Chapter 2

Shortcut or approximate calculation methods
MULTICOMPONENT DISTILLATION Calculation

- Shortcut or approximate calculation methods
- Rigorous calculation or plate to plate methods
Light key & heavy key

- **Light key component**: present in the residue in important amounts while components lighter than the light key are present in only very small amounts.

- **Heavy key component**: present in the distillate in important amounts while components heavier than the heavy key are present in only very small amounts.
Total reflux calculation

In an ideal mixture the ratio of vapor pressures or the ratio of the equilibrium vaporization ratios, K’s are constant, i.e., the relative volatilities are constant

Fenske equation

\[
N_m = \frac{\log\left[\left(\frac{x_{LK}}{x_{HK}}\right)_D \left(\frac{x_{HK}}{x_{LK}}\right)_B\right]}{\log(\alpha_{LK/HK})_{av}}
\]

\[
\alpha_{av} = (\alpha_{top} \alpha_{middle} \alpha_{bot})^{\frac{1}{3}}
\]

Or

\[
1
\]
Fenske equation

The reboiler is considered one theoretical stage & also a partial condenser

Thus, the number of plates in the column utilizing a reboiler and a partial condenser is N-2

The equation can then applied to determine the distribution of other components at total reflux

\[ \frac{x_{j,D}D}{i_{av}} = \alpha_{i_{av}}^{N_{m+1}} \frac{x_{HK,D}D}{i_{av}} \]
Example 2-1 by Treybal

The following feed at 82 C ,1035 kN/m² is to be fractionated at that pressure so that the vapor distillate contains 98% of the C₃H₈ but only 1% of the C₅H₁₂

<table>
<thead>
<tr>
<th>Component</th>
<th>CH₄</th>
<th>C₂H₆</th>
<th>n-C₃H₈</th>
<th>n-C₄H₁₀</th>
<th>n-C₅H₁₂</th>
<th>n-C₆H₁₄</th>
</tr>
</thead>
<tbody>
<tr>
<td>zᵢ, mole fraction</td>
<td>0.03</td>
<td>0.07</td>
<td>0.15</td>
<td>0.33</td>
<td>0.30</td>
<td>0.12</td>
</tr>
</tbody>
</table>

Compute the number of theoretical trays at total reflux and the corresponding products
Solution

Assume distillate temperature 46 C & residue temperature 114 C

<table>
<thead>
<tr>
<th>Component</th>
<th>$\alpha_{46.6}$</th>
<th>$\alpha_{114}$</th>
<th>$\alpha_{nv} = (\alpha_{46.6} \alpha_{114})^{0.5}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_1$</td>
<td>100</td>
<td>31.9</td>
<td>56.4</td>
</tr>
<tr>
<td>$C_2$</td>
<td>23.3</td>
<td>10.43</td>
<td>15.6</td>
</tr>
<tr>
<td>$lK$ $C_3$</td>
<td>8.34</td>
<td>5.00</td>
<td>6.45</td>
</tr>
<tr>
<td>$C_4$</td>
<td>2.78</td>
<td>2.19</td>
<td>2.465</td>
</tr>
<tr>
<td>$hK$ $C_5$</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>$C_6$</td>
<td>0.415</td>
<td>0.521</td>
<td>0.465</td>
</tr>
</tbody>
</table>

$$N_m + 1 = \frac{\log\left((0.147/0.003)(0.297/0.003)\right)}{\log 6.45} = 4.55$$
Solution

For C₄:

\[ \frac{y_{C_4} D}{x_{C_4} W} = \frac{(2.465)^{4.55} \times 0.003}{0.297} = 0.611 \]

A C₄ balance:

\[ y_{C_4} D + x_{C_4} W = z_{C_4} F = 0.33 \]

Solving simultaneously gives

\[ y_{C_4} D = 0.1255 \text{ kmol} \quad x_{C_4} W = 0.2045 \text{ kmol} \]
Solution

Therefore at total reflux

\[ x_{C_1} W \approx 0 \quad y_{C_1 D} D = 0.03 \]
\[ x_{C_2} W \approx 0 \quad y_{C_2 D} D = 0.07 \]
\[ y_{C_6 D} D = 0.00003 \text{ (negligible; assume 0)} \quad x_{C_6} W = 0.12 \]

<table>
<thead>
<tr>
<th>Component</th>
<th>( y_D D )</th>
<th>( x_W W )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( C_1 )</td>
<td>0.03</td>
<td>Nil</td>
</tr>
<tr>
<td>( C_2 )</td>
<td>0.07</td>
<td>Nil</td>
</tr>
<tr>
<td>( C_3 )</td>
<td>0.1470</td>
<td>0.0030</td>
</tr>
<tr>
<td>( C_4 )</td>
<td>0.1255</td>
<td>0.2045</td>
</tr>
<tr>
<td>( C_5 )</td>
<td>0.0030</td>
<td>0.2970</td>
</tr>
<tr>
<td>( C_6 )</td>
<td>Nil</td>
<td>0.12</td>
</tr>
</tbody>
</table>

\[
0.3755 = D \\
0.6245 = W
\]
Solution

The distillate dew point computes to be 46.3°C & the residue bubble point 113°C. The assumed 46 & 114°C are close enough.
Example 2-2 by Van Winkle

The following feed is available at its bubble point at 100 psia and it is to be fractionated to produce a residue containing 95% of the isobutane in the feed and the composition with respect to propane not more than 0.1 mol%. Determine minimum plates at total reflux by the Fenske method. Use K Values from Fig 2.41.

<table>
<thead>
<tr>
<th>Feed</th>
<th>$x_F$</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1) Ethane</td>
<td>0.06</td>
</tr>
<tr>
<td>(2) Propene</td>
<td>0.09</td>
</tr>
<tr>
<td>(3) Propane</td>
<td>0.18</td>
</tr>
<tr>
<td>(4) Isobutane</td>
<td>0.18</td>
</tr>
<tr>
<td>(5) Butene</td>
<td>0.25</td>
</tr>
<tr>
<td>(6) Butane</td>
<td>0.24</td>
</tr>
</tbody>
</table>
The material balance is fixed by the specifications on the bottoms (constant vapor and liquid enthalpics are assumed in this example). basis- 1mole of feed.

