Equipment Fundamentals: Separation & Fractionation

Chapters 4 & 5
With thanks to Tim Rollenhagen, Anadarko
Topics

Fundamentals of separation

- Volatility differences
  - flash calculations
- Multi-stage fractionation
  - Distillation
- Other
  - Adsorption
  - Membranes

Equipment

- Gas/oil/water separators
  - Filters & coalescers
  - Cyclone separators
- Distillation columns
  - Auxiliary equipment
    - Condenser
    - Reboiler
  - Trays or packing?
- Adsorption
  - Mole sieves
- Membranes
Fundamentals
“Flash calculation” – Description of VLE

Incorporate the mass balance equation with equilibrium constraints.

Given a set of equilibrium coefficients, the $K_i$ values, determine the overall molar phase fraction so that the residual equation is equal to zero:

- There is a two phase situation if the phase fraction is between 0 and 1.
- If the phase fraction is outside this range then there is only a single phase. The phase condition corresponds to the value of $R(0)$ or $R(1)$ that is closer to zero.

Can get the expected equations describing the bubble & dew points by setting $\ell=0$ or $\ell=1$.

Ideal gas & liquid: $K_i \approx \frac{P_i}{P}$

\[
R(\ell) = \sum_{i=1}^{N} \frac{z_i (1-K_i)}{\ell (1-K_i) + K_i} = 0 \quad \text{with} \quad \ell \equiv \frac{L}{F}
\]

or

\[
R(\beta) = \sum_{i=1}^{N} \frac{z_i (K_i - 1)}{1 + \beta (K_i - 1)} = 0 \quad \text{with} \quad \beta \equiv \frac{V}{F}
\]
Rackford-Rice Flash Calculation Curves

\[
R(\beta) = \sum_{i=1}^{N} \frac{z_i (K_i - 1)}{1 + \beta (K_i - 1)} = 0 \quad \text{with} \quad \beta \equiv \frac{V}{F}
\]
Entrainment

Small amounts of the coexisting phase gets carried along because of poor physical separation of the phases

Cannot be predicted from thermodynamics because it is dependent on the flow characteristics of the equipment
Gravity Settling Theory

Dispersed droplets will settle out from a continuous phase if the gravitational force overcomes the buoyancy & drag forces on the droplets.

The droplet’s terminal velocity typically calculated assuming it is solid, rigid sphere:

\[
V_t = \sqrt{\frac{4gD_p (\rho_p - \rho_c)}{3 \rho_c C'}}
\]

The drag coefficient can be determined using a definition of Reynolds number based on particle size but fluid properties of the continuous phase:

\[
N_{Re} = \frac{D_p V_t \rho_c}{\mu_c}
\]
Drag Coefficient for Spherical Particles

FIG. 7-5
Drag Coefficient and Reynolds Number for Spherical Particles

Ref: GPSA Data Book, 13th ed.
Fractionation as Cascade of Equilibrium Stages

Ref: GPSA Data Book, 13th ed.
Fractionation Key Concepts

Separation due to differences in boiling points/relative volatilities

- Light key & lighter to the overhead
- Heavy key & heavier to the bottoms

Sections

- Rectifying section – heavy key & heavier absorbed into falling liquid
- Stripping section – light key & lighter stripped by rising gas

Heat exchangers may provide vapor & liquid traffic

- Heated bottoms generates vapor for stripping section
- Condenser cools & condenses overhead vapor generating liquid for rectifying section

Ref: GPSA Data Book, 13th ed.
Separation, Reflux, & Number of Stages

During the design phase there is flexibility between the number of stages, the column “traffic” (i.e., reflux, boilup), & the degree of separation

- Trade off between CAPEX & OPEX

Correlations to determine the minimum stages & reflux

- Minimum stages @ infinite/total reflux – Fenske equation
- Minimum reflux @ infinite number of stages – Underwood equation

