Chemical Process Design / Diseño de Procesos Químicos

Topic 5.4. Distillation and absorption

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Shortcut for Distillation Column Sizing

**Fenske's equation** applies to any two components “lk or light key” and “hk or heavy key” at infinite reflux and is defined by $N_{\text{min}}$, where $\alpha_{ij}$ is the geometric mean of the $\alpha$'s at the $T$ of the feed ($F$), distillate ($D$) and the bottoms ($B$).

$$N_{\text{min}} = \log\left(\frac{x_{Dlk} / x_{Blk}}{x_{Dbk} / x_{Bhk}}\right)$$

$$\bar{\alpha}_{lk/hk} = \left(\alpha_{Dlk/hk}\alpha_{Flk/hk}\alpha_{Blk/hk}\right)^{1/3}$$

$R_{\text{min}}$ is given by **Underwood** with two equations that must be solved, where $q$ is the liquid fraction in the feed.

$$1 - q = \sum \frac{\alpha_i x_{Fi}}{\alpha_i - \phi}$$

$$R_{\text{min}} + 1 = \sum \frac{\alpha_i x_{Di}}{\alpha_i - \phi}$$

**Gilliland used an empirical correlation** to calculate the final number of stage $N$ from the values calculated through the Fenske and Underwood equations ($N_{\text{min}}, R, R_{\text{min}}$). The procedure uses a diagram; one enters with the abscissa value known, and reads the ordinate of the corresponding point on the Gilliland curve. The only unknown design variable of the ordinate is the number of stage $N$. 
Shortcut for Distillation Column Sizing

Simple and direct correlation for (nearly) ideal systems (Westerberg, 1978)

* Determine $\alpha_{lk/hk} ; \beta_{lk} = \xi_{lk} ; \beta_{hk} = 1 - \xi_{hk}$

* Calculate tray number $N_i$ and reflux ratio $R_i$ from correlations ($i = lk, hk$):

  \[ N_i = \frac{12.3}{[(\alpha_{lk/hk} - 1)^{2/3} \cdot (1 - \beta_i)^{1/6}]} \quad Ri = \frac{1.38}{[(\alpha_{lk/hk} - 1)^{0.9} \cdot (1 - \beta_i)^{0.1}]} \]

- Theoretical n° of trays $N_T = \{0.8 \ max[Ni] + 0.2 \ min[Ni]\}$; $R = \{0.8 \ max[Ri] + 0.2 \ min[Ri]\}$

- Actual n° of trays $N = N_T / 0.8$

- For $H$ consider 0.6 m spacing ($H = 0.6 \ N$); Maximum $H = 60 \ m \rightarrow$ else, 2 columns (*)

* Calculate column diameter, $D$, using internal flowrates (*) and taking into account the vapor fraction of $F$. Internal flowrates used for sizing condenser, reboiler.

Design column at 80% of linear flooding velocity (velocity of the vapor rising through the column at which the liquid on each stage is suspended. The flow of vapor up through the column does not allow the liquid to fall down through the column causing the stages to “flood”. The column flooding conditions set the upper limit of vapor velocity for steady operation).

\[ U_f = C_{sb} \left[ \frac{\rho_L - \rho_G}{\rho_G} \right]^{0.5} \left( \frac{20}{\sigma} \right)^{0.2} \]

**Fair’s Correlation:**

- $\rho_g, \rho_l$: density in kg/m$^3$
- $C_{sb}$: capacity parameter, m/s
- $\sigma$: liquid surface tension, in dynes/cm
$L', V'$: mass ratio in Kg/s

$\rho_g, \rho_l$: density in kg/m$^3$
Shortcut for Distillation Column Sizing

From the Continuity equation:

\[ A = \frac{\pi D^2}{4} = \left[ \frac{V}{0.8 U_f \varepsilon \rho_G} \right] \]

If \( D > 3m \) \( \rightarrow \) Parallel columns.