<table>
<thead>
<tr>
<th>Component</th>
<th>Distillate</th>
<th>Residue</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1)</td>
<td>0.060</td>
<td>0.177</td>
</tr>
<tr>
<td>(2)</td>
<td>0.090</td>
<td>0.266</td>
</tr>
<tr>
<td>(3) LK</td>
<td>0.179</td>
<td>0.530</td>
</tr>
<tr>
<td>(4) HK</td>
<td>0.009</td>
<td>0.027</td>
</tr>
<tr>
<td>(5)</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>(6)</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td>0.338</td>
<td>1.00</td>
</tr>
</tbody>
</table>
Fenske Method. the distillate & bottoms temperatures are calculated

### Dew point of distillate

<table>
<thead>
<tr>
<th>Component</th>
<th>$y_1$</th>
<th>$K, 36^\circ F$</th>
<th>$x_1 = y_1/K$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.177</td>
<td>3.7</td>
<td>0.048</td>
</tr>
<tr>
<td>2</td>
<td>0.266</td>
<td>0.98</td>
<td>0.271</td>
</tr>
<tr>
<td>3</td>
<td>0.530</td>
<td>0.79</td>
<td>0.671</td>
</tr>
<tr>
<td>4</td>
<td>0.027</td>
<td>0.275</td>
<td>0.010</td>
</tr>
</tbody>
</table>

\[ x_1 = y_1/K = \frac{0.010}{1.000} \]

### Bubble point of bottoms

<table>
<thead>
<tr>
<th>Component</th>
<th>$x_n$</th>
<th>$K, 127^\circ F$</th>
<th>$y_n = Kx_n$</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>0.001</td>
<td>2.5</td>
<td>0.0025</td>
</tr>
<tr>
<td>4</td>
<td>0.258</td>
<td>1.15</td>
<td>0.297</td>
</tr>
<tr>
<td>5</td>
<td>0.378</td>
<td>1.0</td>
<td>0.378</td>
</tr>
<tr>
<td>6</td>
<td>0.363</td>
<td>0.88</td>
<td>0.319</td>
</tr>
</tbody>
</table>

\[ y_n = Kx_n = 0.9965 \]

\[ \alpha_{\text{top}} = 2.87 \quad \alpha_{\text{bottom}} = 2.17 \quad \bar{\alpha} = (2.87 \times 2.17)^{\frac{1}{2}} = 2.51 \]

\[ N_m = \frac{\log \left(\frac{0.530/0.027}{0.001/0.258}\right)}{\log 2.51} = 9.3 \]
Shortcut minimum Reflux Calculating methods

- Brown-Martin method
- Underwood’s Method
Brown-Martin method

In multicomponent systems if there are assumed to be two zones of constant composition requiring infinite plates for separation of the components, one above the feed plate and one below the feed plate, it can be postulated that there are sections above and below each zone of constant composition wherein some separation between the components is possible.

Under the conditions of minimum reflux, even in multicomponent systems, if the separation takes place between the two least volatile components in the feed in the upper part of the column, the ratio of the mole fractions of the key components in the liquid in the zone of constant composition (upper zone) would be the same as that in the liquid portion of the feed.
Brown-Martin method

Method of calculation (Rectifying Section):

Material balance for the heavy key component around the top of the column:

\[ VK_j x_j = D x_{jD} + L x_j \]

If no heavy component appear in the distillate:

\[ VK_j x_j = L x_j \]

\[ K_j = \frac{L}{V} \]
Brown-Martin method

Thus, the temperature in the pinch zone would be that at which:

\[ K_{HK} = \left( \frac{L}{V} \right)_{\text{min}} \]

Assumption of the method:

1- The LK/HK ratio in the pinch zone is the same as that in the feed

2- The amount of HK will be ignored at the top of the tower

3- Constant molar flow in each part of the tower
Stepwise method for Rectifying Section in Brown-Martin method

1. Assume a value for \((L/V)_{\text{min}}\). This is equal to \(K_{HK}\)

2. At the column pressure determine the temperature from suitable K charts

since the distillate actually contains some of the heavy key, the temperature will be slightly higher in the pinch zone & the K values ,thus the \((L/V)_{\text{min}}\) will be slightly higher than the value indicated previously .so assume a slightly higher value and evaluate the temperature
Stepwise method for Rectifying Section in Brown-Martin method

3. Evaluate the K values for all components in the distillate including the heavy key at the temperature & pressure in the upper zone of constant composition.

4. From the foregoing equations calculate the liquid composition in the pinch zone, for heavy key use: \( x_{HK} = 1 - \sum_{i=1}^{L_K} x_i \)

5. Assume two more minimum reflux values & repeat the calculations.

6. Plot the ratio of \( x_{L_K}/x_{H_K} \) versus \( L_{min} \).

7. At the point where the ratio of the liquid compositions of the light & heavy key equals the ratio in the liquid portion of the feed Read the \( L_{min} \).
Brown-Martin method

Method of calculation (Stripping Section): considering the stripping section involving the lower zone of constant composition:
material balance for Stripping Section

\[
\begin{align*}
\bar{L}x_i &= \bar{V}y_i + Bx_{i_B} \\
\bar{L} &= \bar{V} + B \\
y_i &= K_ix_i \\
x_i &= \frac{Bx_{i_B}}{BK_i + L(1 - K_i)} \\
\Sigma x_i &= 1.0 = \sum \frac{Bx_{i_B}}{BK_i + L(1 - K_i)}
\end{align*}
\]

If none of the light key component \( i \) appears in the bottom product

\[
\begin{align*}
\bar{L}x_i &= \bar{V}y_i + Bx_{i_B} \quad x_{i_B} = 0 \\
\bar{L}x_i &= \bar{V}K_ix_i \\
\frac{\bar{L}}{\bar{V}} &= K_{LK}
\end{align*}
\]
Stepwise method for Stripping Section in Brown-Martin method

