Minimum Energy for the Four-Product Kaibel Distillation Column

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Minimum Energy for the Four-Product Kaibel Distillation Column

- Comparing with Petlyuk + others
- Analytic solution for Kaibel column
- Assessment by the Vmin diagram
Definitions and assumptions

- Vapour flow rate generated from all reboilers is used as the energy measure

Assumptions
- Infinite number of stages
- Constant relative volatility
- Constant molar flow
- Constant pressure
- No internal heat exchange

- Exact analytic solution is obtained
Alternatives for 4-product separation

Conventional Direct Split: DS-DS
Alternatives for 4-product separation...

Conventional indirect+direct split: IS-DS

There are several other conventional combinations
Alternatives for 4-product separation...

Extended Petlyuk arrangement

$V_{\text{min}}$ simple to find (Halvorsen 2001)
Alternatives for 4-product separation...

Prefractionator arrangement

basic layout
Kaibel arrangement structure

Prefractionator Column C1

Feed \( F,z,q \)

ABCD

Total reflux section C2x (\( V=L \))

CD

Column C21

Main column

Column C22
Kaibel column – (1987)
4-product DWC

Separates 4 products in a single shell!

Total reflux section

Vmin?
Extended 4-product Petlyuk arrangement in a single shell with multiple dividing walls

What about complexity?
Other variations
Christiansen-column
4-product DWC in single shell

Equivalent to Kaibel-column in energy consumption

Replaces BC-section with heat exchanger
Conventional Prefractionator arrangement with a single main column

Total reflux BC-section
Prefractionator arrangement – combined main column connections

May come close to Kaibel
3-product Petlyuk arrangement

Petlyuk arrangement

The Dividing Wall Column

Liquid split

Vapor split
Combination of 3 product Petlyuk and Conventional DS

There are other combinations too ...
Minimum Energy Competition

Compare performance for the given feed:

- Four components: A(light)+B+C+D(heavy)
- Flow rate \( F=1, q=1 \) (saturated liquid)
- Composition \( z=[0.3 \ 0.2 \ 0.2 \ 0.3] \)
- Relative volatility \( a=[6 : 4 : 2 : 1] \)
## Minimum Energy – competition

<table>
<thead>
<tr>
<th>No</th>
<th>Configuration</th>
<th>$V_{\min}/F$</th>
<th>Savings</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Four product extended Petlyuk</td>
<td>1.38</td>
<td>50%</td>
</tr>
<tr>
<td>2</td>
<td>Kaibel column</td>
<td>1.83</td>
<td>33%</td>
</tr>
<tr>
<td>3</td>
<td>Three product Petlyuk+ conventional B/C</td>
<td>1.98</td>
<td>28%</td>
</tr>
<tr>
<td>4</td>
<td>Prefractionator+ single main column</td>
<td>2.34</td>
<td>15%</td>
</tr>
<tr>
<td>5</td>
<td>Prefractionator+ 2 separate columns</td>
<td>3.04</td>
<td>-11% (loss)</td>
</tr>
<tr>
<td>6</td>
<td>Conventional direct sequence (3 columns)</td>
<td>2.75</td>
<td>0% (reference)</td>
</tr>
</tbody>
</table>
Analytic solutions for minimum energy

- Conventional: Sequence of binary splits (Classic., Underwood, King and others...)

- Extended Petlyuk: Most difficult binary split – Highest peak in the $V_{\text{min}}$-diagram (Halvorsen 2001)

- Kaibel: Analytic solution presented here – illustrated in the $V_{\text{min}}$-diagram
Key issues for full thermal coupling

- Liquid and vapour flows in equilibrium avoids irreversible loss due to mixing (Petlyuk 1965) =>
  - Explains why Petlyuk columns beat the other arrangements
  - Require operation of every internal column at its “preferred split”

- Underwood roots “carry over” the coupling (Halvorsen 2001) =>
  - Valid for any operating point
  - Simple sequential calculation sequence
  - Extremely simple assessment for n-product Petlyuk arrangement based only on feed properties.
Use of the Underwood Equations 1

Find the common Underwood roots from the feed equation:

\[
\frac{\alpha_A Z_A}{\alpha A - \theta} + \frac{\alpha B Z_B}{\alpha B - \theta} + \frac{\alpha C Z_C}{\alpha C - \theta} + \frac{\alpha D Z_D}{\alpha D - \theta} = 1 - q
\]

Properties of the solution:

\[\alpha_A > \theta_A > \alpha_B > \theta_B > \alpha_C > \theta_C > \alpha_D\]

The common Underwood roots depend only on feed properties – not on flow rates
Use of the Underwood Equations 2

