, $A_C = (\pi / 4) \ D_C^2 = 0.785\ D_C^2$

Down comer C.S.area, $A_D = (\pi / 4) \ D_C^2 (\theta_c / 360) - (L_W / 2) (D_C / 2) \cos(\theta_c / 2)$
\[= 0.0879\ D_C^2\]

$A_N = A_C - A_D$

$D_C = 2.637\ \text{m}$

Take $D_C = 2.65\ \text{m}$

$L_W = 0.75 \times 2.65 = 1.98\ \text{m} = 2\text{m}$

$A_C = 5.515\ \text{m}^2$
\[ A_D = 0.6172 \text{ m}^2 \]
\[ A_N = 4.901 \text{ m}^2 \]

Active area \( A_A = A_C - 2 A_D = 4.28 \text{ m}^2 \)
\[ L_W / D_C = 0.754 \]
\[ \theta_c = 98.0^\circ \]
\[ \alpha = 81.99^\circ \]

Perforated area \( A_P \):

Area of distribution and calming zone
\[ A_{cz} = 2 (L_W \times 100 \times 10^{-3}) = 0.4 \text{ m}^2 \]

Area of waste peripheral zones
\[ A_{wz} = 2 \left[ \left( \frac{\pi}{4} \right) D_C^2 \left( \frac{a}{360} \right) - \left( \frac{\pi}{4} \right) (D_C - 0.12)^2 \left( \frac{a}{360} \right) \right] \]
\[ = 0.22 \text{ m}^2 \]

\[ A_P = A_C - 2 A_D - A_{cz} - A_{wz} = 3.658 \text{ m}^2 \]

Hole area \( A_H = 0.1 \times A_P = 0.3658 \text{ m}^2 \)

Number of holes \[ = 0.3658 / \left[ \left( \frac{\pi}{4} \right) \times 0.005^2 \right] = 18630 \]

III Weeping Check:

Weir height \( h_w = 10 \text{mm} \)

Pressure drop across the dispersion unit
\[ h_d = k_1 + k_2 \left( \frac{\rho_g}{\rho_l} \right) U_h^2 \]

For sieve trays \( k_1 = 0, k_2 = 50.8/ C_v^2 \)

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

For \( t_T / d_h = 0.6; A_H / A_A = 0.0854 \)
\[ C_v = 0.74 \]
\[ k_2 = 92.77 \]

Vol. flow of vapor at top = 14547.8 / (3600 x 0.1569 ) = 25.75 m\(^3\)/s
Vol. flow of vapor at bottom = 16582.12 / (3600 x 0.1704 ) = 27.03 m\(^3\)/s

Linear gas velocity through perforations \( U_h \):
\[ U_h \ (at \ top) = 25.75 / A_H = 25.75 / 0.3658 = 70.95 \text{ m/s} \]
\[ U_h \ (at \ bottom) = 27.03 / A_H = 74.48 \text{ m/s} \]
\[ h_d \ (at \ top) = 92.77 \times (0.1569/ 1083.94) \times (70.95)^2 = 67.59 \text{ mm clear liq} \]
\[ h_d \ (at \ bottom) = 92.77 \times (0.1704/ 1074.8) \times (74.48)^2 = 81.59 \text{ mm clear liq} \]

Head loss due to bubble formation \( h_o \)
\[ h_o = 409 \ (\sigma / \rho_l d_h) \]
\[ \sigma = \text{surface tension} = 28.985 \text{ mN/m} \]
\[ \rho_l = 1079.37 \text{ kg/m}^3 \]
\[ d_h = 5 \text{mm} \]
\[ h_o = 409 \times (28.985 / 1079.37 \times 5) = 2.2 \text{mm} \]
Height of crest over weir \( h_{ow} \)

\[
h_{ow} = F_w (664) \left( \frac{q}{L_w} \right)^{2/3}
\]

\( q \) = liquid flow

\[
= \frac{13638.5}{(3600 \times 1083.94)} = 0.003495 \text{ m}^3/\text{s} = 55.39 \text{ gal/min}
\]

\( L_w = 2 \text{m} = 6.56 \text{ ft} \)

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

For \( q / L_w^{2.5} = 55.39 / 6.56^{2.5} = 0.502 \)

\[L_w / D_C = 0.754\]

\( F_w = 1.01 \)

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

\( h_d + h_r = 67.59 + 2.2 = 69.79 \text{ mm} \)

\( h_{ow} + h_w = 10 + 9.73 = 19.73 \text{ mm} \)

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

For \( A_H / A_A = 0.0854 \)

\( h_{ow} + h_w = 19.73 \text{ mm} \)

\( h_d + h_r = 14 \text{ mm} < \text{design value of 69.79 mm} \)

Hence no weeping occurs

**IV Down comer Flooding Check:**

Down comer back up \( h_{dc} = h_t + h_w + h_{ow} + h_{da} + h_{lg} \)

\( h_t = \text{total pressure drop across the plate , mm liq} \)

\( h_w = \text{height of weir at plate outlet , mm liq} \)

\( h_{ow} = \text{height of crest over weir , mm liq} \)

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

\( h_{lg} = \text{liquid gradient across plate , mm liq (neglected)} \)

Calculated height of clear liquid over the dispersers , \( h_{ds} \text{ mm liq} \)

\( h_{ds} = h_w + h_{ow} + h_{lg} \)

\[
h_{ow} = F_w (664) \left( \frac{q}{L_w} \right)^{2/3}
\]

\( q \) = liquid flow

\[
= \frac{15863.5}{(3600 \times 1074.8)} = 0.0040998 \text{ m}^3/\text{s} = 64.98 \text{ gal/min}
\]

\( L_w = 2 \text{m} = 6.56 \text{ ft} \)

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

For \( q / L_w^{2.5} = 64.98 / 6.56^{2.5} = 0.589 \)

\[L_w / D_C = 0.754\]
\[ F_W = 1.01 \]

\[ h_{ow} = 1.01 \times 664 \times (0.0040998 / 2)^{1/2} = 10.82 \text{ mm} \]

\[ h_{ds} = h_{ow} + h_w = 10.82 + 10 = 20.82 \text{ mm liq} \]

**Total pressure drop \( h_t \):**

\[ h_t = h_d + h_{l'} \quad \text{- pressure drop across the aerated liquid} \]

\[ h_t = \beta h_{ds} \quad \text{(From PERRY : fig 18-15 ; p.no. 18-10 )} \]

linear gas velocity through the active area \( U_a \):

\[ U_a = 16582.12 / (3600 \times 0.1704 \times 4.28) \]

\[ = 6.362 \text{ m/s} = 20.87 \text{ ft/s} \]

\[ \rho_g = 0.1704 \text{ kg/m}^3 = 0.0106 \text{ lb/ft}^3 \]

\[ F_{ga} = U_a \rho_g^{0.5} = 20.87 \times 0.0106^{0.5} = 2.152 \]

Relative froth density \( \Phi = 0.19 \)

Aeration factor \( \beta = 0.59 \)

\[ h_{l'} = 0.59 \times 20.82 = 12.283 \text{ mm liq} \]

**Actual height of froth:**

\[ h_f = h_{l'}/\Phi = 12.28/0.19 = 64.65 \text{ mm} \]

**Head loss due to down comer apron:**

\[ h_{da} = 165.2 \left( q/ A_{da} \right)^2 \]

\[ q = 0.0040998 \text{ m}^3/\text{s} \]

