Minimum Energy for the Four-Product Kaibel Distillation Column

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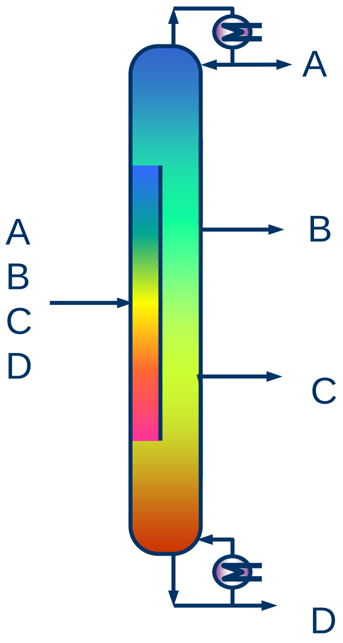
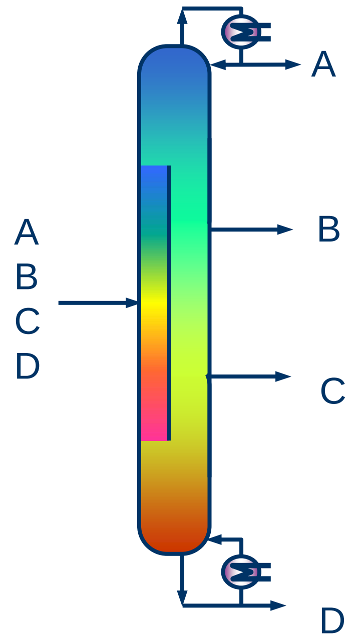


Minimum Energy for the Four-Product Kaibel Distillation Column

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

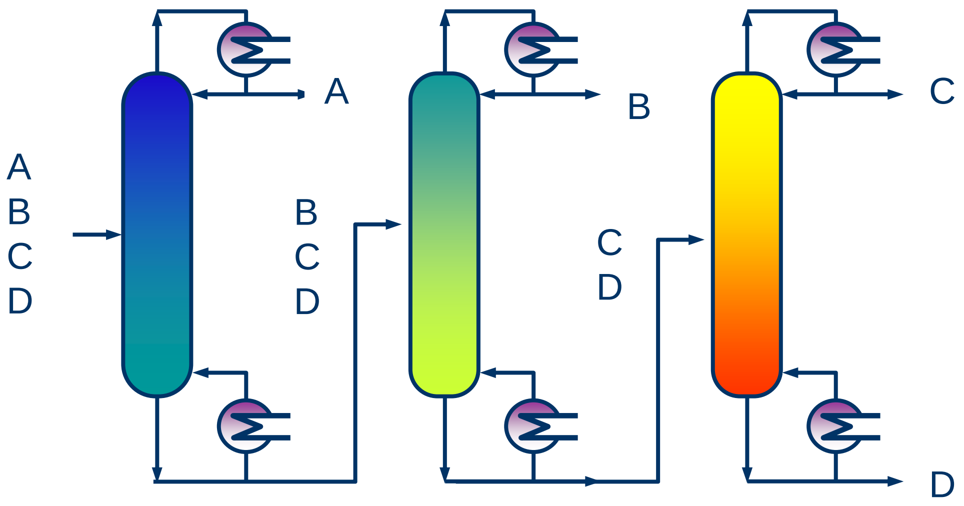


Definitions and assumptions

- 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

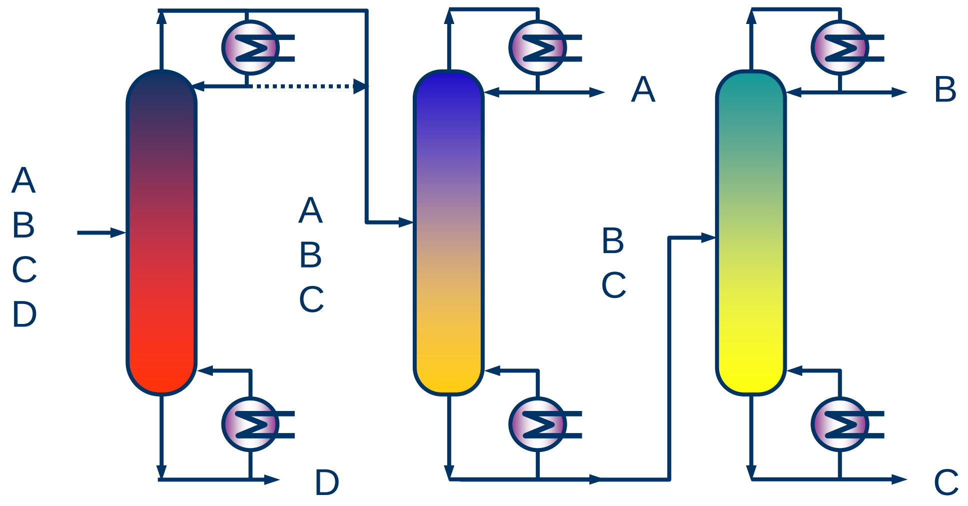
Alternatives for 4-product separation

Conventional Direct Split: DS-DS



Alternatives for 4-product separation...

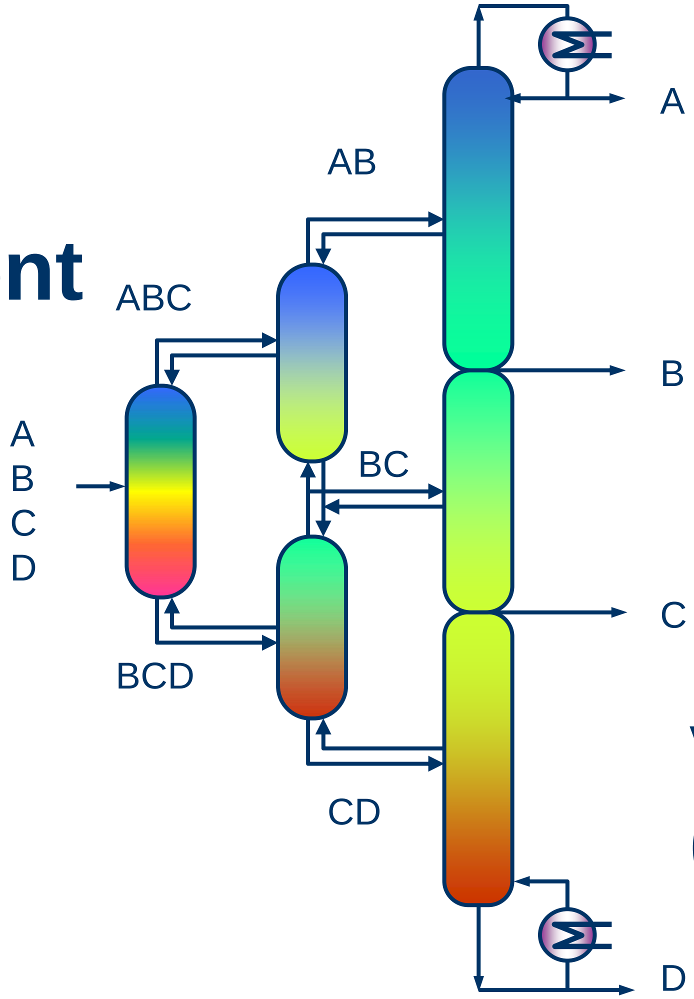
Conventional indirect+direct split: IS-DS



There are several other conventional combinations

Alternatives for 4-product separation...