Typically design to operate at 1.2 to 1.3 times the minimum reflux

- Erbar-Maddox chart to estimate number of stages

Ref: GPSA Data Book, 13th ed.
### Number Theoretical Stages vs. Actual Trays

<table>
<thead>
<tr>
<th>Column Service</th>
<th>Typical No. of Actual Trays</th>
<th>Typical Overall Efficiency</th>
<th>Typical No. of Theoretical Trays</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simple Absorber/Stripper</td>
<td>20 – 30</td>
<td>20 – 30</td>
<td></td>
</tr>
<tr>
<td>Steam Side Stripper</td>
<td>5 – 7</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Reboiled Side Stripper</td>
<td>7 – 10</td>
<td>3 – 4</td>
<td></td>
</tr>
<tr>
<td>Reboiled Absorber</td>
<td>20 – 40</td>
<td>40 – 50</td>
<td></td>
</tr>
<tr>
<td>Deethanizer</td>
<td>25 – 35</td>
<td>65 – 75</td>
<td></td>
</tr>
<tr>
<td>Depropanizer</td>
<td>35 – 40</td>
<td>70 – 80</td>
<td></td>
</tr>
<tr>
<td>Debutanizer</td>
<td>38 – 45</td>
<td>85 – 90</td>
<td></td>
</tr>
<tr>
<td>Alky DeiC4 (reflux)</td>
<td>75 – 90</td>
<td>85 – 90</td>
<td></td>
</tr>
<tr>
<td>Alky DeiC4 (no reflux)</td>
<td>55 – 70</td>
<td>55 – 65</td>
<td></td>
</tr>
<tr>
<td>Naphtha Splitter</td>
<td>25 – 35</td>
<td>70 – 75</td>
<td></td>
</tr>
<tr>
<td>C2 Splitter</td>
<td>110 – 130</td>
<td>95 – 100</td>
<td></td>
</tr>
<tr>
<td>C3 Splitter</td>
<td>200 – 250</td>
<td>95 – 100</td>
<td></td>
</tr>
<tr>
<td>C4 Splitter</td>
<td>70 – 80</td>
<td>85 – 90</td>
<td></td>
</tr>
<tr>
<td>Amine Contactor</td>
<td>20 – 24</td>
<td>4 – 5</td>
<td></td>
</tr>
<tr>
<td>Amine Stripper</td>
<td>20 – 24</td>
<td>45 – 55</td>
<td>9 – 12</td>
</tr>
<tr>
<td>Crude Distillation</td>
<td>35 – 50</td>
<td>50 – 60</td>
<td>20 – 30</td>
</tr>
<tr>
<td>Stripping Zone</td>
<td>5 – 7</td>
<td>30</td>
<td>2</td>
</tr>
<tr>
<td>Flash Zone – 1&lt;sup&gt;st&lt;/sup&gt; Draw</td>
<td>3 – 7</td>
<td>30</td>
<td>1 – 2</td>
</tr>
<tr>
<td>1&lt;sup&gt;st&lt;/sup&gt; Draw – 2&lt;sup&gt;nd&lt;/sup&gt; Draw</td>
<td>7 – 10</td>
<td>45 – 50</td>
<td>3 – 5</td>
</tr>
<tr>
<td>2&lt;sup&gt;nd&lt;/sup&gt; Draw – 3&lt;sup&gt;rd&lt;/sup&gt; Draw</td>
<td>7 – 10</td>
<td>50 – 55</td>
<td>3 – 5</td>
</tr>
<tr>
<td>Top Draw – Reux</td>
<td>10 – 12</td>
<td>60 – 70</td>
<td>6 – 8</td>
</tr>
<tr>
<td>Vacuum Column (G.O. Operation)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stripping</td>
<td>2 – 4</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Flash Zone – HGO Draw</td>
<td>2 – 3</td>
<td>1 – 2</td>
<td></td>
</tr>
<tr>
<td>HGO Section</td>
<td>3 – 5</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>LGO Section</td>
<td>3 – 5</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>FCC Main Fractionator</td>
<td>24 – 35</td>
<td>50 – 60</td>
<td>13 – 17</td>
</tr>
<tr>
<td>Quench Zone</td>
<td>5 – 7</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Quench – HGO Draw</td>
<td>3 – 5</td>
<td>2 – 3</td>
<td></td>
</tr>
<tr>
<td>HGO – LCGO</td>
<td>6 – 8</td>
<td>3 – 5</td>
<td></td>
</tr>
<tr>
<td>LCGO – Top</td>
<td>7 – 10</td>
<td>5 – 7</td>
<td></td>
</tr>
</tbody>
</table>