**Take \( C = 13 \text{ mm} \)**

\[ h_{ap} = h_{ds} - C = 20.82 - 13 = 7.82 \text{ mm} \]

\[ A_{da} = L_w h_{ap} = 2 \times 0.00782 = 0.016 \text{ m}^2 \]

\[ h_{ad} = 165.2 \left( 0.0040998 / 0.016 \right)^2 = 10.84 \text{ mm} \]

\[ h_t = h_d + h_{l'} = 81.59 + 12.28 = 93.87 \text{ mm} \]

\[ h_{dc} = 93.87 + 10 + 10.82 + 10.84 = 125.53 \text{ mm} \]

Actual backup \( h_{dc}/\Phi_{dc} = 125.53/0.5 = 251.06 \text{ mm} < t_s = 500 \text{ mm} \)

Hence down comer flooding does not occur

**STRIPPING SECTION**

I Tray Hydraulics:

Tray spacing \( t_s = 500 \text{ mm} \)

Hole diameter \( d_h = 5 \text{ mm} \)
Hole pitch $L_p = 15$mm  \quad (Δlar)
Tray thickness $t_T = 3$mm
$A_h / A_p = 0.10$

II  Tower Diameter :

$$(L/G)(\rho_i / \rho_g)^{0.5} = 0.01894 \quad \text{(max at the bottom)}$$

(From PERRY : fig 18-10 ; p.no. 18-7)

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

$\sigma$ - liq surface tension = 28.208 dyn/cm
$\rho_i$ = 1078.32 kg/m$^3$
$\rho_g$ = 0.1767kg/ m$^3$

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

Net area $A_N = \text{Max. vol. flow rate of vapor} / U_n$
= $17293.88 / (3600 \times 0.1767 \times 5.547) = 4.901 \text{ m}^2$

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

$A_N = A_C - A_D$

$D_C = 2.65 \text{ m}$
$L_W = 0.75 \times 2.65 = 1.98 \text{ m} = 2\text{m}$
$A_C = 5.515 \text{ m}^2$
$A_D = 0.6172 \text{ m}^2$
$A_N = 4.901 \text{ m}^2$

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

Perforated area $A_P$ :
Area of distribution and calming zone
$A_{cz} = 2 \ (L_W \times 100 \times 10^{-3}) = 0.4 \text{ m}^2$
Area of waste peripheral zones
\[ A_{wz} = 2 \times [(\pi / 4) Dc^2 (a / 360)] - (\pi / 4)(Dc - 0.12)^2 (a / 360) \]
\[ = 0.22 \, m^2 \]
\[ A_p = A_c - 2 A_D - Acz - Awz \]
\[ = 3.658 \, m^2 \]
Hole area \( A_H = 0.1 \times A_p = 0.3658 \, m^2 \)
Number of holes = \( 0.3629 / [(\pi / 4) \times 0.005^2] = 18630 \)

III Weeping Check:

Weir height \( h_w = 10 \)mm

Pressure drop across the dispersion unit
\[ h_d = k_1 + k_2 \left( \frac{\rho_g}{\rho_1} \right) \frac{U_h^2}{C_v^2} \]
For sieve trays \( k_1 = 0 \), \( k_2 = 50.8 / C_v^2 \)
(From PERRY: fig 18-14; p.no. 18-9)
For \( t_T / d_h = 0.6 \); \( A_H / A_A = 0.085 \)
\[ C_v = 0.74 \]
\[ k_2 = 92.77 \]

Vol. flow of vapor at top = \( 15682.12 / (3600 \times 0.1704) = 25.56 \, m^3/s \)
Vol. flow of vapor at bottom = \( 17293.88 / (3600 \times 0.1767) = 27.186 \, m^3/s \)

Linear gas velocity through perforations \( U_h \):
\[ U_h \text{ (at top )} = 25.56 / A_H = 25.56 / 0.3658 = 69.875 \, m/s \]
\[ U_h \text{ (at bottom )} = 27.186 / A_H = 74.32 \, m/s \]
\[ h_d \text{ (at top )} = 92.77 \times (0.1704/1074.8) \times (69.875)^2 = 71.79 \, mm \, clear \, liq \]
\[ h_d \text{ (at bottom )} = 92.77 \times (0.1767/1078.32) \times (74.32)^2 = 83.96 \, mm \, clear \, liq \]

Head loss due to bubble formation \( h_\sigma \):
\[ h_\sigma = 409 \left( \frac{\sigma}{\rho_1 d_h} \right) \]
\( \sigma \) - surface tension = \( 28.208 \, mN/m \)
\( \rho_1 = 1076.56 \, kg/m^3 \)
\( d_h = 5 \, mm \)
\[ h_\sigma = 409 \times (28.208 / 1076.56 \times 5) = 2.14 \, mm \]

Height of crest over weir \( h_{ow} \):
\[ h_{ow} = F_w (664) \left( \frac{q}{L_w} \right)^{\frac{1}{2}} \]
\( q \) = liquid flow
\[ = 25038.3 / (3600 \times 1074.8) = 0.00647 \, m^3/s = 12.57 \, gal/min \]
\( L_w = 2 \, m = 6.56 \, ft \)

(From PERRY: fig 18-16; p.no 18-11)
For \( q / L_W^{2.5} = 102.57 / 6.56^{2.5} = 0.929 \)
\[ L_W / D_C = 0.754 \]
\[ F_W = 1.02 \]

\[ h_{ow} = 1.02 \times 664 \times (0.00647 / 2)^{\frac{3}{2}} = 14.81 \text{ mm} \]

\[ h_d + h_\alpha = 71.79 + 2.14 = 73.93 \text{ mm} \]
\[ h_{ow} + h_w = 10 + 14.81 = 24.81 \text{ mm} \]

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

\[ h_d + h_\alpha = 14 \text{ mm} < \text{design value of 73.93 mm} \]
Hence no weeping occurs

**IV Down comer Flooding Check:**

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

Calculated height of clear liquid over the dispersers, \( h_{ds} \) mm liq
\[ h_{ds} = h_w + h_{ow} + h_{hg} \]

\[ h_{ow} = F_W (664) \times (q / L_W)^{\frac{3}{2}} \]
\[ q = \text{liquid flow} \]
\[ = 25589.8 / (3600 \times 1078.32) = 0.00659 \text{ m}^3/\text{s} = 104.48 \text{ gal/min} \]
\[ L_w = 2 \text{m} = 6.56 \text{ ft} \]

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

\[ h_{ow} = 1.01 \times 664 \times (0.00659 / 2)^{\frac{3}{2}} = 14.99 \text{ mm} \]
\[ h_{ds} = h_{ow} + h_w + h_{hg} = 14.99 + 10 = 24.99 \text{ mm liq} \]

Total pressure drop \( h_t : \)
\[ h_t = h_d + h_{t'} \]

- pressure drop across the aerated liquid

\[ h_{t'} = \beta h_{ds} \]

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

linear gas velocity through the active area \( U_a \):

\[ U_a = \frac{17293.88}{3600 \times 0.1767 \times 4.28} = 6.352 \text{ m/s} = 20.83 \text{ ft/s} \]

\[ \rho_g = 0.1767 \text{ kg/m}^3 = 0.01102 \text{ lb/ft}^3 \]

\[ F_{ga} = U_a \rho_g^{0.5} = 20.83 \times 0.01102^{0.5} = 2.187 \]

Relative froth density \( \phi = 0.19 \)

Aeration factor \( \beta = 0.59 \)

\[ h_{t'} = 0.59 \times 24.99 = 14.74 \text{ mm liq} \]

Actual height of froth \( h_f = h_{t'}/\phi = 14.74/0.19 = 77.6 \text{ mm} \)