1. Assume three values for $\bar{L}/\bar{V}$

2. Evaluate $K$’s of the components at temperatures somewhat less than $K_{LK} = \bar{L}/\bar{V}$

3. For several values of $\bar{L}/\bar{V}$ compute the $x$ $x_{LK}/x_{HK}$

4. Plot $x_{LK}/x_{HK}$ vs $\bar{L}$

5. Read the approximate minimum $\bar{L}$, from which the minimum reflux ratio is calculated
Brown-Martin method

- In this method the values of $(\frac{L}{V})_{min}$ & $(\frac{L}{V}_0)_{min}$ are not consistent (because the same components do not appear in both zones)

- The design minimum reflux ratio is that giving the higher value of $(\frac{L}{V})_{min}$
Example 2-3 by Van Winkle

A 60 mole % methanol, 20 mole % ethanol, 20 mole % 1-propanol mixture is to be fractionated to produce a distillate containing 99% of the methanol in the feed and having a purity of 99 mole % methanol. Assume ideal behavior of the mixture. The data are:

<table>
<thead>
<tr>
<th>Data</th>
<th>MeOH</th>
<th>EtOH</th>
<th>1-PrOH</th>
</tr>
</thead>
<tbody>
<tr>
<td>Antoine constants</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( A )</td>
<td>7.87863</td>
<td>8.04494</td>
<td>7.99733</td>
</tr>
<tr>
<td>( B )</td>
<td>1473.11</td>
<td>1554.3</td>
<td>1569.70</td>
</tr>
<tr>
<td>( C )</td>
<td>230.0</td>
<td>222.65</td>
<td>209.5</td>
</tr>
<tr>
<td>( \lambda ), cal/g mole, BP</td>
<td>8491.0</td>
<td>9255.0</td>
<td>10,030.0</td>
</tr>
<tr>
<td>( C_p, \text{molal}, \text{cal}/(\degree \text{C})(\text{g mole}) )</td>
<td>19.11</td>
<td>26.26</td>
<td>34.74</td>
</tr>
</tbody>
</table>
Example 2-3 by Van Winkle

Calculate the minimum reflux ratio for the following situations by the Brown-Martin method.

1. Bubble-point feed, bubble-point reflux, total condenser
2. Bubble-point feed, reflux 20°C below the bubble point, total condenser
3. Dew-point vapor feed, bubble-point reflux, total condenser
4. Dew-point vapor feed, reflux 20°C below the bubble point, total condenser
Solution

Material Balance Basis—1.0 Mole of Feed

<table>
<thead>
<tr>
<th>Component</th>
<th>Feed</th>
<th>Distillate</th>
<th>Bottoms</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Moles</td>
<td>Mole fr.</td>
</tr>
<tr>
<td>(1) MeOH (LK)</td>
<td>0.60</td>
<td>0.594</td>
<td>0.99</td>
</tr>
<tr>
<td>(2) EtOH (HK)</td>
<td>0.20</td>
<td>0.006</td>
<td>0.01</td>
</tr>
<tr>
<td>(3) 1-PrOH</td>
<td>0.20</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td>1.00</td>
<td>0.600</td>
<td>1.00</td>
</tr>
</tbody>
</table>
Solution

Column temperatures are calculated assuming that Raoult's law holds for the mixture:

Temperature at top plate = 65°C (by interpolation)
Temperature at feed plate = 71.5°C
Temperature, upper pinch ≈ 68°C
Temperature at reboiler = 86°C
Temperature, lower pinch ≈ 79°C

Upper pinch zone.

The ratio of light key to heavy key in the feed is

\[
\left( \frac{x_1}{x_2} \right)_F = \frac{0.6}{0.2} = 3
\]
Solution

Component 3 is excluded from the upper pinch and, consequently,

\[
\frac{x_1}{x_{2/m}} = 3 \quad x_1 = 0.75 \quad x_2 = 0.25
\]

\[
L = \frac{D[(x_D/x)_i - K_i]}{K_i - 1} \quad i = 1, 2
\]

Several temperature trials are made to find the \( L \) value which satisfies the equations for components 1 and 2 simultaneously.
Solution

_Trial 1:_

\[ t = 70^\circ C \quad K_1 = 1.224 \quad K_2 = 0.714 \]

\[ L(1) = \frac{0.6 \left( \frac{0.99}{0.75} - 1.224 \right)}{1.224 - 1} = 0.257 \]

\[ L(2) = \frac{0.6 \left( \frac{0.01}{0.25} - 0.714 \right)}{0.714 - 1} = 1.41 \]
Solution

**Trial 2:**

\[ t = 67^\circ C \quad K_1 = 1.091 \quad K_2 = 0.630 \]
\[ L(1) = 1.510 \quad L(2) = 0.957 \]

**Trial 3:**

\[ t = 68^\circ C \quad K_1 = 1.134 \quad K_2 = 0.658 \]
\[ L(1) = 0.833 \quad L(2) = 1.084 \]
Solution

By interpolation, \( L = 1.04 \)

\( (L/D)_{\text{min}} = 1.733 \)
Solution

Lower pinch zone.

All components are present in the pinch zone.

Several temperature trials are made to find the internal reflux ratio at which

\[(x_1/x_2)_m = 3.0\].

**Trial 1:**

Assume \((L/\bar{V})_{\text{min}} = 1.180, K_1 = 1.180, t = 69^\circ\text{C}, K_2 = 0.687, K_3 = 0.302\).

