Distillation

ChEN 5253 Design II

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Distillation

Feed

light key mole fraction = Zf

Total Condenser

Reflux

Light-key mole fraction = XD

Distillate

Partial Reboiler

Bottoms Light-key mole fraction = XB

condenser

cooling water

accumulator

liquid-level control

top product

vapor from reboiler

steam

bottom product

reboiler
Plate Types

- Bubble Cap Tray
- Sieve Tray
Packed Towers

• Random Packing

• Structured Packing

Note: Importance of Distributor plate
Distillation

• Relative Volatility

• Equilibrium Line

\[ \alpha_{AB} = \frac{y_A / x_A}{y_B / x_B} \]

\[ y_A = \frac{\alpha_{A,B} \times x_A}{1 + x_A (\alpha_{A,B} - 1)} \]

\[ \alpha = \frac{K_L}{K_H} \]
Distillation

• Rectifying Section
  – R = reflux ratio
  – V = vapor flow rate

• Stripping Section
  – \( V_B \) = Boil-up ratio
  \[ V_B = \frac{V_{N+1}}{B} \]

• Feed Line
  \[ q = 1 + \frac{\bar{V} - V}{F} \]
Minimum Reflux Ratio

\[ R_{\text{min}} = \frac{(L/V)_{\text{min}}}{1 - (L/V)_{\text{min}}} \]
Equation:

\[ y = \frac{L}{V} x + \frac{D}{V} x_D \]

Equilibrium curve

Slope = \( \frac{L}{V} \)

Stripping-section operating line

\[ y = \left( \frac{q}{g-1} \right) x - \frac{z_F}{(q-1)} \]

\( q \)-line

\[ x = z_F \]

45° line

\[ x = \frac{L}{V} x - \frac{B}{V} x_B \]

\( x = x_B \)
Step Off Equilibrium Trays
Marginal Vapor Rate

- Marginal Annualized Cost ~ Marginal Vapor Rate
- Marginal Annualized Cost proportional to
  - Reboiler Duty (Operating Cost)
  - Condenser Duty (Operating Cost)
  - Reboiler Area (Capital Cost)
  - Condenser Area (Capital Cost)
  - Column Diameter (Capital Cost)
- Vapor Rate is proportional to all of the above
Short cut to Selecting a Column Design

• Minimum Cost for Distillation Column will occur when you have a
  – Minimum of Total Vapor Flow Rate for column
  – Occurs at
    • \[ R = 1.2 \ R_{\text{min}} \ @ \ N/N_{\text{min}} = 2, \]
    • \[ N_{\text{min}} = \log[(d_{LK}/b_{LK})(b_{HK}/d_{HK})]/\log[\alpha_{LK,HK}] \]
    • \[ R_{\text{min}} \sim (F/D)/(\alpha-1) \]
    – \[ V = D \ (R+1) \]
  • \( V = \) Vapor Flow Rate
  • \( D = \) Distillate Flow Rate (=Production Rate)
  • \( R = \) Reflux Ratio
How To Determine the Column Pressure given coolant

• Cooling Water Available at 90°F
• Distillate Can be cooled to 120°F min.
• Calculate the Bubble Pt. Pressure of Distillate Composition at 120°F
  – equals Distillate Pressure
  – Bottoms Pressure = Distillate Pressure +10 psia delta P
• Compute the Bubble Pt. Temp for an estimate of the Bottoms Composition at Distillate Pressure
  – Give Bottoms Temperature

• Not Near Critical Point for mixture
Design Issues

- **Packing vs Trays**
- **Column Diameter from flooding consideration**
  - Trays, $D_T = \left[\frac{4G}{(f U_{\text{flood}} \pi (1-A_{\text{down}}/A_T) \rho_G)}\right]^{1/2}$  \hspace{1cm} eq. 13.11
  - $U_{\text{flood}} = f(\text{dimensionless density difference})$, $f = 0.75-0.85$  \hspace{1cm} eq. 13.12
  - Packed, $D_T = \left[\frac{4G}{(f U_{\text{flood}} \pi \rho_G)}\right]^{1/2}$  \hspace{1cm} eq. 13.14
  - $U_{\text{flood}} = f(\text{flow ratio})$, $f = 0.75-0.85$  \hspace{1cm} eq. 13.15

- **Column Height**
  - $N_{\text{min}} = \log\left[\frac{(d_{\text{LK}}/b_{\text{LK}})(b_{\text{HK}}/d_{\text{HK}})}{\alpha_{\text{LK,HK}}}\right]$ \hspace{1cm} eq. 13.1
  - $N = N_{\text{min}}/\epsilon$  \hspace{1cm} (or 2 $N_{\text{min}}/\epsilon$)
    - Column Height = $N \times H_{\text{tray}}$
    - Tray Height = typically 1 ft (or larger)
    - Packed Height = $N_{\text{eq}} \times \text{HETP}$ (or 2 $N_{\text{eq}} \times \text{HETP}$)
      - HETP(height equivalent of theoretical plate)
      - HETP$_{\text{random}} = 1.5 \text{ ft/in} \times D_p$  \hspace{1cm} Rule of thumb  \hspace{1cm} eq. 13.9

- **Tray Efficiency**, $\epsilon = f(\text{viscosity}_{\text{liquid}} \times \alpha_{\text{LK,HK}})$  \hspace{1cm} Fig 13.3

- **Pressure Drop**
  - Tray, $\Delta P = \rho_L g \cdot h_{\text{L-wier}} \cdot N$
  - Packed, $\Delta P = \text{Packed bed (weeping)}$
Tray Efficiency

Figure 14.3 Lockhart and Leggett version of O'Connell correlation for plate efficiency.