### Viscosity

<table>
<thead>
<tr>
<th>Viscosity</th>
<th>Drickamer &amp; Bradford in Ludwig</th>
</tr>
</thead>
<tbody>
<tr>
<td>cP</td>
<td>Ave Viscosity of liquid on plates</td>
</tr>
<tr>
<td>0.05</td>
<td>...</td>
</tr>
<tr>
<td>0.10</td>
<td>104</td>
</tr>
<tr>
<td>0.15</td>
<td>86</td>
</tr>
<tr>
<td>0.20</td>
<td>76</td>
</tr>
<tr>
<td>0.25</td>
<td>63</td>
</tr>
<tr>
<td>0.30</td>
<td>56</td>
</tr>
<tr>
<td>0.35</td>
<td>50</td>
</tr>
<tr>
<td>0.40</td>
<td>46</td>
</tr>
<tr>
<td>0.50</td>
<td>43</td>
</tr>
<tr>
<td>0.60</td>
<td>40</td>
</tr>
<tr>
<td>0.70</td>
<td>38</td>
</tr>
<tr>
<td>0.80</td>
<td>36</td>
</tr>
<tr>
<td>0.90</td>
<td>34</td>
</tr>
<tr>
<td>1.00</td>
<td>32</td>
</tr>
<tr>
<td>1.50</td>
<td>30</td>
</tr>
<tr>
<td>1.70</td>
<td>28</td>
</tr>
</tbody>
</table>

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*Rules of Thumb for Chemical Engineers, 4th ed.*
Carl Branan, Gulf Professional Publishing, 2005

*Engineering Data Book, 12th ed.*
Gas Processors Association, 2004

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Refinery Process Modeling
Gerald Kaes, Athens Printing Company, 2000, pg. 32
Other Separation Processes

Adsorption

- Molecules get caught up with the adsorbing material allowing the non-adsorbed molecules to pass through with less hindrance.
- The retained molecules need to be driven off of the adsorbing material to regenerate the adsorbent.
  - PSA – Pressure Swing Adsorption
  - TSA – Temperature Swing Adsorption
- Separation can be based on molecular size, chemical type, ...
Other separation processes

Membranes

- Molecules pass through a semi-permeable barrier at different rates
- Separation can be based on molecular size, chemical type, …

http://www.axiom.at/en/gas-separation-technology

Equipment
Types of Separators Used in Gas Processing

Two-Phase Separators:
- Vapor/Liquid
- Liquid/Liquid
- Vapor/Solid
- Liquid/Solid

Three-Phase Separators:
- Vapor/Liquid/Liquid
- Vapor/Liquid/Solid

Ref: GPSA Data Book, 13th ed.
Separation Considerations

Prioritize key parameters to determine separator selection

- Particle/droplet size to be removed
- Pressure drop
- Turndown ability
- Slug handling requirement
- Fouling service
- Gas or liquid controlled
- Ratio of flowrates for each phase
- Design conditions vs. normal operating conditions vs. upset conditions

Performance requirements

- Liquid carry-over specification
- Gas carry-under specification
- Water in hydrocarbon specification
- Oil in water specification
Zones within a separator

FIG. 7-32
Zones of a Gas-Liquid Separator

Ref: GPSA Data Book, 13th ed.
Vertical Separators

Internals can increase separation efficiency & decreases overall size of vessel

- No internals – bulk separation with no obstructions (e.g., flare knock out drum)
- Mesh pad
- Vane packs
- Cyclones
- Combination internals

Ref: GPSA Data Book, 13th ed.
Vertical Gas-Liquid-Liquid Separators

Can do 3-phase separation in a vertical separator – requires baffling to minimize “whirlpool” effect
Horizontal Separators

Like a vertical separator, internals can aid in the separation efficiency and lead to small vessels.