Extended Petlyuk arrangement

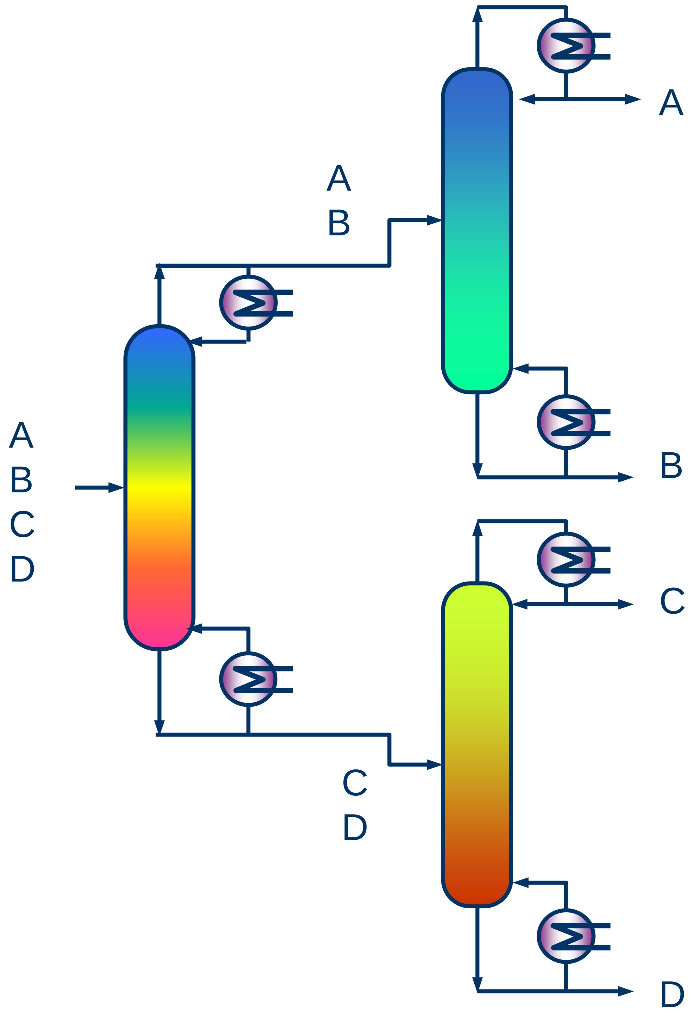


V_{min} simple to find (Halvorsen 2001)

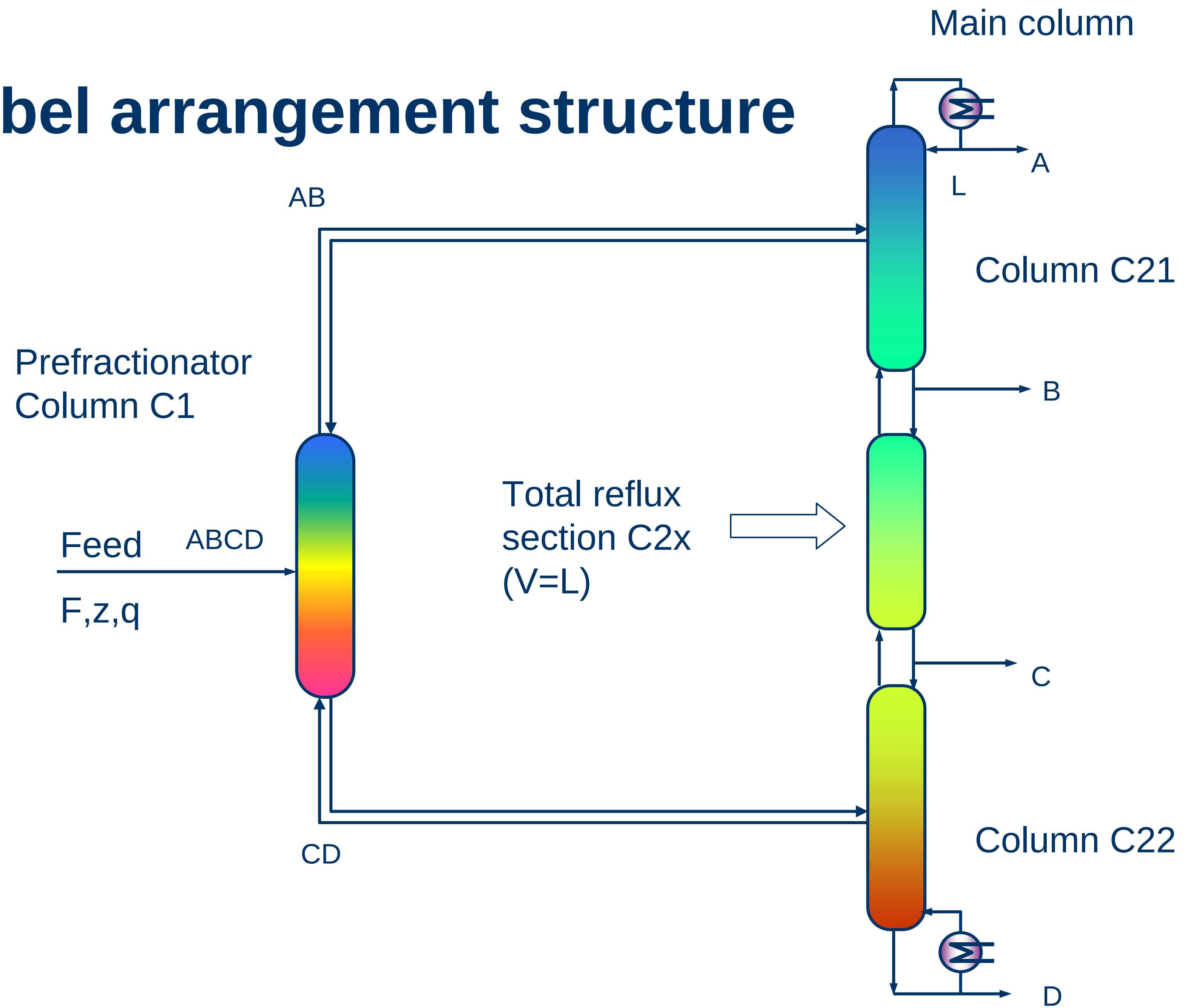
Alternatives for 4-product separation...