\[L = \bar{V} + 0.4 = 1.18\bar{V}\]

\[\bar{V} = \frac{0.4}{0.18} = 2.222\quad L = 2.622\]
Solution

\[ x_2 = \frac{B(x_2)_B}{BK_2 + L(1 - K_2)} = \frac{(0.4)(0.485)}{(0.4)(0.687) + 2.662(1 - 0.687)} = 0.177 \]

\[ x_3 = 0.103 \]

\[ x_1 = 1 - 0.177 - 0.103 = 0.720 \]

\[ \left( \frac{x_1}{x_2} \right)_m = 4.07 \]
Solution

**Trial 2:**

Assume \((L/V)_{\text{min}} = 1.224, \ K_1 = 1.224, \ t = 70^\circ\text{C}, \ K_2 = 0.714, \ K_3 = 0.316,\)

\[V = 1.786, \ L = 2.186.\]

\[x_2 = 0.213 \quad x_3 = 0.123\]

\[x_1 = 1 - 0.213 - 0.123 = 0.664\]

\[\left(\frac{x_1}{x_2}\right)_m = 3.07\]
Solution

**Trial 3:**

Assume \((L/\bar{V})_{\text{min}} = 1.252, \ K_1 = 1.252, \ t = 70.6^\circ C, \ K_2 = 0.733, \ K_3 = 0.326,\)

\[\bar{V} = 1.587, \ L = 1.987.\]

\[x_2 = 0.235 \quad x_3 = 0.136\]

\[x_1 = 1 - 0.235 - 0.136 = 0.629\]

\[\left(\frac{x_1}{x_2}\right)_m = 2.677\]
Solution

By interpolation, $\bar{L} = 2.155$ and $(L/D)_{\text{min}} = 1.925$

$L = \bar{L} - F = 2.155 - 1 = 1.155$
Solution

Upper pinch zone. \( (L/D)_{\text{min}} = 1.733 \)

Lower pinch zone. \( (L/D)_{\text{min}} = 1.925 \)

The larger value is chosen as a factor of safety. \( (L/D)_{\text{min}} = 1.925 \)

For (2): Cold reflux. Using the reflux ratio calculated in (1), i.e., 1.925,

\[
\frac{R_{\text{min}}}{R'_{\text{min}}} = \frac{Qc}{Qc'} \to \left( \frac{L'_0}{D} \right)_{\text{min}} = \frac{8491}{8491 + 382} 1.925 = 1.84
\]

For (3): Dew-point vapor feed. The liquid at the feed plate is taken as that in equilibrium with the feed
Solution

### Dew-point Temperature and Composition of Liquid in Equilibrium with Feed

<table>
<thead>
<tr>
<th>Component</th>
<th>$y_F$</th>
<th>$K$, 78°C</th>
<th>$x_F = y_F/K$</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1) MeOH (LK)</td>
<td>0.60</td>
<td>1.645</td>
<td>0.365</td>
</tr>
<tr>
<td>(2) EtOH (HK)</td>
<td>0.20</td>
<td>0.988</td>
<td>0.202</td>
</tr>
<tr>
<td>(3) 1-PrOH</td>
<td>0.20</td>
<td>0.454</td>
<td>0.441</td>
</tr>
</tbody>
</table>

\[
\left(\frac{x_1}{x_2}\right)_F = \frac{0.365}{0.202} = 1.81
\]
Solution

For the *upper pinch zone* the trials are summarized:

<table>
<thead>
<tr>
<th>Trial</th>
<th>$t$, °C</th>
<th>$L(1)$</th>
<th>$L(2)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>70</td>
<td>0.833</td>
<td>1.439</td>
</tr>
<tr>
<td>2</td>
<td>69</td>
<td>1.19</td>
<td>1.26</td>
</tr>
<tr>
<td>3</td>
<td>68.5</td>
<td>1.46</td>
<td>1.18</td>
</tr>
</tbody>
</table>

By interpolation, $L = 1.24$, $(L/D)_{\text{min}} = 2.067$. 
Solution

For the lower pinch zone:

<table>
<thead>
<tr>
<th>Trial</th>
<th>$t$, °C</th>
<th>$L$</th>
<th>$(x_1/x_2)_m$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>70.6</td>
<td>1.987</td>
<td>2.677</td>
</tr>
<tr>
<td>2</td>
<td>72</td>
<td>1.65</td>
<td>1.913</td>
</tr>
<tr>
<td>3</td>
<td>72.5</td>
<td>1.553</td>
<td>1.713</td>
</tr>
</tbody>
</table>

By interpolation, $L = L = 1.6$

$\rightarrow (L/D)_{\text{min}} = 2.67$
Solution

For (4): Using cold reflux and a dew-point vapor feed,

\[
\left( \frac{L_0'}{D} \right) = (0.957)(2.67) = 2.55
\]
Underwood’s Method

assumption \[
\begin{aligned}
\text{constant molal overflow} \\
\text{constant relative volatility}
\end{aligned}
\] at the mean column temperature.

Where the light key and heavy key are adjacent

1. The value of \( \theta \), the correct value of which must lie numerically between the \( \alpha \) values of the keys, is found by trial and error from

\[
\sum_{1}^{n} \frac{x_F}{(\alpha - \theta)/\alpha} = 1 - q = \frac{(\alpha_a x_a)_F}{\alpha_a - \theta} + \frac{(\alpha_b x_b)_F}{\alpha_b - \theta} + \cdots + \frac{(\alpha_n x_n)_F}{\alpha_n - \theta}
\]
Underwood’s Method

\[ x_{a_f} = \text{mole fraction total of } a \text{ in the feed} \]

\[ \alpha_a = \text{relative volatility of } a \text{ referred to the heaviest component or to the heavy key} \]

\[ q = \text{the number of moles of saturated liquid formed on the feed plate by the introduction of one mole of feed.} \]

For

\[ \begin{cases} 
\text{a bubblepoint feed } q = 1.0 \\
\text{dew-point feed } q = 0 
\end{cases} \]
Underwood’s Method

2. Substitute the value of $\theta$ into

$$\left(\frac{L_0}{D}\right)_{\text{min}} + 1 = \sum_{1}^{n} \frac{x_D}{(\alpha - \theta)/\alpha} = \frac{(\alpha_a x_a)_D}{\alpha_a - \theta} + \frac{(\alpha_b x_b)_D}{\alpha_b - \theta} + \cdots + \frac{(\alpha_n x_n)_D}{\alpha_n - \theta}$$

calculate the value of $(L/D)_{\text{min}}$
Example 2-4 by Van Winkle

A multicomponent mixture of the composition below and consisting of 66% vapor is to be fractionated to produce the products shown. Determine the minimum reflux by the Underwood method. The reflux is a bubble-point liquid.