Ref: GPSA Data Book, 13th ed.
### FIG. 7-16
Factors that Determine Vessel Orientation

<table>
<thead>
<tr>
<th>Feature</th>
<th>Vertical</th>
<th>Horizontal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compact Separators</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Small Footprint</td>
<td>Yes</td>
<td>—</td>
</tr>
<tr>
<td>Small Liquid Surge Drums</td>
<td>Yes</td>
<td>—</td>
</tr>
<tr>
<td>Solids Removal with Liquid</td>
<td>Yes</td>
<td>—</td>
</tr>
<tr>
<td>Small Capacity Flare K.O. Drums</td>
<td>Yes</td>
<td>—</td>
</tr>
<tr>
<td>Gas Dominated Services</td>
<td>Yes</td>
<td>*Yes</td>
</tr>
<tr>
<td>Liquid Dominated Services</td>
<td>—</td>
<td>Yes</td>
</tr>
<tr>
<td>Three-Phase (G/L/L) Separation</td>
<td>—</td>
<td>Yes</td>
</tr>
<tr>
<td>Liquid-Liquid Separation</td>
<td>—</td>
<td>Yes</td>
</tr>
<tr>
<td>High Liquid Degassing Residence Time</td>
<td>—</td>
<td>Yes</td>
</tr>
<tr>
<td>Pigging &amp; Slug Flow Separation</td>
<td>**Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Foaming Feeds</td>
<td>—</td>
<td>Yes</td>
</tr>
<tr>
<td>High Liquid Surge Capacity</td>
<td>—</td>
<td>Yes</td>
</tr>
<tr>
<td>Large Capacity Flare K.O. Drums</td>
<td>—</td>
<td>Yes</td>
</tr>
<tr>
<td>Solid Removal Through Jetting</td>
<td>—</td>
<td>Yes</td>
</tr>
<tr>
<td>High Vapor and Liquid Flow Rates</td>
<td>Yes</td>
<td>Yes</td>
</tr>
</tbody>
</table>

* Some horizontal separators, such as a double barrel type, are also good applications for gas dominated services.

**In some applications where small slugs are possible, slugs can be managed in vertical separators.

Ref: GPSA Data Book, 14th ed.
Vertical or Horizontal?

![FIG. 7-20
Gas-Liquid-Liquid Separator Selection](image)

<table>
<thead>
<tr>
<th>Separator Types</th>
<th>Horizontal No Internals</th>
<th>Horizontal w/Baffle</th>
<th>Horiz./Vert. w/Plate Pack or Mesh</th>
<th>Horizontal w/Boot</th>
<th>Horiz. w/Bucket &amp; Underflow Baffle</th>
<th>Vertical</th>
</tr>
</thead>
<tbody>
<tr>
<td>Easy to Settle</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Bulk Separation</td>
<td>Yes</td>
<td>Yes</td>
<td></td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Most Efficient Separation</td>
<td>With coalescer</td>
<td>Yes</td>
<td>With coalescer</td>
<td>With coalescer</td>
<td>With coalescer</td>
<td></td>
</tr>
</tbody>
</table>

Ref: *GPSA Data Book*, 14th ed.
Mist Extraction

Internals chosen based on gas flow & droplet size.

Fig. 5.2 Vane Pack
*Fundamentals of Natural Gas Processing, 2nd ed.*
Kidnay, Parrish, & McCartney
Coalescing filters

Remove very fine liquid particles (less than 3 μm)

Coalescers have media that allow the very small particles to combine & the drain via gravity

http://www.kelburneng.co.uk/gas-filtration.php

Fundamentals of Natural Gas Processing, 2nd ed.
Kidnay, Parrish, & McCartney
Separation by centrifugal force

Vortex flow. Heavier particles hit outside walls & fall downward.