Prefractionator arrangement

basic layout



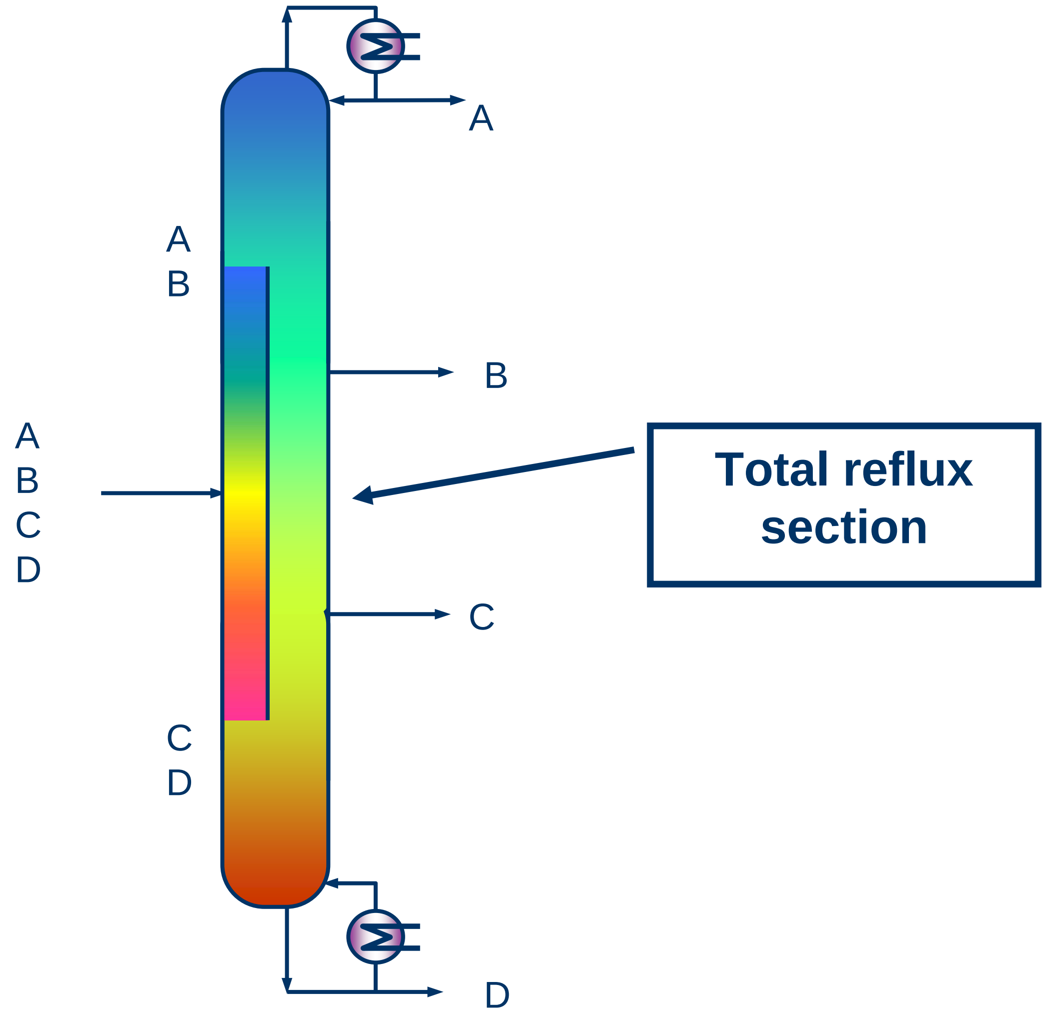
Kaibel arrangement structure



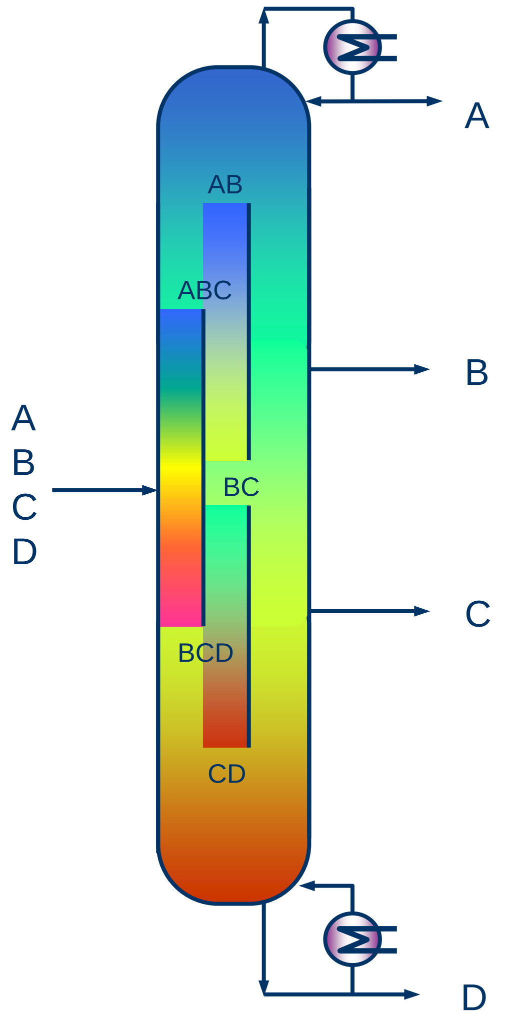
Kaibel column – (1987)
4-product DWC

Separates 4 products in a single shell!

Vmin ?



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

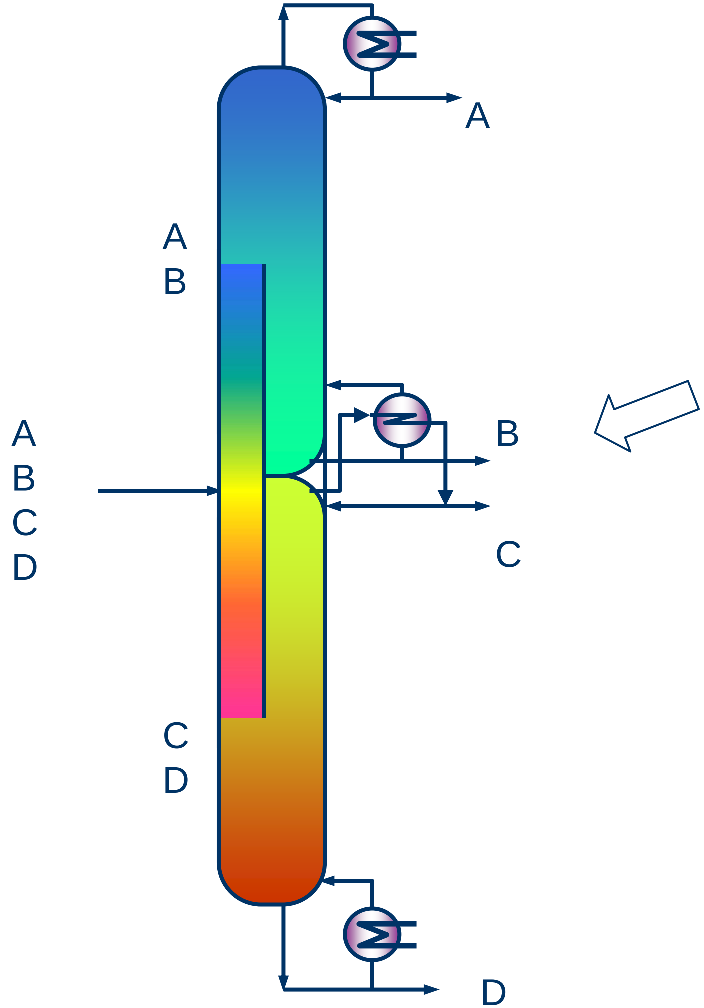


What about complexity?

Other variations

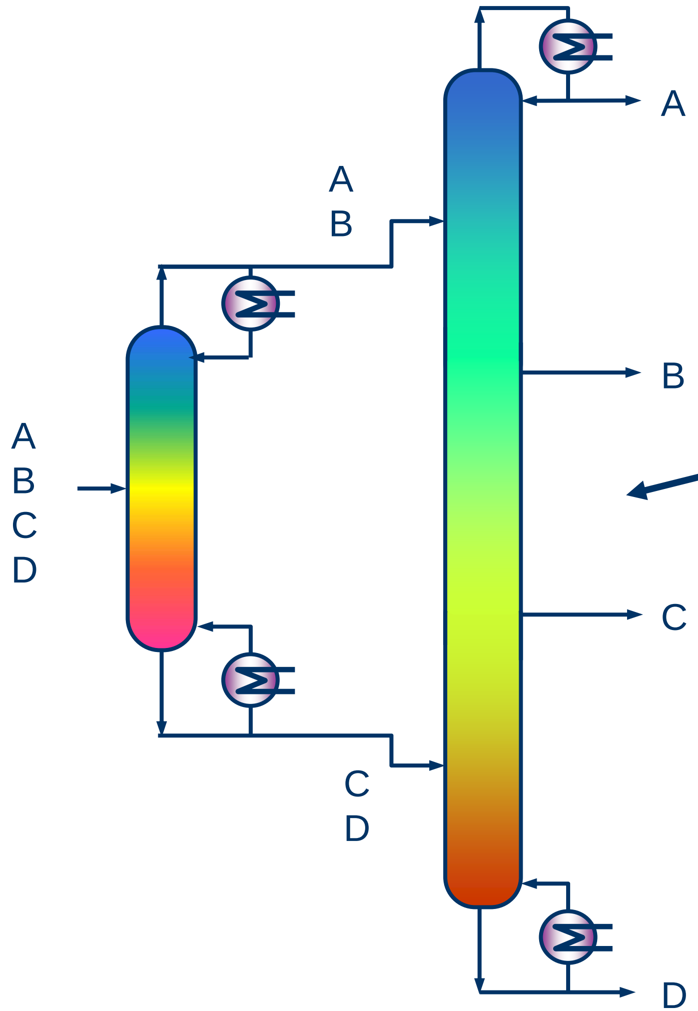
Christiansen-column
4-product DWC in single shell