<table>
<thead>
<tr>
<th>Component</th>
<th>$x_F$</th>
<th>$x_D$</th>
<th>$x_B$</th>
<th>$\alpha$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a$</td>
<td>0.26</td>
<td>0.434</td>
<td>—</td>
<td>100</td>
</tr>
<tr>
<td>$b$</td>
<td>0.09</td>
<td>0.150</td>
<td>—</td>
<td>24.6</td>
</tr>
<tr>
<td>(LK) $c$</td>
<td>0.25</td>
<td>0.411</td>
<td>0.010</td>
<td>10.0</td>
</tr>
<tr>
<td>(HK) $d$</td>
<td>0.17</td>
<td>0.005</td>
<td>0.417</td>
<td>4.85</td>
</tr>
<tr>
<td>$e$</td>
<td>0.11</td>
<td>—</td>
<td>0.274</td>
<td>2.08</td>
</tr>
<tr>
<td>$f$</td>
<td>0.12</td>
<td>—</td>
<td>0.299</td>
<td>1.00</td>
</tr>
</tbody>
</table>
Solution

Base on the *heaviest* component (not the heavy key)

Since the feed consists of 66% vapor  \( 1 - q = 0.66 \)

\[
\sum \frac{x_F}{(\alpha - \theta)/\alpha} = 1 - q = 0.66
\]

**Trial 1: Assume \( \theta = 6.73 \)**

<table>
<thead>
<tr>
<th>Component</th>
<th>( \alpha )</th>
<th>( \frac{\alpha - \theta}{\alpha} )</th>
<th>( x_F )</th>
<th>( \frac{x_F}{(\alpha - \theta)/\alpha} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>100</td>
<td>0.9327</td>
<td>0.26</td>
<td>0.279</td>
</tr>
<tr>
<td>b</td>
<td>24.6</td>
<td>0.726</td>
<td>0.09</td>
<td>0.124</td>
</tr>
<tr>
<td>c</td>
<td>10.0</td>
<td>0.327</td>
<td>0.25</td>
<td>0.765</td>
</tr>
<tr>
<td>d</td>
<td>4.85</td>
<td>0.388</td>
<td>0.17</td>
<td>-0.438</td>
</tr>
<tr>
<td>e</td>
<td>2.08</td>
<td>-2.235</td>
<td>0.11</td>
<td>-0.049</td>
</tr>
<tr>
<td>f</td>
<td>1.00</td>
<td>-6.73</td>
<td>0.12</td>
<td>-0.018</td>
</tr>
</tbody>
</table>

\[
\sum \frac{x_F}{(\alpha - \theta)/\alpha} = 0.661
\]
Solution

Calculated $0.661 = 1 - q$  This is a satisfactory solution

The $(L/D)_m$ calculation is:

<table>
<thead>
<tr>
<th>Component</th>
<th>$\alpha - \theta$</th>
<th>$x_D$</th>
<th>$\frac{x_D}{(\alpha - \theta)/\alpha}$</th>
<th>$(L/D)_m + 1 = 1.911$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a$</td>
<td>0.938</td>
<td>0.434</td>
<td>0.462</td>
<td></td>
</tr>
<tr>
<td>$b$</td>
<td>0.726</td>
<td>0.150</td>
<td>0.207</td>
<td>$(L/D)_m = 0.911$</td>
</tr>
<tr>
<td>$c$</td>
<td>0.327</td>
<td>0.411</td>
<td>1.255</td>
<td></td>
</tr>
<tr>
<td>$d$</td>
<td>-0.388</td>
<td>0.005</td>
<td>-0.013</td>
<td></td>
</tr>
</tbody>
</table>
Empirical evaluation of number of equilibrium stages

- Gilliland
- Erbar and Maddox
The method of determining the number of equilibrium stages at a desired reflux ratio is:

1. Determine the minimum reflux ratio by one of the shortcut methods
2. Determine the minimum number of stages at total reflux by Fenske method
3. Compute the values of the abscissae & evaluate the corresponding ordinate
4. From this value with the the minimum number of equilibrium stages known, the number of equilibrium stages at the required reflux is calculated
Gilliland correlation

**Constrains:**

- Number of component: 2-11
- Pressure: up to 600 psig
- Volatility: 1.26-4.05
- $R_m=0.53-7$
- Number of stages= 2.4-43.1

This correlation is empirical and generalized with respect to system & conditions, therefore, it cannot be expected that highly accurate results can be obtained.

*Gilliland correlation of reflux ratio, theoretical stages, minimum reflux ratio, and minimum stages. [From Gilliland, Ind. Eng. Chem., 32:1101 (1940).]*
Erbar and Maddox

it is now generally considered to give more reliable predictions
Feed-point location

Empirical equation given by Kirkbride

\[
\log \left[ \frac{N_r}{N_s} \right] = 0.206 \log \left[ \left( \frac{B}{D} \right) \left( \frac{x_{f,\text{HK}}}{x_{f,\text{LK}}} \right) \left( \frac{x_{b,\text{LK}}}{x_{d,\text{HK}}} \right)^2 \right]
\]

- \( N_r \) = number of stages above the feed, including any partial condenser
- \( N_s \) = number of stages below the feed, including the reboiler
- \( B \) = molar flow bottom product
- \( D \) = molar flow top product
- \( x_{f,\text{HK}} \) = concentration of the heavy key in the feed.
- \( x_{f,\text{LK}} \) = concentration of the light key in the feed
- \( x_{b,\text{LK}} \) = concentration of the light key if in the bottom product.
- \( x_{d,\text{HK}} \) = concentration of the heavy key in the top product
Hengstebeck and Geddes have shown that Fenske equation can be written in the form:

$$\log \left( \frac{d_i}{b_i} \right) = A + C \log \alpha_i$$

$d_i$ = the flow rate of component $i$ in the tops

$b_i$ = the flow rate of component $i$ in the bottoms.