Can be used to separate liquids and/or solids from gas flow.

http://energyeducation.ca/encyclopedia/Cyclone_separator
Sizing of Vertical Separators

When gas flowrate controls sizing:
- Diameter is based on allowable velocity through internal (mesh pad, vane, etc.)
- Height is based on liquid volume requirements and physical height requirements of internals

When liquid flowrate controls sizing:
- Liquid dictates volume requirements
- Height and diameter based on most economic ratio (i.e. L:D of 3)

Ref: GPSA Data Book, 13th ed.
## Typical Surge & Retention Times

<table>
<thead>
<tr>
<th>Service</th>
<th>Control Surge Time, LLL to HLL</th>
<th>Retention Time, Empty to NLL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compressor Drum</td>
<td>2 minutes</td>
<td></td>
</tr>
<tr>
<td>Flash Drum</td>
<td>2 – 5 minutes</td>
<td></td>
</tr>
<tr>
<td>Reflux Drum</td>
<td>5 minutes on product plus reflux</td>
<td></td>
</tr>
<tr>
<td>Surge Drum Upstream of Tower</td>
<td>5 – 10 minutes</td>
<td></td>
</tr>
<tr>
<td>Surge Drum Upstream of Fired Heater</td>
<td>10 minutes</td>
<td></td>
</tr>
<tr>
<td>Tower Sump</td>
<td>Depends on Tower type</td>
<td></td>
</tr>
<tr>
<td>Net Product to Storage</td>
<td>5 minutes</td>
<td></td>
</tr>
<tr>
<td>Amine Flash Drum</td>
<td>5 – 10 minutes</td>
<td></td>
</tr>
<tr>
<td>Glycol Flash Drum</td>
<td>10 – 20 minutes</td>
<td></td>
</tr>
<tr>
<td>Cold Separator (Gas/NGL/EG)</td>
<td>15 – 30 minutes</td>
<td></td>
</tr>
<tr>
<td>Refrigeration Accumulator</td>
<td>5 minutes or based on system requirements</td>
<td></td>
</tr>
<tr>
<td>Refrigeration Economizer</td>
<td>3 minutes</td>
<td></td>
</tr>
<tr>
<td>Heat Medium Surge Drum</td>
<td>Max liquid expansion based on 25% - 75% full</td>
<td></td>
</tr>
</tbody>
</table>

Ref: Fig. 7-42 GPSA Data Book, 14th ed.
**Fractionators: Typical Parameters**

<table>
<thead>
<tr>
<th></th>
<th>Operating Pressure, psig</th>
<th>Number of Actual Trays</th>
<th>Reflux(^1) Ratio</th>
<th>Reflux(^2) Ratio</th>
<th>Tray Efficiency, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Demethanizer</td>
<td>200 – 400</td>
<td>18 – 26</td>
<td>Top Feed</td>
<td>Top Feed</td>
<td>45 – 60</td>
</tr>
<tr>
<td>Deethanizer</td>
<td>375 – 450</td>
<td>25 – 35</td>
<td>0.9 – 2.0</td>
<td>0.6 – 1.0</td>
<td>60 – 75</td>
</tr>
<tr>
<td>Depropanizer</td>
<td>240 – 270</td>
<td>30 – 40</td>
<td>1.8 – 3.5</td>
<td>0.9 – 1.1</td>
<td>80 – 90</td>
</tr>
<tr>
<td>Debutanizer</td>
<td>70 – 90</td>
<td>25 – 35</td>
<td>1.2 – 1.5</td>
<td>0.8 – 0.9</td>
<td>85 – 95</td>
</tr>
<tr>
<td>Butane Splitter</td>
<td>80 – 100</td>
<td>60 – 80</td>
<td>6.0 – 14.0</td>
<td>3.0 – 3.5</td>
<td>90 – 100</td>
</tr>
<tr>
<td>Rich Oil Fractionator (Still)</td>
<td>130 – 160</td>
<td>20 – 30</td>
<td>1.75 – 2.0</td>
<td>0.35 – 0.40</td>
<td>Top 67 Bottom 50</td>
</tr>
<tr>
<td>Rich Oil Deethanizer</td>
<td>200 – 250</td>
<td>40</td>
<td>–</td>
<td>–</td>
<td>Top 25 – 40 Bottom 40 – 60</td>
</tr>
<tr>
<td>Condensate Stabilizer</td>
<td>100 – 400</td>
<td>16 – 24</td>
<td>Top Feed</td>
<td>Top Feed</td>
<td>50 – 75</td>
</tr>
</tbody>
</table>