Equivalent to Kaibel-column in energy consumption



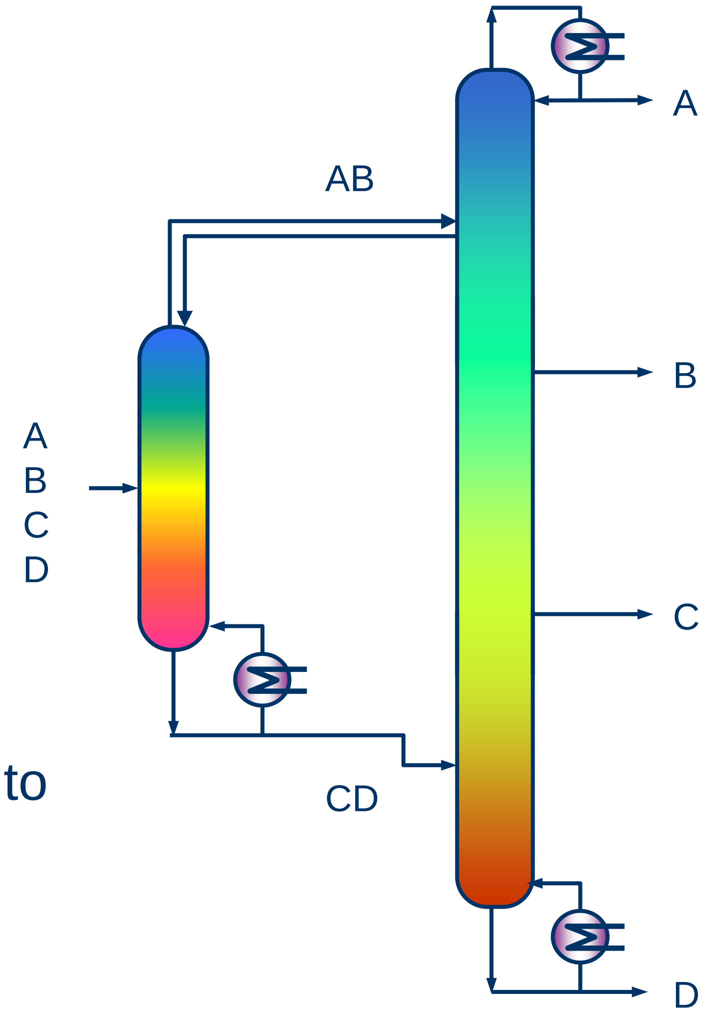
Replaces BC-section with heat exchanger

Conventional Prefractionator arrangement with a single main column



Total reflux BC-section

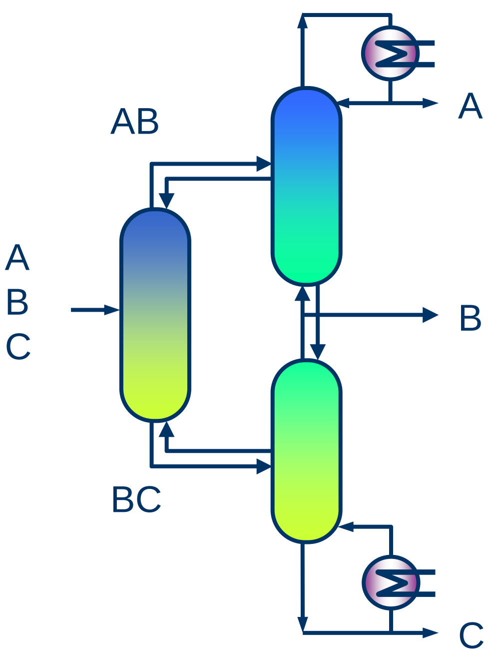
Prefractionator arrangement – combined main column connections