Head loss due to down comer apron \( h_{da} = 165.2 \left( \frac{q}{A_{da}} \right)^2 \)

\[ q = 0.00659 \text{ m}^3/\text{s} \]

Take \( C = 13 \text{ mm} \)

\[ h_{ap} = h_{ds} - C = 24.99 - 13 = 11.99 \text{ mm} \]

\[ A_{da} = LW \quad h_{ap} = 2 \times 0.01199 = 0.02398 \text{ m}^2 \]

\[ h_{da} = 165.2 \left( \frac{0.00659}{0.02398} \right)^2 = 12.476 \text{ mm} \]

\[ h_t = h_d + h_{t'} = 83.96 + 14.74 = 98.7 \text{ mm} \]

\[ h_{dc} = 98.7 + 10 + 14.99 + 12.476 = 136.166 \text{ mm} \]

Actual backup \( h_{dc}' = h_{dc} / \phi_{dc} = 136.166 / 0.5 = 272.332 \text{ mm} < t_s = 500 \text{ mm} \)

Hence down comer flooding does not occur.
COLUMN EFFICIENCY

ENRICHING SECTION

Point efficiency:

\[ E_{og} = 1 - \exp(-N_{og}) \]
\[ N_{og} = \text{overall transfer unit} \]
\[ N_{og} = 1 / \left[ (1/N_g) + (\lambda / N_i) \right] \]

\[ N_g = \text{gas phase transfer units} \]
\[ N_g = \left[ 0.776 + 0.00457 h_w - 0.238 U_a \rho_g^{0.5} + 105 W \right] / N_{scg}^{0.5} \]
\[ h_w = \text{ weir height } = 10 \text{ mm} \]
\[ U_a = \text{ gas velocity through active area } \]
\[ = 15564.96 / (3600 \times 0.1636 \times 4.28) \]
\[ = 6.174 \text{ m/s} \]
\[ W = \text{ liquid flow rate } m^3 / s.m \]
\[ W = q / D_f ; \]
\[ D_f = (D_C + L_W) / 2 = 2.32 \text{ m} \]
\[ \text{ Average liq flow rate } = 14751 \text{ kg/hr} \]
\[ \text{ Average liq density } = 1079.36 \text{ kg/m}^3 \]
\[ q = 14751 / (3600 \times 1079.36) = 0.00379 \text{ m}^3/\text{s} \]
\[ W = 0.00379 / 2.32 = 0.001636 \text{ m}^3/\text{m.s} \]
\[ N_{scg} = \text{ gas phase Schmidt number } \]
\[ = \mu_g / \rho_g D_g = 0.528 \]
\[ N_g = [0.776 + 0.00457 \times 10 - 0.238 \times 6.174 \times 0.1636 \times 0.5 + 105 \times 0.00163] / 0.528^{0.5} \]

\[ = 0.55 \]

\[ N_l = k_l \theta_l \]
\[ k_l = \text{ liq phase transfer coefficient } m/s \]
\[ a = \text{ effective interfacial area for mass transfer } m^2/m^3 \]
\[ k_l a = (3.875 \times 10^8 D_l)^{0.5} \times (0.4 U_a \rho_g^{0.5} + 0.17) \]
\[ D_l = \text{ liq phase diffusion } = 3.463 \times 10^{-9} \text{ m}^2/\text{s} \]
\[ k_l a = 1.354 \text{ s}^{-1} \]
\[ \theta_l = \text{ residence time of liquid in froth } s \]
\[ = h_l A_A / (1000 q) \]
\[ h_l = h_{h} = 12.28 \text{ mm} \]
\[ \theta_l = 12.28 \times 4.28 / (1000 \times 0.003463) = 13.87 \text{ s} \]
\[ N_l = 1.354 \times 13.87 = 18.77 \]

\[ m_{top} = 0.333 \]
\[ m_{bottom} = 1.01 \]
\[ G_m / L_m = 1.653 \]
\[ \lambda_a = m_t (G_m / L_m) = 0.55 \]
\[ \lambda_b = m_b (G_m / L_m) = 1.669 \]
\[ \lambda_{avg} = 1.105 \]
\[ N_{og} = 1 \left( \frac{1}{N_g + \lambda/N_l} \right) = 0.533 \]
\[ E_{og} = 1 - \exp(-0.533) = 0.413 \]

**Murgheev vapor efficiency:**

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

- \( Z_l = \text{length of liquid travel}, \text{m} = D_c \cos \left( \theta_c / 2 \right) = 1.73 \text{ m} \)
- \( D_E = \text{Eddy diffusion coefficient} \)
  \[ D_E = 6.75 \left( 10^{-3} \right) U_a^{1.44} + 0.922 \left( 10^{-4} \right) h_l - 0.00562 \]
  \[ = 0.0904 \text{ m}^2/\text{s} \]

\[ N_{pe} = 1.73^2 / 0.0873 \times 13.87 = 2.47 \]
\[ \lambda E_{og} = 1.105 \times 0.413 = 0.456 \]

(From PERRRY: fig 18-29a; p.no. 18-18)
\[ E_{mv} / E_{og} = 1.16 \]
\[ E_{mv} = 0.479 \]

**Overall Column Efficiency:**

\[ \left( \frac{L}{G} \right) \left( \frac{\rho_g}{\rho_l} \right)^{0.5} = 0.0116 \]
From PERRY for 80% flooding; \( \psi = 0.25 \)
\[ E_a / E_{mv} = 1 / \left[ 1 + E_{mv} \left( \psi / (1 - \psi) \right) \right] \]
\[ E_a = 0.413 \]

\[ E_{oe} = \log \left[ 1 + E_a (\lambda - 1) \right] / \log \lambda \]
\[ = 0.425 \]

\[ E_{oe} = N_{theoretical} / N_{actual} \]

\[ N_{act} = 7 / 0.425 = 17 \]
Tower height = 500 x 17 = 8500mm

**STIRRING SECTION**

**Point efficiency:**

\[ E_{og} = 1 - \exp\left( - N_{og} \right) \]
\[ N_{og} = \text{overall transfer unit} \]
\[ N_{og} = 1 / \left[ (1/N_g) + (\lambda/N_l) \right] \]
\[ N_g = \text{gas phase transfer units} \]
\[ N_g = \left[ 0.776 + 0.00457 \frac{h_w}{G_{scg}} - 0.238 \frac{U_a}{G_{scg}}^{0.5} + 105 \frac{W}{G_{scg}}^{0.5} \right] / N_{scg}^{0.5} \]

- \( h_w = \text{weir height} = 10\text{mm} \)
- \( U_a = \text{gas velocity through active area} \)
  \[ = \frac{16938}{(3600 \times 0.1735 \times 4.28)} = 6.336 \text{ m/s} \]
- \( W = \text{liquid flow rate} \text{ m}^3 / \text{s.m} \)
  \[ W = \frac{q}{D_f} ; \]
  \[ D_f = \frac{(D_C + L_W)}{2} = 2.32 \text{ m} \]