\(^1\)Reflex ratio relative to overhead product, mol/mol
\(^2\)Reflex ratio relative to feed, gal./gal.

Ref: GPSA Data Book, 13th ed.
Fractionation Columns & Trays

Drawings by Henry Padleckas
http://en.wikipedia.org/wiki/Fractionating_column
Fractionation Tray Types

Sieve

Valve

Bubble-cap

http://www.termoconsult.com/empresas/acs/fractionation_trays.htm
Trays & Packing

Packed towers

Liquid & vapor flow countercurrent through packing

- No specific “tray” or number of “trays”
- A mass transfer zone or “transfer unit” consists of a quantity of packing

Types:

- Random packing
- Structured packing
- Grids

Sizing of tower (diameter) is based on

- Jet flooding (combination of vapor/liquid limit)
- Pressure drop limit (indicates excessive loading)
- Typically smaller diameter than trays

[Image of a packed tower]

Tower Height Calculation

Height based on:

- Number of trays, tray spacing
- Number of packed beds, bed height
- Nozzles and feed internals
- Sump height
- Vapor disengagement
- Manways
- Other internals
  - Chimney trays
  - Bed limiters
  - Redistributors
Reboiler considerations

Hydraulics
- Forced circulation
- Natural circulation – most typical

Configuration
- Once through
  - Treat as a stage of separation
- Recirculation
Absorption & Stripping

Absorbers: desired component in feed gas
- Absorb a gas phase component (solute) into a liquid (solvent)
- Amine, Selexol, glycol dehydration, etc.

Strippers: desired component in feed liquid
- Strip a dissolved component from liquid into the gas phase
- Sour water, glycol regeneration (stripping gas), etc.
Adsorption – Mole Sieve Dehydration

Typically fixed beds with at least two vessels – on in adsorption & one in desorption

Forms of desorption
- TSA – Temperature Swing Adsorption
- PSA – Pressure Swing Adsorption

Ref: GPSA Data Book, 13th ed.
Membrane separation

Typical vessel configurations

- Rolled membrane
- Hollow fiber


http://www.mtrinc.com/faq.html
Summary

Separation of components based on phase equilibrium in separators & fractionators

- Material balance calculation based on a “flash” calculation
- Can further control with adsorbents & membranes

Vessels sized to get the physical separation between vapor & liquid phases

- Internals can greatly increase the separation efficiency leading to smaller vessels

Fractionators can be thought of as cascaded contactors & separators

- Internals may consist of trays and/or packing
Supplemental Slides
Inlet devices

Figures GPSA Data Book, 14th ed.

Shell Schoepentoeter™
Separator Zones

Filter Separators

http://cdn2.hubspot.net/hubfs/2041813/Brochure_PDFs/Filter-Separator_brochure.pdf?hsCtaTracking=c1b7a92d-bf53-47b8-92c6-ca06c50058ec%7C1651fd38-b4ac-4e94-9a5c-4825cef0e900&_hsesc=6098668.694ff329e9e46f2ca61b78dfda4d809e.1486868568715.1486868568715.1486868568715.186868568715.1&__hsfp=3776107698
Filter Separators

Full-Access Closures or Blind Flanges
Multiple options available

Lower Barrel
Multiple control and sump options

Gas flows around stand pipes and through filters where solids are captured and mist droplets coalesced

Gas and remaining liquid flows through stand pipes to vane separator

Solid and liquid laden gas

Clean dry gas

Harp Design Slug Catcher