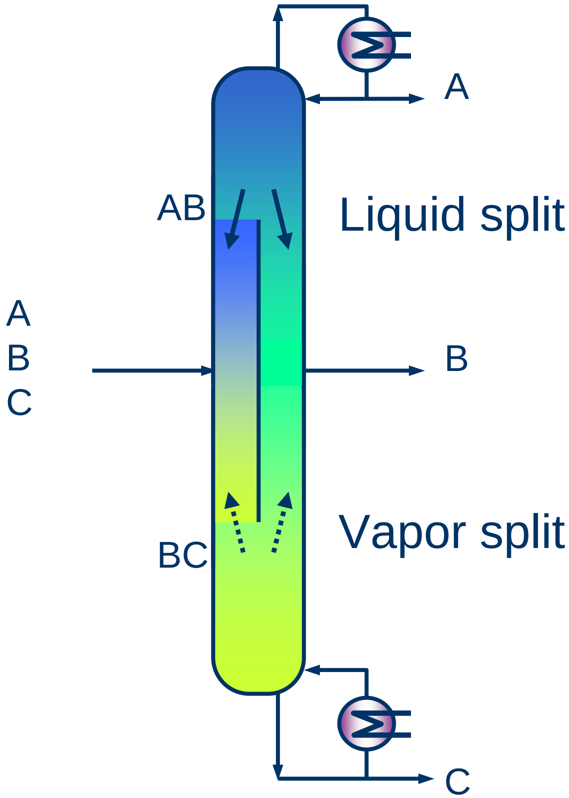
May come close to Kaibel

3-product Petlyuk arrangement

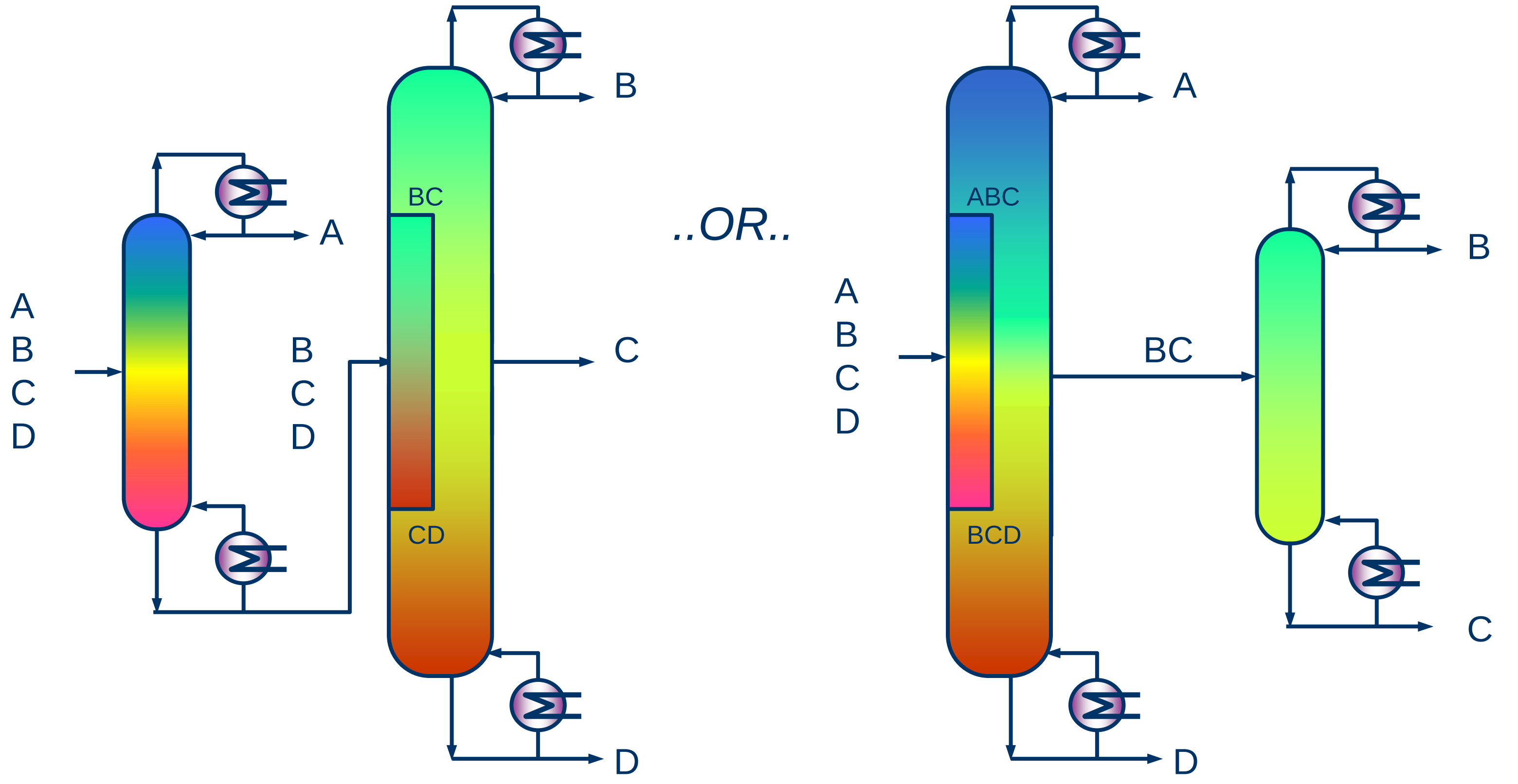
Petlyuk arrangement



The Dividing Wall Column



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

No	Configuration	V_{min}/F	Savings
1	Four product extended Petlyuk	1.38	50%
2	Kaibel column	1.83	33%
3	Three product Petlyuk+ conventional B/C	1.98	28%
4	Prefractionator+ single main column	2.34	15%
6	Conventional direct sequence (3 columns)	2.75	0% (reference)
5	Prefractionator+ 2 separate columns	3.04	-11% (loss)

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_{min}-diagram (Halvorsen 2001)
- Kaibel: Analytic solution presented here – illustrated in the V_{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 <u>common</u> Underwood roots from the feed equation:

$$\frac{\alpha_A z_A}{\alpha_A - \theta} + \frac{\alpha_B z_B}{\alpha_B - \theta} + \frac{\alpha_C z_C}{\alpha_C - \theta} + \frac{\alpha_D z_D}{\alpha_D - \theta} = 1 - q$$

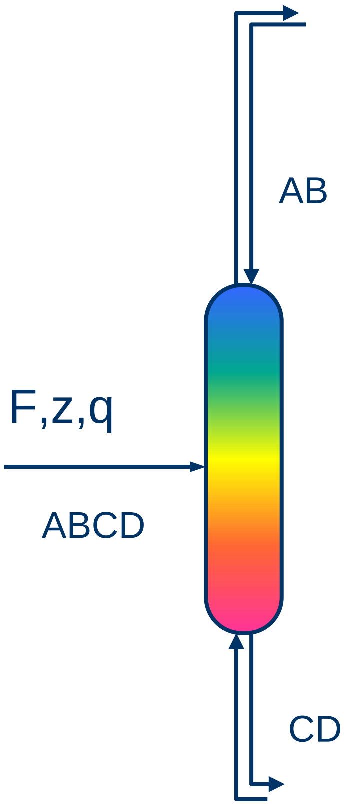
Properties of the solution:

$$\alpha_A > \theta_A > \alpha_B > \theta_B > \alpha_C > \theta_C > \alpha_D$$

The common Underwood roots depend only on feed properties – not on flow rates

Use of the Underwood Equations 2

Prefractionator
Column C1



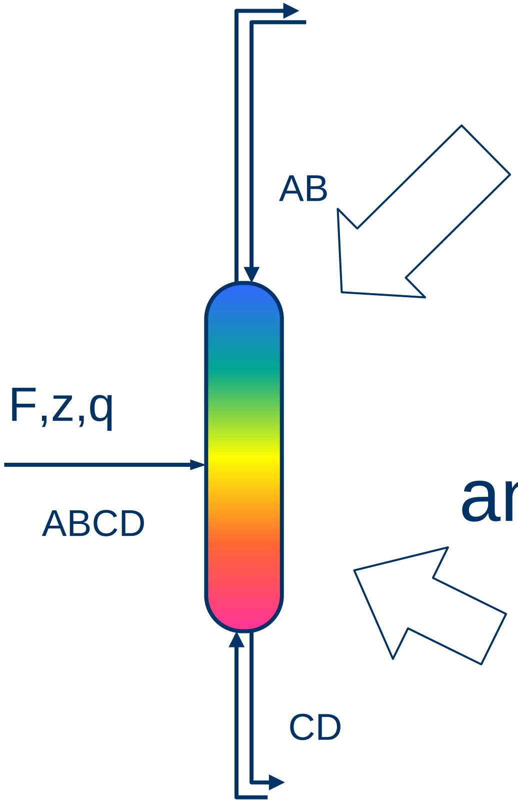
Find V_{min} in C1 for sharp AB/BC split

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

Note: θ_B is the *only* active common root

Use of the Underwood Equations 3

Prefractionator Column C1



Find the actual root ϕ_A in C1 (top):

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

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

and the actual root ψ_C in C1 (bottom):

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

where: $\alpha_C > \theta_C > \psi_C > \alpha_D$

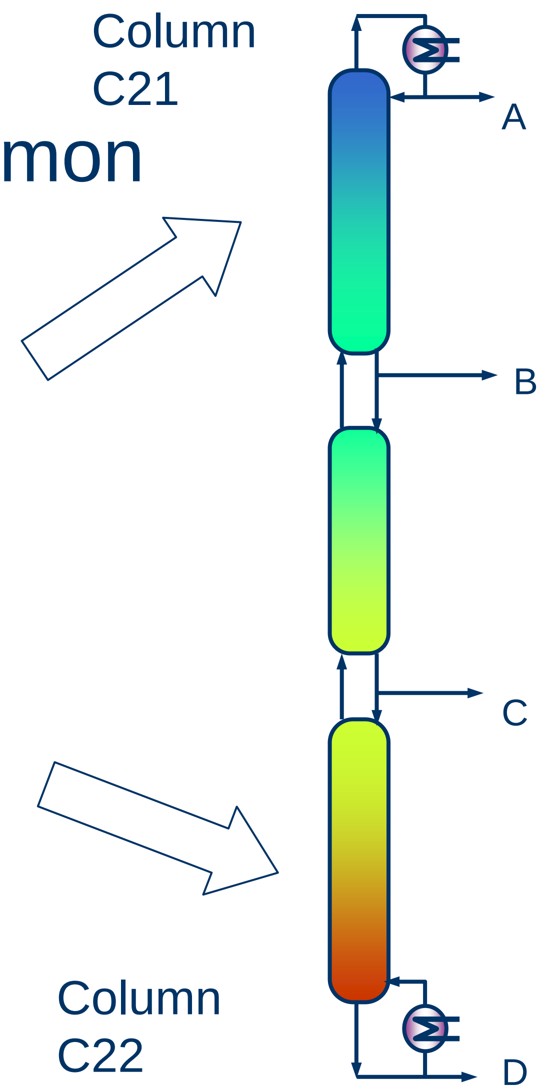
Use of the Underwood Equations 4

Root ϕ_A from C1 carry over as common root in C21 (Halvorsen 2001)

$$V_{T\min}^{C21} = \frac{\alpha_A z_A}{\alpha_A - \theta_A^{C21}} F = \frac{\alpha_A z_A}{\alpha_A - \phi_A} F$$