Specifying the split of the key components determines the constants $A$ and $C$ in the equation

The distribution of the other components can be readily determined by plotting the distribution of the keys against their relative volatility on log-log paper, and drawing a straight line through these two points. The method is illustrated in Example 11.6
Pseudo-binary systems

- If the presence of the other components does not significantly affect the volatility of the key components, the keys can be treated as a pseudo-binary pair.
- The number of stages can then be calculated using a McCabe-Thiele diagram, or the other methods developed for binary systems.
- This simplification can often be made when:
  - the amount of the non-key components is small
  - the components form near-ideal mixtures
- For concentrations higher than 10 percent the method proposed by Hengstebeck can be used to reduce the system to an equivalent binary system.
Hengstebeck’s method

For any component $i$ the material balance equations for rectifying section

\[ v_{n+1,i} = l_{n,i} + d_i \]
\[ v_{n+1} = V y_{n+1,i} \]
\[ d_i = D x_{D,i} \]
\[ y_{n,i} = K_{n,i} x_{n,i} \]

By multiplying each side in $V$:

\[ V y_{n,i} = K_{n,i} V \frac{L x_{n,i}}{L} \]
\[ v_{n,i} = K_{n,i} \frac{V}{L} l_{n,i} \]
Hengstebeck’s method

for the stripping section:

\[ \bar{l}_{m+1,i} = \bar{v}_{m,i} + b_i \]

\[ \bar{v}_{m,i} = K_{m,i} \frac{\bar{V}}{L} \bar{l}_{m,i} \]

\( V \) and \( L \) are the total flow-rates, assumed constant

\( l_{n,i} \) = the liquid flow rate of any component \( i \) from stage \( n \)

\( v_{n,i} \) = the vapour flow rate of any component \( i \) from stage \( n \).

\( d_i \) = the flow rate of component \( i \) in the tops

\( b_i \) = the flow rate of component \( i \) in the bottoms.

\( K_{n,i} \) = the equilibrium constant for component \( i \) at stage \( n \).
Hengstebeck’s method

To reduce a multicomponent system to an equivalent binary it is necessary to estimate the flow-rate of the key components throughout the column.

In a typical distillation, the flow-rates of each of the light non-key components approach a constant, limiting, rate in the rectifying section; and the flows of each of the heavy non-key components approach limiting flow-rates in the stripping section.

Putting the flow-rates of the non-keys equal to these limiting rates in each section enables the combined flows of the key components to be estimated.
Hengstebeck’s method

Rectifying section

\[ L_e = L - \Sigma l_i \]
\[ V_e = V - \Sigma v_i \]

Stripping section

\[ L'_e = L' - \Sigma l'_i \]
\[ V'_e = V' - \Sigma v'_i \]

\( V_e \) and \( L_e \) are the estimated flow rates of the combined keys.

\( l_i \) and \( v_i \) are the limiting liquid and vapour rates of components lighter than the keys in the rectifying section.

\( l'_i \) and \( v'_i \) are the limiting liquid and vapour rates of components heavier than the keys in the stripping section.
Hengstebeck’s method

The method used to estimate the limiting flow-rates is that proposed by Jenny Hengstebeck:

\[ l_i = \frac{d_i}{\alpha_i - 1} \]
\[ v_i = l_i + d_i \]
\[ v'_i = \frac{\alpha_i b_i}{\alpha_{LK} - \alpha_i} \]
\[ l'_i = v'_i + b_i \]

\( \alpha_i \) = relative volatility of component \( i \), relative to the heavy key (HK)

\( \alpha_{LK} \) = relative volatility of the light key (LK), relative to the heavy key.
Estimates of the flows of the combined keys enable operating lines to be drawn for the equivalent binary system.

The equilibrium line is drawn by assuming a constant relative volatility for the light key

\[ y = \frac{\alpha_{LK}x}{1 + (\alpha_{LK} - 1)x} \]

where \( y \) and \( x \) refer to the vapour and liquid concentrations of the light key
Example 2-5 by Coulson V6

Estimate the number of ideal stages needed in the butane-pentane splitter defined by the compositions given in the table below. The column will operate at a pressure of 8.3 bar, with a reflux ratio of 2.5. The feed is at its boiling point.

<table>
<thead>
<tr>
<th></th>
<th>Feed (f)</th>
<th>Tops (d)</th>
<th>Bottoms (b)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Propane, C₃</td>
<td>5</td>
<td>5</td>
<td>0</td>
</tr>
<tr>
<td>i-Butane, iC₄</td>
<td>15</td>
<td>15</td>
<td>0</td>
</tr>
<tr>
<td>n-Butane, nC₄</td>
<td>25</td>
<td>24</td>
<td>1</td>
</tr>
<tr>
<td>i-Pentane, iC₅</td>
<td>20</td>
<td>1</td>
<td>19</td>
</tr>
<tr>
<td>n-Pentane, nC₅</td>
<td>35</td>
<td>0</td>
<td>35</td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>45</td>
<td>55 kmol</td>
</tr>
</tbody>
</table>
Solution

The top and bottom temperatures were calculated by determining dew points and bubble points.

\[ \alpha_i = \frac{K_i}{K_{HK}} \]

Relative volatilities

<table>
<thead>
<tr>
<th>Temp. °C</th>
<th>Top</th>
<th>Bottom</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>C_3</td>
<td>5.5</td>
<td>4.5</td>
<td>5.0</td>
</tr>
<tr>
<td>iC_4</td>
<td>2.7</td>
<td>2.5</td>
<td>2.6</td>
</tr>
<tr>
<td>(LK) nC_4</td>
<td>2.1</td>
<td>2.0</td>
<td>2.0</td>
</tr>
<tr>
<td>(HK) iC_5</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>nC_5</td>
<td>0.84</td>
<td>0.85</td>
<td>0.85</td>
</tr>
</tbody>
</table>
### Solution

Calculations of non-key flows

<table>
<thead>
<tr>
<th></th>
<th>$\alpha_i$</th>
<th>$d_i$</th>
<th>$l_i = d_i / (\alpha_i - 1)$</th>
<th>$v_i = l_i + d_i$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\text{C}_3$</td>
<td>5</td>
<td>5</td>
<td>1.3</td>
<td>6.3</td>
</tr>
<tr>
<td>$\text{iC}_4$</td>
<td>2.6</td>
<td>15</td>
<td>9.4</td>
<td>24.4</td>
</tr>
</tbody>
</table>