\[ \mu_L \times \alpha_{LK,HK} \]
Costing
Column Costs

- Column – Material of Construction gives $\rho_{\text{metal}}$
  - Pressure Vessel $C_p = F_M C_v(W) + C_{\text{Platform}}$
  - Height may include the reboile accumulator tank
  - Tray Cost = $N * C_{\text{tray}}(D_T)$
  - Packing Cost = $V_{\text{packing}} C_{\text{packing}} + C_{\text{distributors}}$
- Reboiler $C_B \alpha A_{\text{HX}}$
- Condenser $C_B \alpha A_{\text{HX}}$
- Pumping Costs – feed, reflux, reboiler
  - Work = $Q * \Delta P$
- Tanks
  - Surge tank before column
  - Maybe reboiler accumulator and condensate accumulator Tanks
    - May be part of HX design
  - Pressure Vessel $C_p = F_M C_v(W) + C_{\text{Platform}}$
Economic Indicators

CPI

Download the CEPCI two weeks sooner at www.chemengonline.com/pci

CHEMICAL ENGINEERING PLANT COST INDEX (CEPCI)

<table>
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<tr>
<th>(1957-59 = 100)</th>
<th>Sept.'18 Prelim.</th>
<th>Aug.'18 Final</th>
<th>Sept.'17 Final</th>
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<td>CPI Index</td>
<td>817.8</td>
<td>814.4</td>
<td>574.0</td>
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<tr>
<td>Equipment</td>
<td>753.3</td>
<td>739.3</td>
<td>662.5</td>
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<td>Heat exchangers &amp; tanks</td>
<td>671.1</td>
<td>669.3</td>
<td>608.8</td>
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<td>Process machinery</td>
<td>731.5</td>
<td>728.1</td>
<td>685.3</td>
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<td>Pipe, valves &amp; fittings</td>
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<td>Process equipment</td>
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<td>411.0</td>
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<td>Buildings</td>
<td>854.0</td>
<td>622.5</td>
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<td>Engineering &amp; supervision</td>
<td>317.2</td>
<td>317.0</td>
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Starting in April 2007, several data series for labor and compressors were converted to accommodate smaller differentials required by the U.S. Bureau of Labor Statistics (BLS). Starting in March 2018, the data series for chemical industry special machinery was replaced because the series was discontinued by BLS (see Chem. Eng. April 2018, p. 76-77.)

CURRENT BUSINESS INDICATORS

<table>
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<tr>
<th>LATEST</th>
<th>PREVIOUS</th>
<th>YEAR AGO</th>
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<tr>
<td>CPI output index (2019 = 100)</td>
<td>103.4</td>
<td>102.7</td>
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<td>CPI value of output, $ billions</td>
<td>Sept.'18 = 2,039.8</td>
<td>Aug.'18 = 2,038.6</td>
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<td>CPI operating rate, %</td>
<td>Oct.'18 = 79.9</td>
<td>Sept.'18 = 76.4</td>
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<td>Producer prices, industrial chemicals (1982 = 100)</td>
<td>Oct.'18 = 297.7</td>
<td>Sept.'18 = 276.8</td>
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<td>Industrial Production in Manufacturing (2012 = 100)*</td>
<td>Oct.'18 = 105.4</td>
<td>Sept.'18 = 105.1</td>
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<td>Hourly earnings index, chemicals &amp; Allied products (1992 = 100)</td>
<td>Oct.'18 = 184.6</td>
<td>Sept.'18 = 185.4</td>
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<tr>
<td>Productivity index, chemicals &amp; Allied products (1992 = 100)</td>
<td>Oct.'18 = 96.9</td>
<td>Sept.'18 = 97.3</td>
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CPI OUTPUT INDEX (2000 = 100)

CPI OUTPUT VALUE ($ BILLIONS)

CPI OPERATING RATE (%)

*Due to discontinuities, the Index of Industrial Activity has been replaced by the Industrial Production in Manufacturing index from the U.S. Federal Reserve Board.

†For the current month's CPI output index values, the base year was changed from 2000 to 2012

Problem

- Methanol-Water Distillation
- Feed
  - 10 gal/min
  - 50/50 (mole) mixture
- Desired to get
  - High Purity MeOH in D
  - Pure Water in B
Simulator Methods - Aspen

• Start with simple distillation method
  – DSDTU or Distil

• Then go to more complicated one for sizing purposes
  – RadFrac
  – Sizing in RadFrac

• Costing
Simulation Methods- ProMax

- Start with 10 trays (you may need up to 100 for some difficult separations)
- set $\Delta P$ on column, reboiler, condenser and separator
- set $\Delta T$ on condenser
- Create a component recovery for HK in bottom with large ±
- Set Reflux ratio = 0.1 (increase to get simulation to run w/o errors)
  - Or $R \sim 1.2*(F/D)/(\alpha-1)$
- May need pump around loop estimate.
- Determine $\alpha_{LK,HK}^*$ viscosity
- (use Plots Tab to determine extra trays) determine $N_{min}$ and feed tray
- Use Fig. 19.1 to determine $R_{min}$ from $R$, $N$ from $N_{min}$
- Redo calc with tray efficiency defined see Figure 19.3 correlation.
- Recommendations for final design
  - Use $N/N_{min}=2$ (above and below feed tray) @
  - $R/R_{min}=1.2$
Figure 19.1

Figure 14.1 Gilliland correlation for ordinary distillation.
Tray Efficiency

Figure 14.3 Lockhart and Leggett version of O’Connell correlation for plate efficiency.

\[ \mu_L \times \alpha_{LK,HK} \]
Distillation Problems

• Multi-component Distillation
  – Selection of Column Sequences

• Azeotropy
  – Overcoming it to get pure products

• Heat Integration
  – Decreasing the cost of separations