Average liq flow rate: 25581 kg/hr
Average liq density: 1076.56 kg/m^3
\[ q = \frac{25581}{(3600 \times 1076.56)} = 0.0066 \text{ m}^3/\text{s} \]
\[ W = \frac{0.0066}{2.32} = 0.002838 \text{ m}^3/\text{m.s} \]

\[ N_{scg} = \text{gas phase Schmidt number} \]
\[ = \frac{\mu_g}{\rho_g D_g} = 0.478 \]

\[ N_g = \left[ 0.776 + 0.0045 \times 10 - 0.238 \times 6.336 \times 0.1735^{0.5} + 105 \times 0.002838 \right] / 0.478^{0.5} \]

\[ = 0.711 \]

\[ N_l = k_l a \theta_l \]
\[ k_l = \text{liq phase transfer coefficient} \text{ m/s} \]
\[ a = \text{effective interfacial area for mass transfer} \text{, m}^2/\text{m}^3 \]
\[ k_l a = (3.875 \times 10^8 D_l)^{0.5} \times (0.4 U_a \rho_g^{0.5} + 0.17) \]
\[ D_l = \text{liq phase diffusion} = 3.343 \times 10^{-9} \text{ m}^2/\text{s} \]
\[ k_l a = 1.395 \text{ s}^{-1} \]
\[ \theta_l = \text{residence time of liquid in froth} \text{, s} \]
\[ = \frac{h_L A_A}{(1000 q)} \]
\[ h_L = h_{\text{L}} = 14.99 \text{ mm} \]
\[ \theta_l = 14.99 \times 4.28 / (1000 \times 0.0066) = 9.72s \]

\[ N_l = 1.395 \times 9.72 = 13.56 \]

\[ m_{\text{top}} = 1.142 ; \ m_{\text{bottom}} = 1.15 ; \ \frac{G_m}{L_m} = 1.047 \]
\[ \lambda_t = m_t (\frac{G_m}{L_m}) = 1.195 \]
\[ \lambda_b = m_b (\frac{G_m}{L_m}) = 1.204 \]
\[ \lambda_{\text{avg}} = 1.199 \]

\[ N_{og} = 1 / \left[ 1/ N_g + \lambda/N_l \right] = 0.669 \]

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

**Muphee vapor efficiency**:

\[ \text{Peclet number} \ N_{pe} = Z_l^2 / D_E \theta_l \]
\[ Z_l = \text{length of liquid travel} \text{, m} \]
\[ = \frac{D_c}{\cos(\theta_c / 2)} = 1.73 \text{ m} \]
\[ D_E = \text{Eddy diffusion coefficient} \]
\[ = 6.675 \left(10^{-3}\right) U_a^{1.44} + 0.922 \left(10^{-4}\right) h_l - 0.00562 \]
\[ = 0.091 \text{ m}^2 / \text{s} \]

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

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

**Overall Column Efficiency :**

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

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

\[ E_{oc} = N_{theoretical} / N_{actual} \]
\[ N_{act} = 4 / 0.533 = 8 \]

Tower height = 500 x 8 = 4000mm
MECHANICAL DESIGN OF VACUUM DISTILLATION COLUMN

Material of construction - Stainless steel
    Type 304 SA- 167 grade 3
Composition - 18 Cr- 8 Ni
Maximum allowable stress - 117.2 N/mm² = 17000 psi
Design pressure = 1 bar (external ) = 14.7 psi
Maximum temperature = 75°C
Design temperature = 85°C
Column inner diameter \( d_i \) = 2.65 m = 8.694 ft = 104.328 in
Tray spacing = 500 mm
Number of trays = 25
Height of top chamber = 2 m
Height of the base chamber = 2 m
Total height of the column = 16.5 m = 54.13 ft

Shell thickness with Stiffeners :

Tray spacing = \( l \) = 500 mm = 1.64 ft = 19.86 in
Assume a shell thickness of \( \frac{1}{4} \) in
\[ \frac{l}{d_o} = 19.68 / \left[ 104.328 + 0.5 \right] = 0.187 \]
\[ d_o / t = 104.828 / 0.25 = 419.312 \]
From chart for determining shell thickness of cylindrical vessels under external pressure
\[ \text{factor } A = f / E = \varepsilon = 0.01 \]
\[ B = 7800 \]
\[ P_{allow} = B / (d_o / t) = 7800 / 419.3 = 18.6 \text{ psi} \]
This pressure is higher than the desired external pressure of 15 psi for full vacuum
Hence it is adequate.
Shell thickness = 6.35 mm + corrosion allowance = 8mm = 0.315 in.
Shell plate of this thickness weighs \( p = 10.2 \text{ lb/ft}^2 \)
Shell weight = \( \pi d \text{ lp} = \pi \times 8.694 \times 54.13 \times 10.2 = 15080.22 \text{ lb} \)

Design of circumferential stiffeners

Assuming a 6 in. channel weighing 10.5 lb/ft²
\[ I - \text{required moment of inertia of stiffening ring} = 15.1 \text{ in}^4 \]
Area of section \( A_y = 3.07 \text{ in}^2 \)
\[ B = P_{allow} \frac{d_o}{[t_s + (A_y / 1)]} = 15 \times 104.828 / \left[ 0.315 + (3.07 / 19.68) \right] = 3338.5 \]
From chart for \( B= 3338 \)
\[ \varepsilon = 0.0003 \]
\[ I = (d^2 / 12) [t_s + A_y / 1] \varepsilon = 2.193 \text{ in}^4 \]
As the required moment of inertia is less than that produced by the assumed
6 in.channel, the design is satisfactory.
Design of Elliptical dished closure

A elliptical dished closure ; \( a/b = 2 \)

Average radius of curvature / vessel dia = \( r_c / d = 0.9 \) for \( a/b \) ratio of 2

thickness \( t_h = 5/16 \) in.

\[ r_c = 0.9 \times 105 = 94.5 \text{ in.} \]

\[ r_c / 100 \times t_h = 94.5 / 100 \times 0.3125 = 3.024 \]

From chart, \( \epsilon = 0.0004 \)

\( B = 5250 \)

\( P_{allow} = B / r_c / t_h = 17.36 \text{ psi} < 15 \text{ psi} \)

As the vessel is designed for 1 atm (14.7 psi)

Hence thickness of 8mm is taken

Calculation of Stresses:

Compressive stress resulting from external pressure

Induced compressive axial stresses

\[ f_{ap} = \frac{P d_i}{4} \times [t_s - C] = 1533.62 \text{ psi} \]

Circumferential stress

\[ f = \frac{P d_i}{2} \times [t_s - C] = 3067.24 \text{ psi} \]

Compressive stress caused by dead loads:

Stress induced by shell and insulation;

At any distance \( X \) ft from the top of a vessel having a constant thickness.

\[
\begin{align*}
    f_{\text{dead wt. shell}} &= (\pi / 4) \times (D_o^2 - D_i^2) \times \rho_s / \left[ (\pi / 4) \times (D_o^2 - D_i^2) \times \rho_s \right] \\
    &= \rho_s \times X / 144 = 3.4 X \\
    \rho_s &= \text{density of shell material} = 490 \text{ lb/ft}^3
\end{align*}
\]

\[
\begin{align*}
    f_{\text{dead wt. ins}} &= \pi D_m \rho_{\text{ins}} t_{\text{ins}} / 144 \pi D_m (t_s - C) \\
    &= \rho_{\text{ins}} t_{\text{ins}} X / 144 [t_s - C] \\
    &= 3.33 X \\
    D_m &= \text{mean dia of the shell, ft } \\
    \rho_{\text{ins}} &= 40 \text{ lb/ ft}^3 \\
    D_{\text{ins}} &= D_0 \\
    t_{\text{ins}} &= \text{insulation thickness, 3 in.}
\end{align*}
\]

\[ f_{\text{dead wt. attachment}} = \Sigma W / \pi d [t_s - C] \]
Weight of head = \((\pi \, d^2 \, 1/4) \, \rho / 1728\)
Dia \(d = OD + OD/24 + 2 \, sf \times 2/3 \, icr\); icr = 0; sf = 3in.
\(d = 115.19\) in.; \(l =\) head thickness = 8mm = 0.315 in.