Find $V_{\text{min}}$ in C1 for sharp AB/BC split

$$\frac{V_{T\min}^{AB/CD}}{F} = \frac{\alpha_A z_A}{\alpha_A - \theta_B} + \frac{\alpha_B z_B}{\alpha_B - \theta_B}$$

Note: $\theta_B$ is the only active common root
Use of the Underwood Equations 3

Find the actual root $\phi_A$ in C1 (top):

$$V_{T\text{ min}}^{AB/CD} = \left( \frac{\alpha_A z_A}{\alpha_A - \phi} + \frac{\alpha_B z_B}{\alpha_B - \phi} \right) F$$

where: $\alpha_A > \phi_A > \theta_A > \alpha_B$

and the actual root $\psi_C$ in C1 (bottom):

$$V_{T\text{ min}}^{AB/CD} - (1 - q)F = -\left( \frac{\alpha_C z_C}{\alpha_C - \psi} + \frac{\alpha_D z_D}{\alpha_D - \psi} \right) F$$

where: $\alpha_C > \theta_C > \psi_C > \alpha_D$
Use of the Underwood Equations 4

Root $\phi_A$ from C1 carry over as common root in C21 (Halvorsen 2001)

$$V_{T_{\min}}^{C21} = \frac{\alpha_A z_A}{\alpha_A - \theta_{C21}^A} F = \frac{\alpha_A z_A}{\alpha_A - \phi_A} F$$

Similarly $\psi_C$ to C22, and:

$$V_{B_{\min}}^{C22} = -\frac{\alpha_D z_D}{\alpha_D - \theta_{C22}^C} F = -\frac{\alpha_D w_D}{\alpha_D - \psi_C} F$$
Use of the Underwood Equations 5

The maximum requirement in C21 or C22 determines the overall requirement

\[
\frac{V^{Kaiibel}_{T_{\text{min}}}}{F} = \max\left(\frac{V^{C21T}_{\text{min}}}{F}, \frac{V^{C22B}_{\text{min}}}{F} + (1 - q)\right)
\]

\[
= \max\left(\frac{\alpha_A z_A}{\alpha_A - \phi_A}, \frac{z_D}{\psi_C - 1} + (1 - q)\right)
\]

Note error in CD proceedings: replace min() with max()
The $V_{\text{min}}$-diagram

Binary column – multicomponent feed

Operation point $f(D/F, V/F)$

Feed comp. distribution ?
Minimum energy ?

Two degrees of freedom – choose D/F, V/F
The $V_{\text{min}}$-diagram – 3 component example
$V_{min}$ for the Petlyuk column:
The highest peak:

$$\frac{V_{T_{min}}}{F} = \max \left( \sum_{i=1}^{j} \frac{\alpha_i \theta_i}{\alpha_i - \theta_j} \right)$$

$V_{min}$-diagram
Petlyuk column: $V_{\text{min}} = \text{the most difficult binary split}$
The most difficult split in this standard two-product column... gives is the minimum energy of a directly coupled extended Petlyuk arrangement.

The $V_{min}$-diagram illustrates the behaviour in this simple column and...

Exact analytical expressions by the Underwood equations... gives all the required flows in this complex arrangement.
$V_{min}$-diagram for the Kaibel column
Assessment by the $V_{min}$-diagram

Conv. Kaibel Petlyuk

Very Good

Bad

Not so bad

Conv. Kaibel Petlyuk

Very Good

Bad

Not so bad

a) Simpler B/C split, $\alpha=[6\ 4.6\ 1.3\ 1]$  
b) Difficult B/C split, $\alpha=[6\ 2.8\ 2.5\ 1]$

c) Simpler A/B split, $\alpha=[6\ 2.1.4\ 1]$  
d) Simpler C/D split, $\alpha=[6\ 5.4\ 1]$
Assessment by the $V_{min}$-diagram...

e) Less BC, $z=[0.4 \ 0.1 \ 0.1 \ 0.4]$

Very Good

f) More BC, $z=[0.1 \ 0.4 \ 0.4 \ 0.1]$

Quite good
A Complex Refinery Stream

Kaibel

Petlyuk
Conclusion

- $V_{min}$ solution is based on the extended Petlyuk arrangement
- Fast and exact solution by use of the Underwood equations
- Can be applied for any product splits and n-component feed
- Simple visualisation and assessment in the $V_{min}$ diagram

Here is the answer
The Kaibel column
Summary

- Saves above 30% energy (compared to conv.)
- Built in a single shell as a DWC => saves capital cost
- Much simpler configuration than the 4-product Petlyuk
- Why not try it?
The Kaibel column at NTNU, Trondheim, Norway

- Lab installation
- Height: 8 meters
- Atmospheric pressure
- Vacuum glass sections
- Contact: Sigurd Skogestad or Heinz Preisig