Similarly ψ_C to C22, and:

$$V_{B\min}^{C22} = -\frac{\alpha_D z_D}{\alpha_D - \theta_C^{C22}} F = -\frac{\alpha_D w_D}{\alpha_D - \psi_C} F$$

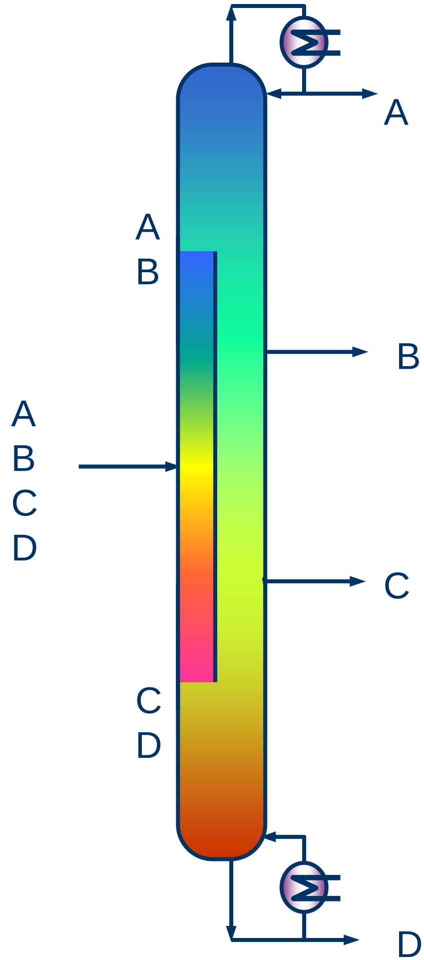


Use of the Underwood Equations 5

The maximum requirement in C21 or C22 determines the overall requirement

$$\frac{V_{T\min}^{Kaibel}}{F} = \max\left(\frac{V_{\min}^{C21T}}{F}, \frac{V_{\min}^{C22B}}{F} + (1-q)\right)$$

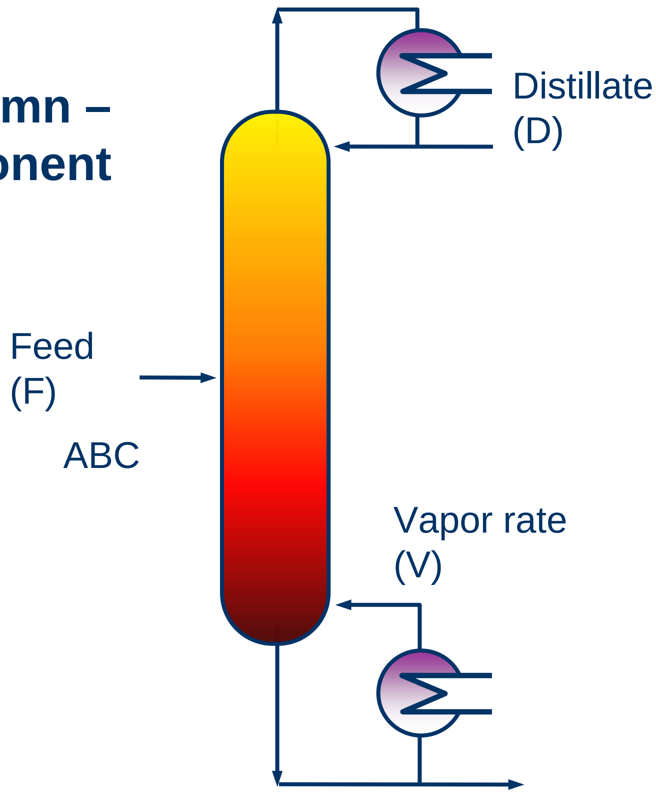
$$= \max\left(\frac{\alpha_A z_A}{\alpha_A - \phi_A}, \frac{z_D}{\psi_C - 1} + (1-q)\right)$$

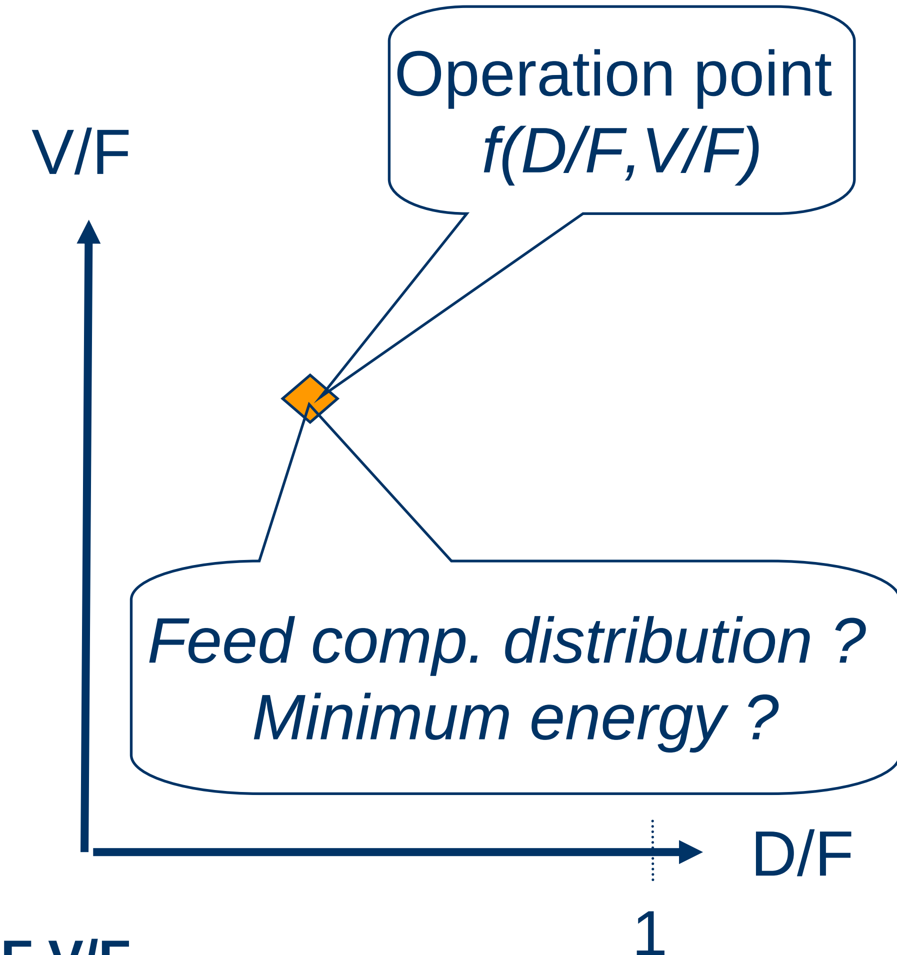


Note error in CD proceedings: replace min() with max()