Weight of the head = 923.56 lb
Weight of ladder = 25 lb/ft
Weight of 12 in.
schedule 30 pipe = 438 lb/ft
Weight of insulation = 39.3 lb/ft

Total weight = \((923.56 + 108.1 \times X)\) lb

\(f_{\text{dead wt. attachment}} = \left[923.56 + 108.1X\right] / \pi \times 104.578 \times 0.25\)
\(= 11.24 + 1.32X\)

\(f_{\text{dead wt. (liq + trays)}} = \left[\left(\frac{X}{2} - 1\right) \times 25 \times \left(\pi \, d^2 / 4\right)\right] / \left[12 \times D \times (ts - C)\right]\)
Assume tray loading including liq = 25 lb/ft²
\(= 18.125 \left[\left(\frac{X}{2} - 1\right)\right]\)
\(= 9.062 \times X - 18.125\)

Total stress due to dead weight
\(f_{dx} = 3.4 \times X + 3.33 \times X + 11.24 + 1.32 \times X + 9.062 \times X - 18.125\)
\(= 17.115 \times X - 6.885\)

**Calculation of stress due to wind load**

Assumption: design wind pressure of 25 psf will be used in the design calculation.
Over head vapor line = 12 in OD
\(d_{\text{eff}} = \text{insulated tower} + \text{vapor line}\)
\(= (104.828 + 6 ) + (12+6) = 128.828\) in.
\(f_{wx} = 2 \times P \times X^2 / d_{\text{eff}} \times (ts - C)\)
\(= 0.745 \times X^2\)

**Calculation of combined stress under operating condition**

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

\(f_{t(max)} = f_{wx} - f_{ap} - f_{dx}\)
\(= 0.745 \times X^2 -17.11 \times X - 1526.735\)

For allowable stress of 17000 psi and joint efficiency = 0.85

17000 \times 0.85 = 0.745 \times X^2 -17.11 \times X - 1526.735
X = 97.09 ft

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

\[ f_{c(max)} = f_{wx} + f_{ap} + f_{dx} \]

\[ = 0.745 X^2 + 17.115 X + 1526.73 \]

Allowable compressive stress due to stiffening effect of tray support rings

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

\( A_y = \text{CSA of one circumferential stiffeners} = 3.07 \text{ in}^2 \)

\( d_y = \text{distance between circumferential stiffeners} \)

\[ t_x = t_s \]

\[ t_y = 0.315 + (3.07 / 19.68) = 0.47 \text{ in.} \]

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

\[ = 9117.52 \leq \frac{y.p. - \text{minimum yield point}}{30000 \text{psi}} \]

\[ 9117.52 = 0.745 X^2 + 17.115 X + 1526.73 \]

X = 90.10 ft

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

Calculation of stresses

Upwind side:

Calculation dead weight

\[ f_{\text{dead wt. shell}} = 3.4 X \]

\[ f_{\text{dead wt. attachments}} = \sum \frac{W}{\pi d [t_s - C]} \]

wt. of top head = 923.56 lb
wt. of ladder = 25 lb/ft
wt. of vapor line = 43.8 lb/ft

total = 923.56 + 68.8 X

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

\[ = 0.839 X + 11.27 \]

\[ f_{dx} = 3.4 X + 0.839 X + 11.27 \]

\[ = 4.239 X + 11.27 \]
Wind side stress

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

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

f_{wx} = 15.89 \times 121.828 \times X^2 / 104.828^2 \times 0.25
= 0.704 X^2

Calculation of combined stress for condition of partial erection.

Upwind side:

f_{i(max)} = f_{wx} - f_{dx}
17000 \times 0.85 = 0.727 X^2 - 4.239 X - 11.27
X = 143.97 ft

Down wind side:

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

f_{c(max)} = 1.5 \times 10^6 ( t / r )
= 1.5 \times 10^6 x( 0.315 / 52.414 ) = 9014.76 psi
9014.76 = 0.727 X^2 + 4.239 X + 11.27
X = 111.34 ft

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

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

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

Flanges, Gasket, Bolt:

Gasket material - Serrated steel (asbestos filled)
Gasket factor m = 2.75
Minimum design seating stress y = 3700

Flange material - ASTM A-201 grade B
Allowable stress of flange = 15000 psi

Bolting steel - ASTM A-193 grade B-7
Allowable stress of bolting material = 15000 psi

Calculation of gasket width:

\frac{d_o}{d_i} = \sqrt{\frac{(y - Pm) / (y - P(m+1))}{\frac{P}{x}}}
\frac{d_o}{d_i} = 1.002

Assume d_i of gasket d_i = 105.828 in
\frac{d_o}{d_i} = 1.002 \times 105.828 = 106.03 in

Minimum gasket width = \frac{106.03 - 105.828}{2} = 0.211 in
Use a 0.5 in. gasket width
Mean gasket dia \( G = 105.828 + 0.5 = 106.328 \) in.

**Calculation of bolt loads:**

Load to seat gasket \( W_{m2} = H_y = b \pi G y \)

Basic gasket seating width \( b_o = 0.5 / 2 = 0.25 \) in.

\( b = b_0 \) if \( b_0 \leq 0.25 \) in.

\( W_{m2} = H_y = 0.25 \pi \times 106.328 \times 3700 = 308986.3 \) lb

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

\( = 6751.76 \) lb

Load from pressure \( H = \pi G^2 \) P / 4 = 130527.64 lb

Total operating load \( W_{m1} = H + H_p = 137279.4 \) lb

Since \( W_{m2} > W_{m1} \); Controlling load is \( W_{m2} = 308986.3 \) lb

**Calculation of minimum bolting area:**

\( A_{m2} = W_{m2} / f_b = 308986.3 / 15000 = 20.59 \) in\(^2\)

Optimum bolt size :

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

No. of bolts = 52

Bolt circle dia \( C = 108.25 \) in

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

Check gasket width :

\( A_{b \text{ actual}} = 52 \times 0.419 = 21.788 \) in\(^2\)

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

Hence acceptable.

**Moment Computations:**

For bolting up condition:

Design load = \( W = \frac{1}{2} (A_b + A_m) f_a \)

\( = \frac{1}{2} (20.59 + 21.788) 15000 = 317835 \) lb

Corresponding lever arm is given by

\( h_G = \frac{1}{2} (C - G) = 0.961 \) in.

Flange moment, \( M_a = W h_G = 305439.43 \) in lb

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

\( H_D = (\pi / 4) B^2 P = 0.785 \times 104.33^2 \times 14.7 \)
\[
\text{Lever arm }, h_D = \frac{(C - B)}{2} = 1.96 \text{ in} \\
\text{Moment } M_D = H_D \times h_D = 246188.25 \text{ in lb} \\
\]

\[
H_G = W - H = W_{in2} - H = 6751.76 \text{ lb} \\
\text{Lever arm } h_G = \frac{(C - G)}{2} = 0.961 \text{ in.} \\
M_G = H_G \times h_G = 6488.44 \text{ in. lb} \\
H_T = H - H_D \\
\quad = 4921.64 \text{ in.lb} \\
\text{Lever arm } h_T = \frac{(h_D + h_G)}{2} = 1.46 \text{ in.} \\
\text{Moment } M_T = H_T \times h_T = 7188.15 \text{ in.lb.} \\
\]

Summation of moments for the operating condition
\[
M_o = M_D + M_G + M_T = 259864.7 \text{ in.lb} \\
\]

Therefore the bolting up is controlling \( M_{max} = 305439.43 \text{ in. lb.} \)