$\Sigma l_i = 10.7$ \hspace{1cm} $\Sigma v_i = 30.7$

<table>
<thead>
<tr>
<th></th>
<th>$\alpha_i$</th>
<th>$b_i$</th>
<th>$v'<em>i = \alpha_i b_i / (\alpha</em>{\text{LK}} - \alpha_i)$</th>
<th>$l'_i = v'_i + b_i$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\text{nC}_5$</td>
<td>0.85</td>
<td>35</td>
<td>25.9</td>
<td>60.9</td>
</tr>
</tbody>
</table>

$\Sigma v'_i = 25.9$ \hspace{1cm} $\Sigma l'_i = 60.9$
Solution

Flows of combined keys

\[ L_e = 2.5 \times 45 - 10.7 = 101.8 \]
\[ V_e = (2.5 + 1)45 - 30.7 = 126.8 \]
\[ V'_e = (2.5 + 1)45 - 25.9 = 131.6 \]
\[ L'_e = (2.5 + 1)45 + 55 - 60.9 = 151.6 \]

Slope of top operating line

\[ \frac{L_e}{V_e} = \frac{101.8}{126.8} = 0.8 \]

Slope of bottom operating line

\[ \frac{L'_e}{V'_e} = \frac{151.6}{131.6} = 1.15 \]
Solution

\[ x_b = \frac{\text{flow LK}}{\text{flow (LK + HK)}} = \frac{1}{19 + 1} = 0.05 \]

\[ x_d = \frac{24}{24 + 1} = 0.96 \]

\[ x_f = \frac{25}{25 + 20} = 0.56 \]

\[ y = \frac{2x}{1 + (2 - 1)x} = \frac{2x}{1 + x} \]

<table>
<thead>
<tr>
<th></th>
<th>0</th>
<th>0.20</th>
<th>0.40</th>
<th>0.60</th>
<th>0.80</th>
<th>1.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>x</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>y</td>
<td></td>
<td>0.33</td>
<td>0.57</td>
<td>0.75</td>
<td>0.89</td>
<td>1.0</td>
</tr>
</tbody>
</table>
Solution

The McCabe-Thiele diagram is shown in Figure below

12 stages required

feed on 7th plate from top
Example 2-6 by Coulson V6

Use the Geddes-Hengstebeck method to check the component distributions for the separation specified in Example 11.5

<table>
<thead>
<tr>
<th>Component</th>
<th>( \alpha_i )</th>
<th>Feed ( (f_i) )</th>
<th>Distillate ( (d_i) )</th>
<th>Bottoms ( (b_i) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>C_3</td>
<td>5</td>
<td>5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>iC_4</td>
<td>2.6</td>
<td>15</td>
<td></td>
<td></td>
</tr>
<tr>
<td>nC_4 (LK)</td>
<td>2.0</td>
<td>25</td>
<td>24</td>
<td>1</td>
</tr>
<tr>
<td>iC_5 (HK)</td>
<td>1.0</td>
<td>20</td>
<td>1</td>
<td>19</td>
</tr>
<tr>
<td>nC_5</td>
<td>0.85</td>
<td>35</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Solution

The average volatilities will be taken as those estimated in Example 11.5. Normally, the volatilities are estimated at the feed bubble point, which gives a rough indication of the average column temperatures.

The dew point of the tops and bubble point of the bottoms can be calculated once the component distributions have been estimated.

The calculations repeated with a new estimate of the average relative volatilities, as necessary.

For the light key, \( \frac{d_i}{b_i} = \frac{24}{1} = 24 \)

These values are plotted on Figure 11.12.

For the heavy key, \( \frac{d_i}{b_i} = \frac{1}{19} = 0.053 \)
The distribution of the non-keys are read from Figure 11.12 at the appropriate relative volatility

the component flows calculated from the following equations:

Overall column material balance:

\[ f_i = d_i + b_i \]

\[ d_i = \frac{f_i}{\left(\frac{b_i}{d_i} + 1\right)} \]

\[ b_i = \frac{f_i}{\left(\frac{d_i}{b_i} + 1\right)} \]
Solution

<table>
<thead>
<tr>
<th></th>
<th>$\alpha_i$</th>
<th>$f_i$</th>
<th>$d_i/b_i$</th>
<th>$d_i$</th>
<th>$b_i$</th>
</tr>
</thead>
<tbody>
<tr>
<td>C3</td>
<td>5</td>
<td>5</td>
<td>40,000</td>
<td>5</td>
<td>0</td>
</tr>
<tr>
<td>iC4</td>
<td>2.6</td>
<td>15</td>
<td>150</td>
<td>14.9</td>
<td>0.1</td>
</tr>
<tr>
<td>nC4</td>
<td>2.0</td>
<td>25</td>
<td>21</td>
<td>24</td>
<td>1</td>
</tr>
<tr>
<td>iC5</td>
<td>1.0</td>
<td>20</td>
<td>0.053</td>
<td>1</td>
<td>19</td>
</tr>
<tr>
<td>nC5</td>
<td>0.85</td>
<td>35</td>
<td>0.011</td>
<td>0.4</td>
<td>34.6</td>
</tr>
</tbody>
</table>

As these values are close to those assumed for the calculation of the dew points and bubble points in Example 11.5, there is no need to repeat with new estimates of the relative volatilities.
Example 2-7 Coulson V6

For the separation specified in Example 11.5, evaluate the effect of changes in reflux ratio on the number of stages required. This is an example of the application of the Erbar-Maddox method.
Solution

The relative volatilities estimated in Example 11.5, and the component distributions calculated in Example 11.6 will be used for this example.