The V_{min}-diagram

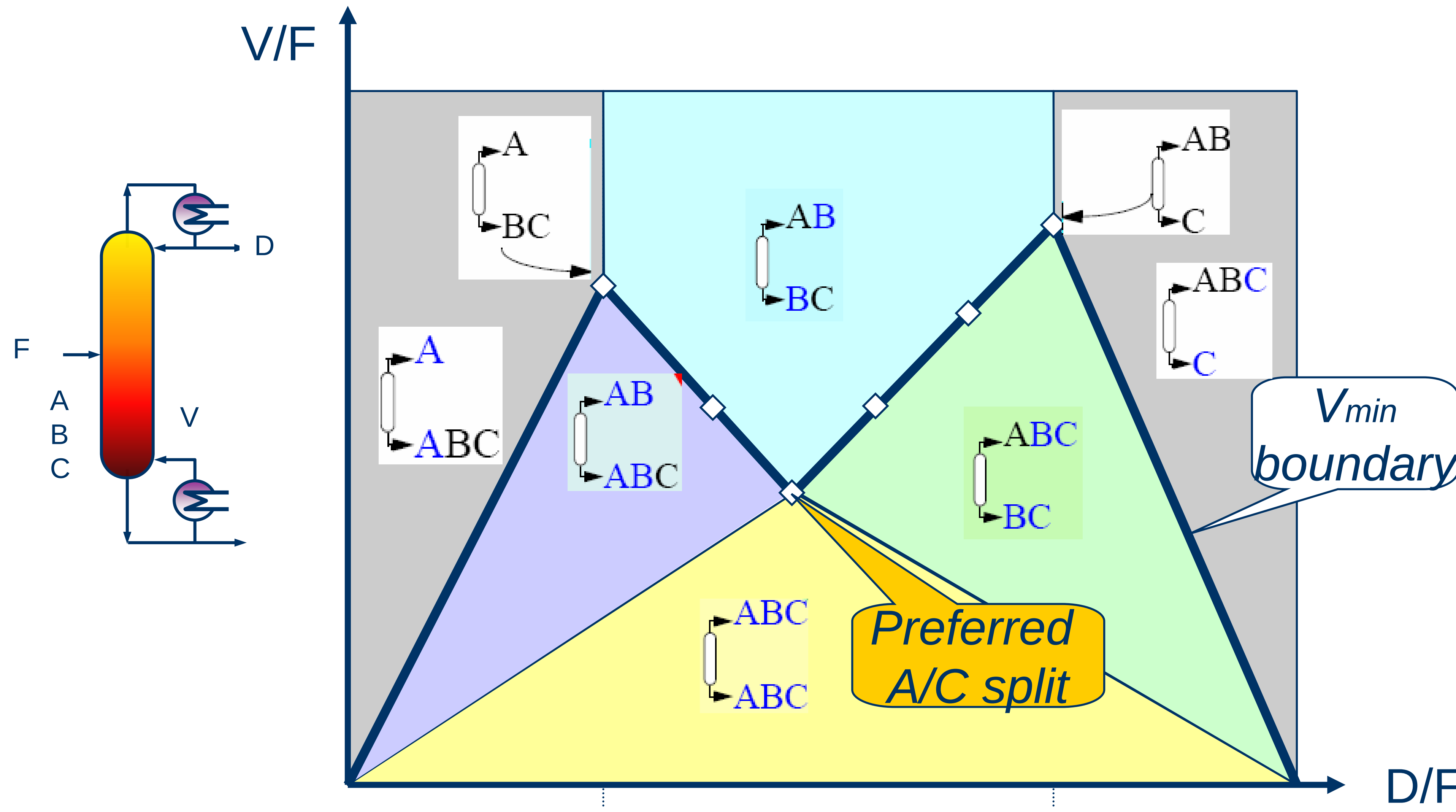
Binary column – multicomponent feed





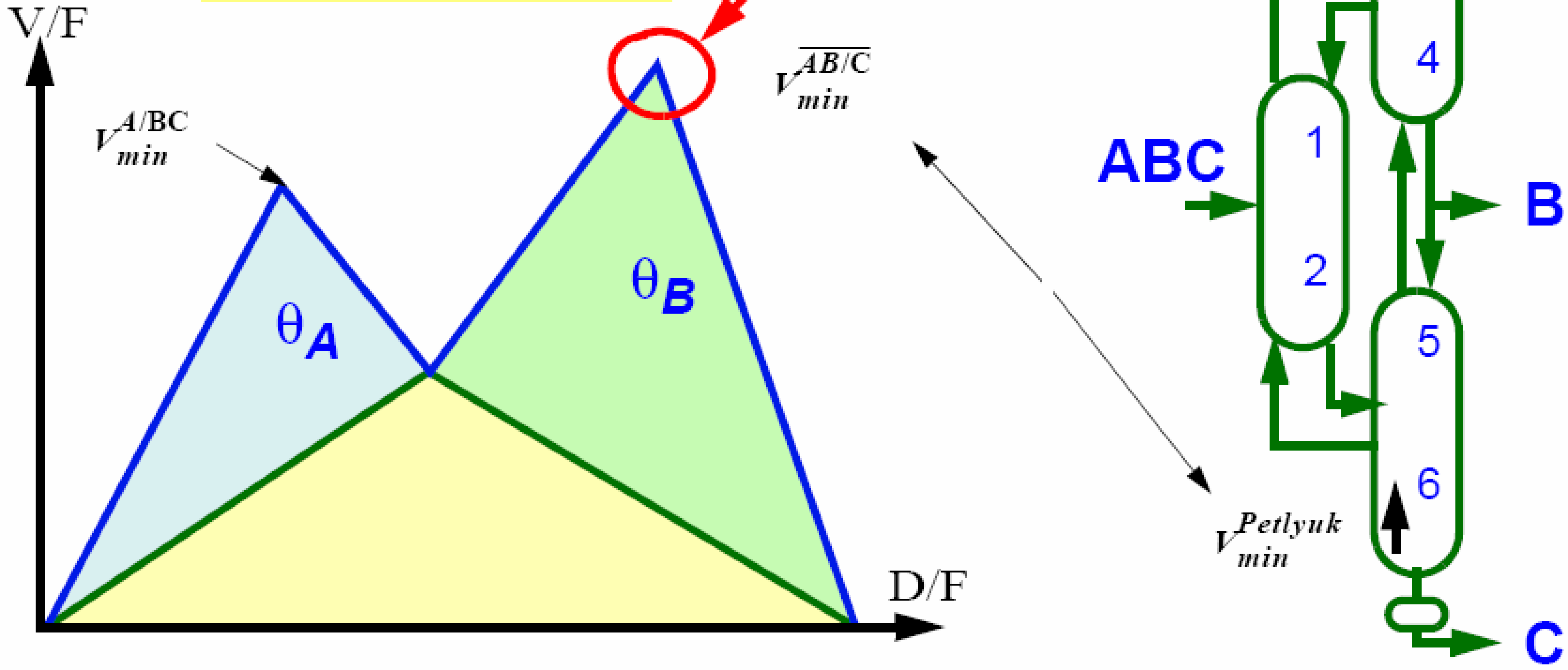
Two degrees of freedom – choose D/F,V/F

The V_{min}-diagram – 3 component example



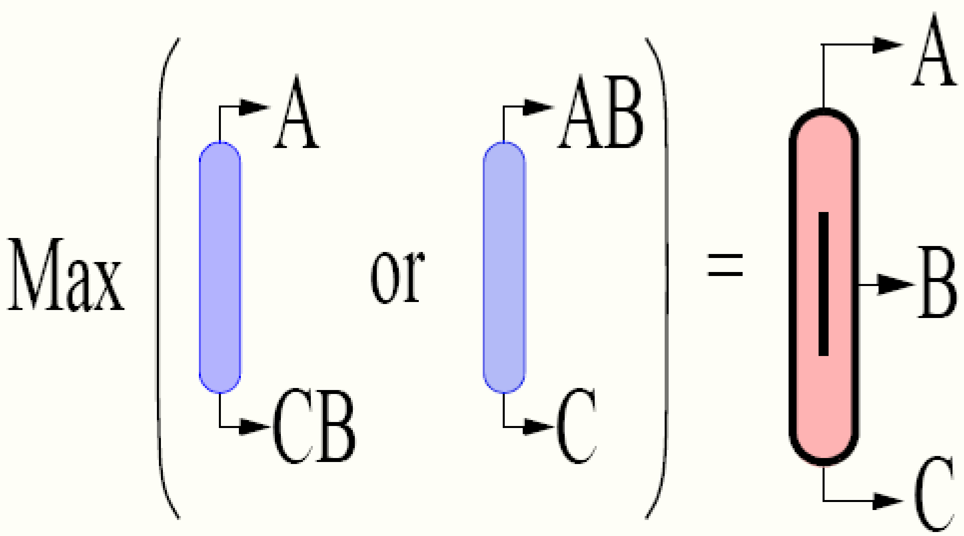
V_{min} for the Petlyuk column: The highest peak:

$$\frac{V_{Tmin}}{F} = \max_j \left(\sum_{i=1}^{j} \frac{\alpha_i z_i}{\alpha_i - \theta_j} \right)$$