**Calculation of flange thickness**
\[
t = \sqrt{\left( \frac{Y \times M_{max}}{f_B} \right)} \\
K = \frac{A}{B} = \frac{\text{Flange OD}}{\text{shell ID}} = \frac{110.12}{104.838} = 1.0504 \text{ in} \\
\text{For } K = 1.05, Y = 40 \\
t = 2.8 \text{ in. plate.} \\
\]

\[= 125606.26 \text{ lb} \]

\[\text{Lever arm }, h_D = \frac{(C - B)}{2} = 1.96 \text{ in}\]

\[\text{Moment } M_D = H_D \times h_D = 246188.25 \text{ in lb}\]

\[H_G = W - H = W_{in2} - H = 6751.76 \text{ lb}\]

\[\text{Lever arm } h_G = \frac{(C - G)}{2} = 0.961 \text{ in.}\]

\[M_G = H_G \times h_G = 6488.44 \text{ in. lb}\]

\[H_T = H - H_D \]
\[\quad = 4921.64 \text{ in.lb}\]

\[\text{Lever arm } h_T = \frac{(h_D + h_G)}{2} = 1.46 \text{ in.}\]

\[\text{Moment } M_T = H_T \times h_T = 7188.15 \text{ in.lb.}\]

**CHAPTER VI**

**PROCESS DESIGN OF INTER STAGE COOLER (Minor equipment)**

*(Shell and tube heat exchanger)*

**I ) Exchanger Duty:**

\[Q = 5535049 \text{ kJ/hr} \]
\[= 1537.5 \text{ kJ/sec}\]

Coolant used is Water at 27°C.

**Cooling water balance:**

\[Q = m \times C_p \times \Delta T \]
\[1537.5 = m \times 4.187 \times (42 - 27)\]
\[ m_w = 24.498 \text{ kg/sec} \]

Flow rate of liq mix to be cooled:
\[ m_{\text{mix}} = 28786.7 \text{ kg/hr} = 7.996 \text{ kg/sec} \]

Liquid mixture Balance:
\[ Q = m_{\text{mix}} \times C_{p\text{mix}} \times (T_i - 80) \]
\[ 1537.5 = 7.996 \times 3.212 \times (T_i - 80) \]
\[ T_i = 140 \degree C. \]

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

**Properties**: (at mean temperatures)

<table>
<thead>
<tr>
<th>Properties</th>
<th>Water</th>
<th>Liquid Mixture</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density ( \rho ) kg/ m(^3)</td>
<td>993.68</td>
<td>992.99</td>
</tr>
<tr>
<td>Specific heat ( C_p ) kJ/kg*K</td>
<td>4.187</td>
<td>3.212</td>
</tr>
<tr>
<td>Viscosity ( \mu ) cp</td>
<td>1.00</td>
<td>0.1612</td>
</tr>
<tr>
<td>Thermal conductivity ( K ) W/m(^2) K</td>
<td>0.578</td>
<td>0.513</td>
</tr>
</tbody>
</table>

**II Log Mean Temperature Difference** \((\Delta T_{lm})\)

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

\[
(T_1 - t_2) = 140 - 42 = 98
\]
\[
(T_2 - t_1) = 80 - 27 = 53
\]

\[ \Delta T_{lm} = 73.21 \degree C. \]

\[
R = (T_1 - T_2) / (t_2 - t_1) = 4
\]

\[
S = (t_2 - t_1) / (T_1 - t_1) = 0.132
\]

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

\[ F_T = 0.97. \]

**III Routing of Fluids:**

- Water - Tube side
- Liquid Mixture - Shell Side

**IV Heat Transfer Area:**
Assumed Value of Overall heat transfer Coefficient: 
\( U_d = 570 \text{ W/m}^2 \text{ K} \).

Dirt factor = 5.283 \times 10^{-4} \text{ m}^2 \text{ K/ W}.

\[
Q = U A(\Delta T_{lm}) F_T.
\]

\[
A = \frac{(1537.5 \times 10^3)}{(570 \times 73.21 \times 0.97)} = 37.98 \text{ m}^2
\]

V Number of Tubes:

Choose \( D_0 \) (Tube outside dia) = \( \frac{3}{4} \text{ in} = 0.01905 \text{ m} \)

\( D_i \) (Tube inside dia) = 0.62 in = 0.01575 m

Length = \( L = 14 \text{ ft} = 4.2672 \text{ m} \)

Heat transfer Area : \( a = \pi D_0 = \pi \times 0.01905 = 0.05987 \text{ m}^2 / \text{ m length} \)

Heat transfer Area for one tube = 0.05987 x 4.2672 = 0.2555 \text{ m}^2 / tube

Number of Tubes = \( 37.98 / 0.2555 = 149 \)

From Tube Count Table (PERRY : table 11-3 ; P.No. 11-13)

TEMA P or S ; for 1-2 pass 

Number of tubes \( N_t = 198 \)

Shell ID = 438 mm

Corrected Heat Transfer Area = 198 x 0.2555 = 50.589 \text{ m}^2

Corrected \( U_d = 427.977 \text{ W/m}^2 \text{ K} \).

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

Flow Area = \( a_i = \pi / 4 \times D_i^2 \times (N_t / N_p) \)

\[
= 0.01928 \text{ m}^2
\]

Velocity = \( v_t = (m_t / \rho \times a_i) = 24.498 / 993.68 \times 0.01905 \)

\[
= 1.278 \text{ m/sec}
\]

Reynolds Number \( N_{Re} = v_t D_i \rho / \mu \)

\[
= 1.278 \times 0.01575 \times 993.68 / 1.00 \times 10^{-3}
\]

\[
= 20001.28
\]

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

\[
= 7.2439
\]

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

\[
= 143.19
\]
Heat transfer coefficient \( h_i = \frac{N_{Nu} K}{D_i} \)
\[= 5254.89 \text{ W/m}^2\text{ K.}\]

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

Assumption: Shell Dia is equal to tube bundle dia.

Pitch: Equilateral Triangular Pitch is used.

\( P' = \) standard pitch = 1 in = 25.4 mm.

\( p_p = \) pitch parallel to flow = \( (\sqrt{3}/2)P' = 21.997 \) mm

\( p_n = \) pitch normal to flow = \( (1/2)P' = 12.7 \) mm

\( S_m = \) Cross flow area at center of shell
\[= [(P' - D_o) L_s] \frac{D_s}{P'}\]

\( L_s = \) baffle spacing
\[= D_s/2 = 0.219 \text{ m}\]

\( N_b = \) number of baffles

\( N_b + 1 = L/L_s = 20\)

\( N_b = 19\)

\( S_m = 0.02398 \text{ m}^2\)

Shell side velocity \( v_s = m_s/S_m \rho \)
\[= 7.996/0.0479 \times 992.99\]
\[= 0.3357 \text{ m/sec}\]

Reynolds Number \( N_{Re} = v_s D_o \rho / \mu \)
\[= 0.3357 \times 0.01905 \times 992.99/0.16128 \times 10^{-3}\]
\[= 39374.1\]

Prandtl Number \( N_{Pr} = \mu C_p / K = (0.16128 \times 10^{-3} \times 3.205 \times 10^{-3})/0.513\]
\[= 1.0076\]

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

\( j_H = 5 \times 10^{-3}\)

\( N_{Nu} = 197.36\)

Heat transfer coefficient \( h_o = N_{Nu} K / D_o\)
\[= 5314.94 \text{ W/m}^2\text{ K.}\]

**VIII Overall Heat Transfer Coefficient \( U_o \)**

\[\left(1/U_o\right)_{clean} = 1/h_o + 1/h_i (D_o/D_1) + D_o \ln(D_o/D_1) / 2 K_w\]

\( K_w = 50 \text{ W/m}^2\text{ K.}\)
\[
(1/ U_o)_{\text{clean}} = [1/ 5314.94] + [(1/ 5254.89) (0.01905/ 0.01575) ] \\
+ [(0.01905 \ln (0.01905/ 0.01575)) / (2 \times 50)]
\]
\[
= 4.5459 \times 10^{-4}
\]

\[
(1/ U_o)_{\text{dirt}} = 4.549 \times 10^{-4} + 5.283 \times 10^{-4}
\]

\[
U_o = 1017.4 \text{ W/m}^2 \text{ K}
\]
Which is greater than the assumed \( U_o \)
Hence design is acceptable.