<table>
<thead>
<tr>
<th></th>
<th>$\alpha_i$</th>
<th>$f_i$</th>
<th>$d_i$</th>
<th>$b_i$</th>
</tr>
</thead>
<tbody>
<tr>
<td>C₃</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>0</td>
</tr>
<tr>
<td>iC₄</td>
<td>2.6</td>
<td>15</td>
<td>14.9</td>
<td>0.1</td>
</tr>
<tr>
<td>nC₄ (LK)</td>
<td>2.0</td>
<td>25</td>
<td>24</td>
<td>1</td>
</tr>
<tr>
<td>iC₅ (HK)</td>
<td>1</td>
<td>20</td>
<td>1</td>
<td>19</td>
</tr>
<tr>
<td>nC₅</td>
<td>0.85</td>
<td>35</td>
<td>0.4</td>
<td>34.6</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>$D = 45.3$</th>
<th>$B = 54.7$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>100</td>
<td></td>
</tr>
</tbody>
</table>
Solution

Minimum number of stages; Fenske equation

\[ N_m = \log \left( \frac{24}{1} \right) \left( \frac{19}{1} \right) \log 2 = 8.8 \]

Minimum reflux ratio; Underwood equations

As the feed is at its boiling point q=1

\[ \sum \frac{\alpha_i x_{i,f}}{\alpha_i - \theta} = 0 \]
Solution

\[
\begin{array}{cccccc}
 x_{i,f} & \alpha_i & \alpha_i x_{i,f} & \theta = 1.5 & \theta = 1.3 & \theta = 1.35 \\
 0.05 & 5 & 0.25 & 0.071 & 0.068 & 0.068 \\
 0.15 & 2.6 & 0.39 & 0.355 & 0.300 & 0.312 \\
 0.25 & 2.0 & 0.50 & 1.000 & 0.714 & 0.769 \\
 0.20 & 1 & 0.20 & -0.400 & -0.667 & -0.571 \\
 0.35 & 0.85 & 0.30 & -0.462 & -0.667 & -0.600 \\
 \hline
 \Sigma = 0.564 & -0.252 & 0.022 & \text{close enough} \\
\end{array}
\]

\[
\begin{array}{cccc}
 x_{i,d} & \alpha_i & \alpha_i x_{i,d} & \alpha_i x_{i,d} / (\alpha_i - \theta) \\
 0.11 & 5 & 0.55 & 0.15 \\
 0.33 & 2.6 & 0.86 & 0.69 \\
 0.53 & 2.0 & 1.08 & 1.66 \\
 0.02 & 1 & 0.02 & -0.06 \\
 0.01 & 0.85 & 0.01 & -0.02 \\
 \hline
 \Sigma = 2.42 \\
\end{array}
\]

\[R_m + 1 = 2.42\]

\[R_m = 1.42\]
Solution

Specimen calculation, for $R = 2.0$

\[
\frac{R_m}{(R_m + 1)} = \frac{1.42}{2.42} = 0.59
\]

\[
\frac{R}{(R + 1)} = \frac{2}{3} = 0.66
\]

\[
\frac{N_m}{N} = 0.56
\]

\[
N = \frac{8.8}{0.56} = 15.7
\]

from Figure 11.11
Above a reflux ratio of 4 there is little change in the number of stages required, and the optimum reflux ratio will be near this value.
Example 2-8 by Coulson V6

Estimate the position of the feed point for the separation considered in Example 11.7, for a reflux ratio of 3.
Solution

Use the Kirkbride equation, equation 11.62. Product distributions taken from Example 11.6

\[ x_{b,\text{LK}} = \frac{1}{54.7} = 0.018 \]

\[ x_{d,\text{HK}} = \frac{1}{45.3} = 0.022 \]

\[ \log \left( \frac{N_r}{N_s} \right) = 0.206 \log \left[ \frac{54.7}{45.3} \left( \frac{0.20}{0.25} \right) \left( \frac{0.018}{0.022} \right)^2 \right] \]

\[ \log \left( \frac{N_r}{N_s} \right) = 0.206 \log(0.65) \]
Solution

\[ \frac{N_r}{N_s} = 0.91 \]

number of stages, excluding the reboiler = 11

\[ N_r + N_s = 11 \]

\[ N_s = 11 - N_r = 11 - 0.91N_s \]

\[ N_s = \frac{11}{1.91} = 5.76, \text{ say } 6 \]
Simulation of Shortcut column Using Hysys
Methods

- The shortcut column performs Fenske calculation for minimum number of trays

- The shortcut column performs Underwood calculation for minimum reflux
Problem

A methanol-water solution containing 50% wt methanol at 37.8°F is to be continuously rectified at 1 std atm pressure at a rate of 5000 kg/h to provide a distillate containing 95% methanol and a residue containing 1% methanol (by weight). The distillate is to be totally condensed to a liquid. A reflux ratio of 1.5 times the minimum will be used.

Find the minimum reflux ratio & other design parameters
Step1: creating a fluid package
Creating a fluid package
Creating a fluid package
Step 2: installing the column

<table>
<thead>
<tr>
<th></th>
<th>MassFraction</th>
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<tbody>
<tr>
<td>Methanol</td>
<td>5.0000e+01</td>
</tr>
<tr>
<td>H2O</td>
<td>5.0000e+01</td>
</tr>
</tbody>
</table>

Composition Basis:
- Mole Fractions
- Mass Fractions
- Liq Volume Fractions
- Mole Flows
- Mass Flows
- Liq Volume Flows

Equalize Composition: Total 1.0000e+02

OK
Step3: Installing the shortcut column
Installing the shortcut column
Installing the shortcut column
Step 4: Results of simulation

<table>
<thead>
<tr>
<th>Performance</th>
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<tbody>
<tr>
<td>Trays</td>
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<tr>
<td>Minimum Number of Trays</td>
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<tr>
<td>Actual Number of Trays</td>
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<td>Optimal Feed Stage</td>
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<tr>
<td>Temperatures</td>
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<tr>
<td>Condenser [C]</td>
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<tr>
<td>Reboiler [C]</td>
<td>165.4</td>
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<td>Flows</td>
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<td>Rectify Vapour [kgmole/h]</td>
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<tr>
<td>Rectify Liquid [kgmole/h]</td>
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<tr>
<td>Stripping Vapour [kgmole/h]</td>
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<tr>
<td>Stripping Liquid [kgmole/h]</td>
<td>316.366</td>
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<tr>
<td>Condenser Duty [kJ/h]</td>
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<tr>
<td>Reboiler Duty [kJ/h]</td>
<td>7973475.469</td>
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