- Calculate heat duties for reboiler and condenser.

\[ Q_{\text{cond}} = H_V - H_L = \sum_{k=1}^{n} \left( \mu_D^k + \mu_L^k \right) \Delta H_{vap}^k = \frac{V}{D} \sum_{k=1}^{n} \mu_{dk} \Delta H_{vap}^k \]

\[ Q_{\text{reb}} = V \Delta H_{vap}^k \]

- Costing vessel and stack trays (24” spacing).
# Distillation Columns

**Guthrie MPF for Tray Stacks**

\[
\text{MPF: } F_m + F_s + F_t
\]

<table>
<thead>
<tr>
<th>Tray Type</th>
<th>(F_t)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grid</td>
<td>0.0</td>
</tr>
<tr>
<td>Plate</td>
<td>0.0</td>
</tr>
<tr>
<td>Sieve</td>
<td>0.0</td>
</tr>
<tr>
<td>Valve o trough</td>
<td>0.4</td>
</tr>
<tr>
<td>Bubble Cap</td>
<td>1.8</td>
</tr>
<tr>
<td>Koch Kascade</td>
<td>3.9</td>
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</table>

<table>
<thead>
<tr>
<th>Tray Spacing, (F_s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(inch)</td>
</tr>
<tr>
<td>24&quot;</td>
</tr>
<tr>
<td>18&quot;</td>
</tr>
<tr>
<td>12&quot;</td>
</tr>
<tr>
<td>Fs</td>
</tr>
<tr>
<td>1.0</td>
</tr>
<tr>
<td>1.4</td>
</tr>
<tr>
<td>2.2</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Tray Material, (F_m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon Steel</td>
</tr>
<tr>
<td>Stainless Steel</td>
</tr>
<tr>
<td>Monel</td>
</tr>
</tbody>
</table>

 Distillation in Aspen software.

[Perforated Tray](https://www.sulzer.com/)

[Bubble Cap Tray](http://www.wermac.org/)

[Sieve Tray](http://www.wermac.org/)

[Valve Tray](http://www.wermac.org/)
Distillation Columns

Column Cost = Cost of Tray Stack + Cost of pressure vessel (Vertical fabrication)

BMC_{Column} = [UF(BC) (MPF + MF – 1)]_{Tray Stack} + [UF(BC) (MPF + MF – 1)]_{Vessel}

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Tray Stack.
Sulzer Chemtech Ltd., Switzerland.

A vacuum distillation column in a petroleum refinery.
U.K. Association for School Science.
Distillation Columns

Materials and Pressure correction Factor (Vessels): $\text{MPF} = F_m \cdot F_p$

Materials and Pressure correction Factor (Tray Stack): $\text{MPF} = F_m + F_s + F_t$

Update Factor $UF = \frac{\text{Present Cost Index (CI}_{\text{actual}})}{\text{Base Cost Index (CI}_{\text{base}})}$

Updated bare (simple) module cost: $\text{BMC} = UF(BC) \cdot (\text{MPF} + \text{MF} - 1)$
Tray and Packet Bed Distillation Column

https://thermalkinetics.net/distillation-equipment.

Structured packing [CC BY-SA 3.0](http://en.citizendium.org/wiki/Packed_bed).
Distillation Column

Packed bed distillation column used in petrochemical industry. © Sulzer Chemtech Ltd., Switzerland.

A 40 tray column used for mineral oils. © Odfjell, Norway.
Shortcut for Absorber Column Sizing

Sizing similar to the distillation columns.

\[ N = \frac{\ln \left( \frac{l^n_0 + (r^n - A^n_E)v^n_{N+1}}{l^n_0 - A^n_E(1 - r^n)v^n_{N+1}} \right)}{\ln(A^n_E)} \]

• Assumption: v – l equilibrium → but actually there is mass transfer phenomena (e.g. simulation of CO\textsubscript{2} – MEA absorption) → 20% efficiency in n° trays → \( N = N_T / 0.2 \)

• Calculate H and D for costing vessel and stack trays (24” spacing).
  – Natural Gas Dehydration video:
    https://www.youtube.com/watch?v=ULu3DTmlkV0.

Ammonia stripping in wastewater treatment plant of manure (purines) and additional acid absorption.
Absorption column with different types of contact devices:

- Random packing.
- Structured packing.
- Trays.
Absorbers

Cyclone Spray Chambers.
US EPA Public Domain.

Spray Towers.
US EPA Public Domain.
Absorbers


Impingement Scrubbers. Impingement or perforated plate scrubbers.