**IX Tube Side Pressure Drop**

Friction factor \( f \) = 0.079 x \( (N_{Re})^{-0.25} \)
\[
= 0.079 x (20000)^{-0.25}
\]
\[
= 0.0066
\]

Pressure Drop \( \Delta P_L = (4 f L v_t^2 / 2 g D_i) \rho g \)
\[
= 2 x 0.0066 x 4.2672 x 1.278^2 x 993.68 / 0.01575
\]
\[
= 5842.0 \text{ N/ m}^2
\]

Pressure Drop \( \Delta P_E = 2.5 (\rho v_t^2 / 2) \)
\[
= (2.5 x 993.68 x 1.278^2) / 2
\]
\[
= 2028.7 \text{ N/ m}^2
\]

Total Pressure Drop \( \Delta P_T = N_p \left[ \Delta P_E + \Delta P_L \right] \)
\[
= 2 x [5842.0 + 2028.7]
\]
\[
= 15741.48 \text{ N/ m}^2
\]
\[
= 15.74 \text{ kPa. which is less than permissible } \Delta P = 70\text{kPa}
\]

**X Shell Side Pressure Drop**

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

\( \Delta P \) in Cross Flow Section :

\[ \Delta P_C = \left[ (b f_k w^2 N_C) / \rho S_m^2 \right] (\mu_m / \mu_b) \]

\( f_k \) (shell side friction factor ) = 0.15 \{PERRY:Fig 10-25a ;P.no.10-31\}
\( b = 2 \times 10^{-3} \) (constant )
\( w = 7.996 \text{ kg / sec} \)
\( S_m = 0.02398 \text{ m}^2 \)
\( N_C = \text{Number of cross flow zones} \)
\[
= \{D_S [ 1- (2 L_c / D_s)] \} / P_p
\]
\( L_c = \text{Baffle cut} = 0.25 D_S = 109.5 \text{ mm} \)
\( N_C = 438 x [ 1- (2 x 109.5 / 438)] / 22
\]
\[
= 10
\]
\[ \Delta P_C = \frac{(2 \times 10^{-3} \times 0.15 \times 7.996^2 \times 10)}{992.99 \times 0.02398^2} = 0.335 \text{ kPa} \]

\( \Delta P \) in end zones

\[ \Delta P_E = \Delta P_C \left[ 1 + \left( \frac{N_{CW}}{N_C} \right) \right] \]

\[ N_{CW} = \text{Number of effective cross flow region in each window} \]
\[ = 0.8 \frac{L_C}{P_p} \]
\[ = 4 \]
\[ N_C = 10 \]
\[ \Delta P_E = 0.335 \times [1 + 4/10] = 0.469 \text{ kPa} \]

\( \Delta P \) in window zones

\[ \Delta P_W = \left[ b \ w^2 \left( 2 + 0.6 \frac{N_{CW}}{N_C} \right) \right] / S_m S_w \rho \]

\[ b = 5 \times 10^{-4} \text{ (constant)} \]
\[ S_w = \text{Area for flow through window} \]
\[ = S_{wg} - S_{wt} \]
\[ S_{wg} = \text{gross window area} \]
\[ (\text{From PERRY : Fig 10-18 ; P.No. 10-29}) \]
\[ \text{For } L_C / D_S = 0.25 ; \ D_S = 17 \frac{1}{4} \text{ in.} \]
\[ S_{wg} = 0.029 \text{ m}^2 \]
\[ S_{wt} = \text{window area occupied by tubes} \]
\[ = \left( \frac{N_t}{8} \right) \left( 1 - F_c \right) \pi D_o^2 \]
\[ F_c = \text{Fraction of total tube in cross flow} \]
\[ (\text{From PERRY : Fig 10-16 ; P.No. 10-28}) \]
\[ F_c = 0.67 \]
\[ S_{wt} = (198 / 8) \times (1 - 0.67) \times \pi \times 0.01905^2 = 0.009311 \text{ m}^2 \]
\[ S_w = 0.029 - 0.009311 = 0.0196 \text{ m}^2 \]
\[ \Delta P_W = \frac{[5 \times 10^{-4} \times 7.996^2 \times (2 + 0.6 \times 4)]}{(0.02898 \times 0.0196 \times 992.99)} = 0.3013 \text{ kPa} \]

Total Pressure Drop

\[ (\Delta P)_\text{Total} = 2 (\Delta P_E) + (19 - 1) \Delta P_C + (19) \Delta P_W \]
\[ = 12.692 \text{ kPa} < 70 \text{ kPa (max allowable)} \]
MECHANICAL DESIGN

Shell Side

Material of construction : Carbon Steel
Permissible Stress (f ) : 95 N/ mm²
Fluid : Liquid mixture from absorber bottom
Working Pressure : 1 atm = 0.1013 N/ mm²
Design Pressure (P_d) : 0.11143  N/ mm²
Inlet temperature : 140 °C
Outlet temperature : 80°C
Nominal Shell Diameter : 438 mm
Length : 14 ft

Shell thickness \( t_s = \frac{P_d D_S}{[2 f J + P_d]} \) (J joint efficiency = 0.85)
\[ t_s = \frac{0.1143 \times 438}{[2 \times 95 \times 0.85 + 0.11143]} \]
= 0.3019 mm
Corrosion allowance = 3mm
Minimum thickness of 8mm is chosen

Head thickness \( t_h = \frac{P_d R_C W}{2 f J} \)
\( R_C - \text{crown radius} = 438 \text{ mm} \)
\( R_J - \text{knuckle radius} = 10\% \text{ of} \ R_C = 43.8 \text{ mm} \)
\( W - \text{stress intensifying factor} \)
\[ W = \frac{1}{4} [3 + \sqrt{(R_C / R_J)}] \]
= 1.54

\[ t_h = \frac{0.11143 \times 438 \times 1.54}{2 \times 95 \times 1} \]
= 0.39 mm
Corrosion allowance = 3mm
Thickness taken same as shell = 8mm

Baffles, tie rods and spacers

19 transverse baffles are used with 25 % baffle cut
Baffle spacing = \( \frac{D_S}{2} = 219 \text{ mm} \)
Thickness of baffles = 6mm
Number of tie rods = 6
Diameter of tie rods = 10mm

Flanges, gasket, bolts

Flange material used - ASTM A-201 grade B
Allowable stress \( f_f = 100 \text{ N/ mm}² \)
Material used for bolts - 5% Cr Mo steel
Allowable stress $f_b = 138 \text{ N/mm}^2$
Gasket material - Asbestos composition
Gasket factor $m = 2.75$
Minimum design seating stress $y = 3700$
Shell outside dia = 454 mm (B): Shell thickness = 8mm ($g_o$)

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

Estimation of bolt load
Load due to design pressure
$H = \pi G^2 P_d/4$
$= 0.01982 \text{ MN}$

Load to keep joint tight under operation
$H_p = \pi G (2b)m P_d$ (m - gasket factor = 2.75)
$= 0.005498 \text{ MN}$

Total operating load $W_o = H + H_p = 0.0253 \text{ MN}$

Load to seat gasket under bolting up condition
$W_g = \pi G b y$
$= 0.2287 \text{ MN}$

Since $W_g > W_o$, $W_g$ is the controlling load
Minimum bolting area $A_m = W_g / f_b$
$= 0.00166 \text{ m}^2$

Bolt size = M 18 x 2
Actual number of bolts = 64
Minimum bolt circle $C = 0.54 \text{ m}$
Flange outside dia $A = C + \text{ bolt dia} + 0.02$
$= 0.58 \text{ m}$

Flange moment
a) For operating condition
$W_0 = W_1 + W_2 + W_3$
$W_1 = \pi B^2 P_d/4$
$= 0.018 \text{ MN}$
$W_2 = H - W_1$
$= 0.00178 \text{ MN}$
$W_3 = W_0 - H$
$= 0.005498 \text{ MN}$
$M_o = W_1 a_1 + W_2 a_2 + W_3 a_3$
$a_1 = (C - B) / 2$
$= 0.043$
$a_2 = (C - G) / 2 = 0.032$
$a_3 = (a_1 + a_2) / 2$
\[ M_o = 0.0010166 \text{ MJ} \]

b) For bolting up condition
\[ M_g = W \times (a_3) \]
\[ W = \left[ \frac{(A_m + A_b)}{2} \right] f_b \]
\[ = 0.581 \text{ MN} \]
\[ M_g = 0.0185 \text{ MJ} \]
Since \( M_g > M_o \), \( M = M_g \)

Flange thickness \( t = (M C_F Y / B f_f) \)
\[ = 0.0576 \text{ m} \]
Actual bolt spacing \( B_s = \pi C / 44 \)
\[ = 0.0385 \text{ m} \]
Bolt pitch correction factor \( C_F = B_s / (2 \times d + t) \)
\[ d - \text{bolt dia} = 18 \text{mm} \]
\[ C_F = 0.641 \]
Actual flange thickness \( = \sqrt{C_F x 0.0576} = 0.0461 \text{ m} \)
\[ = 50 \text{mm} \]

Shell side Nozzle
Nozzle dia :
\[ m_{mix} = \rho_{mix} \times A \times v_s \]
\[ 7.996 = 992.99 \times A \times 0.3357 \]
\[ A = 0.0239 \text{ m}^2 \]
\[ A = (\pi/4) \times D_n^2 \quad : D_n = 175 \text{ mm} \]
Nozzle thickness \( t_n = P_d D_n / [2 f J - P_d] \)
\[ = 0.1026 \text{ mm} \]
Corrosion allowance = 3mm
\[ t_n = 3 \text{mm} \]

Tube side
Tube and tube sheet material - Stainless steel
Grade : S
Type : 304
Nominal composition : 18 Cr 8Ni
Maximum permissible stress = 106.52 N/ mm²
Number of tubes = 198
Tube outer dia = 19.05 mm
Tube inner dia = 15.75 mm
Length = 14 ft
Pitch (\( \Delta l \)) = 25mm
Fluid - water
Working pressure = 5 atm
Design pressure = 0.557 N/ mm²
Inlet temperature = 27 °C
Outlet temperature = 42°C

Tube thickness
\[ t_h = \frac{P_d}{D_o} \left[ \frac{2 f J + P_d}{2 f J} \right] \]
\[ = 0.0496 \text{ mm} \]
[t_h = 2mm (minimum thickness)]

Tube Sheet
thickness \[ t_{sh} = F \sqrt{0.25 \frac{P_d}{f}} \]
\[ = 1.25 \times 476 \sqrt{0.25 \times 0.557 / 106.52} \]
\[ = 21.5 \text{ mm} \]
Assuming standard fit, tube hole diameter = \( d + 0.2 = 19.2 \text{mm} \)

Channel and channel cover
Nozzle dia \( t_N \)
\[ m_t = \rho_t \cdot A \cdot v_t \]
\[ 24.498 = 993.68 \times A \times 1.278 \]
\[ A_N = 0.0193 \text{ m}^2 ; D_N = 157 \text{ mm} \]

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

Saddle Support
Equal angle support
Material of construction - Carbon steel
Density = 7800kg/m³
Outside shell dia = 454mm
Length of the shell and channel = 5209.2 mm
Total depth of head \( H = \sqrt{(D_o r_o / 2)} \)
\( r_o \) - knuckle radius = 6\% of dia = 27.24 mm
\( H = \sqrt{(454 \times 27.24 / 2)} = 78.63 \text{ mm} \)
\( A = 0.5 \times R = 113.5 \text{ mm} \)

Total weight of exchanger:
- Wt. of shell + Wt. of channel = \( (\pi / 4) (D_o^2 - D_i^2) (L + 2 b) \rho_{\text{steel}} \)
  = 455.29 kg
- Wt. of tube = \( n_t (\pi / 4) (D_o^2 - D_i^2) \rho_{\text{steel}} \)
  = 594.41 kg
- Wt. of tube sheet = \( 2 (\pi / 4) (D_o^2) t \rho_{\text{steel}} \)
  = 50.53 kg
- Wt. of liquid in shell + channel
  = (Shell volume - tube volume)\( \rho_{\text{mix}} \) + liq in channel
  = \([ (\pi / 4) (D_o^2 L - n_t (\pi / 4) D_o^2 L \] \rho_{\text{mix}}
  \quad + 2 (\pi / 4) D_i^2 b \rho_{\text{tube liq}}
  = 540.26 kg
- Wt. of liquid in tube = \( n_t (\pi / 4) D_i^2 L \rho_{\text{tube liq}} \)
  = 163.46 kg
- Wt. of end cover = \( 2 (\pi / 4) D_s^2 \rho_{\text{steel}} \)
  = 18.804 kg
- Total weight = 1822.75 kg

To account for the weight of baffles, tie rods, spacers, pass partition, plates, nozzles, bolts, nuts, total weight obtained above is multiplied by 1.3
\( W \) (wt. / support) = 1.3 \times 1822.75 / 2 = 1184.78 kg

Longitudinal Bending Moment
\( M_1 = Q A \left[ 1 - \left( \frac{L}{4} \right) \right] \left\{ \frac{1 - (A/L)}{1 + (4/3 \times H/L)} \right\} \]
\( M_2 = (Q L 4) \left[ 1 + 2 \left( R^2 - H^2 \right)/L^2 \right] / \left[ 1 + (4/3 \times H/L) \right] - (4A/L) \)

Q = W [ L + 4xH/3] = 10359.87 kg
\( M_1 = 4.995 \text{ kg m} \)
\( M_2 = 5696.58 \text{ kg m} \)

Stress in Shell at the saddle
\( f_1 = M_1 / k_1 \pi R^2 t \)
  = 4.995 / 1 \times \pi \times 0.008 \times 0.227^2 = 0.3856 \text{ kg/ cm}^2 \)

\( f_2 = M_1 / k_2 \pi R^2 t \)
  = 0.3856 \text{ kg/ cm}^2 \quad (k_1 = k_2 = 1) \)

Stress are within the permissible values.

Stress in the shell at midspan
\( f_3 = M_2 / \pi R^2 t = 439.868 \text{ kg/ cm}^2 \)

Axial stress in the shell due to internal pressure
\[ f_p = \frac{PD}{4t} = \frac{0.1143 \times 0.438}{4 \times 0.008} = 15.94 \text{ kg/cm}^2 \]

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