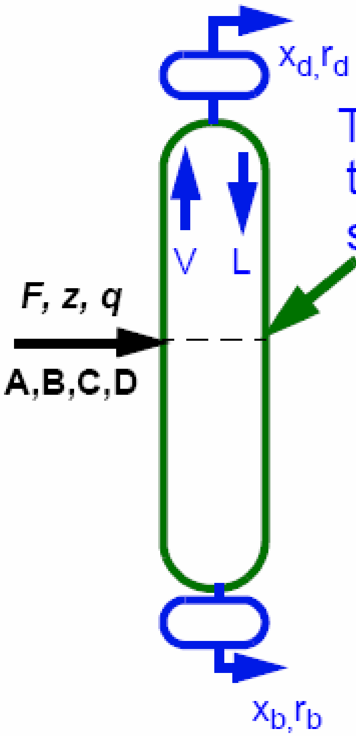


V_{min}-diagram

Petlyuk column: V_{min} = the most difficult binary split

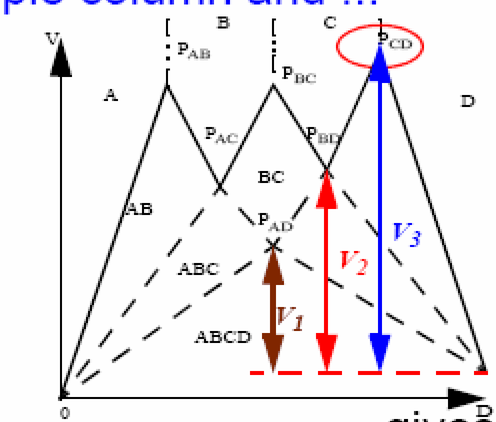


The most difficult split in
this standard two-product column..

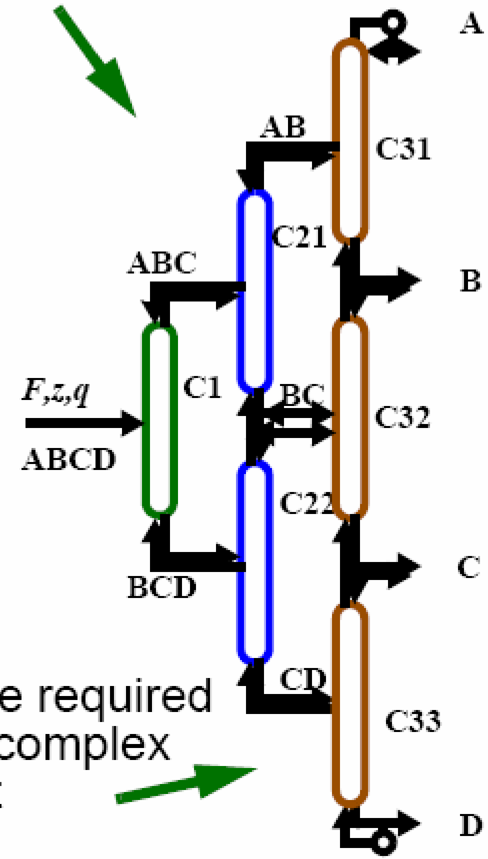


..gives is the minimum energy
of a directly coupled extended
Petlyuk arrangement

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

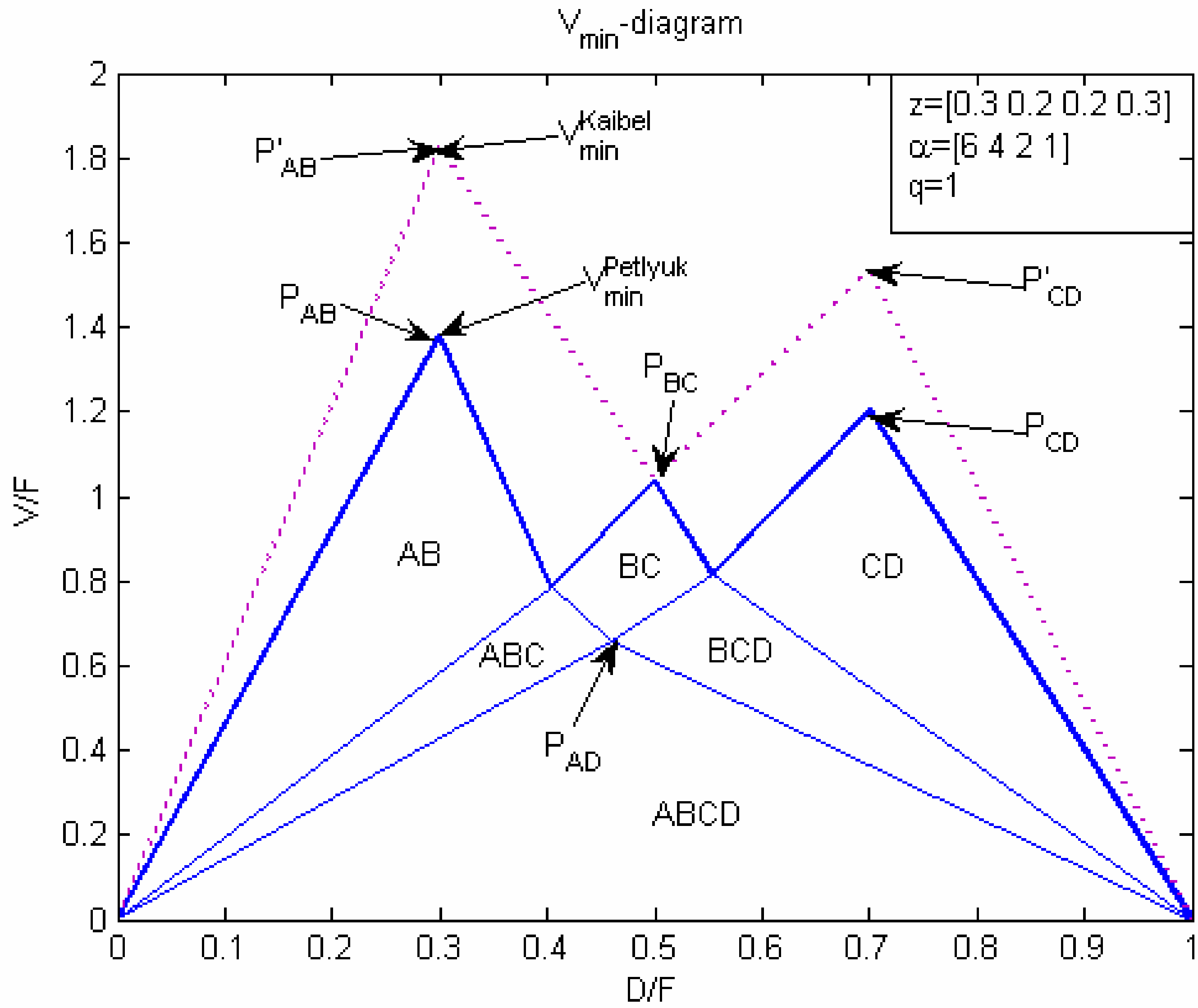


...gives all the required
flows in this complex
arrangement

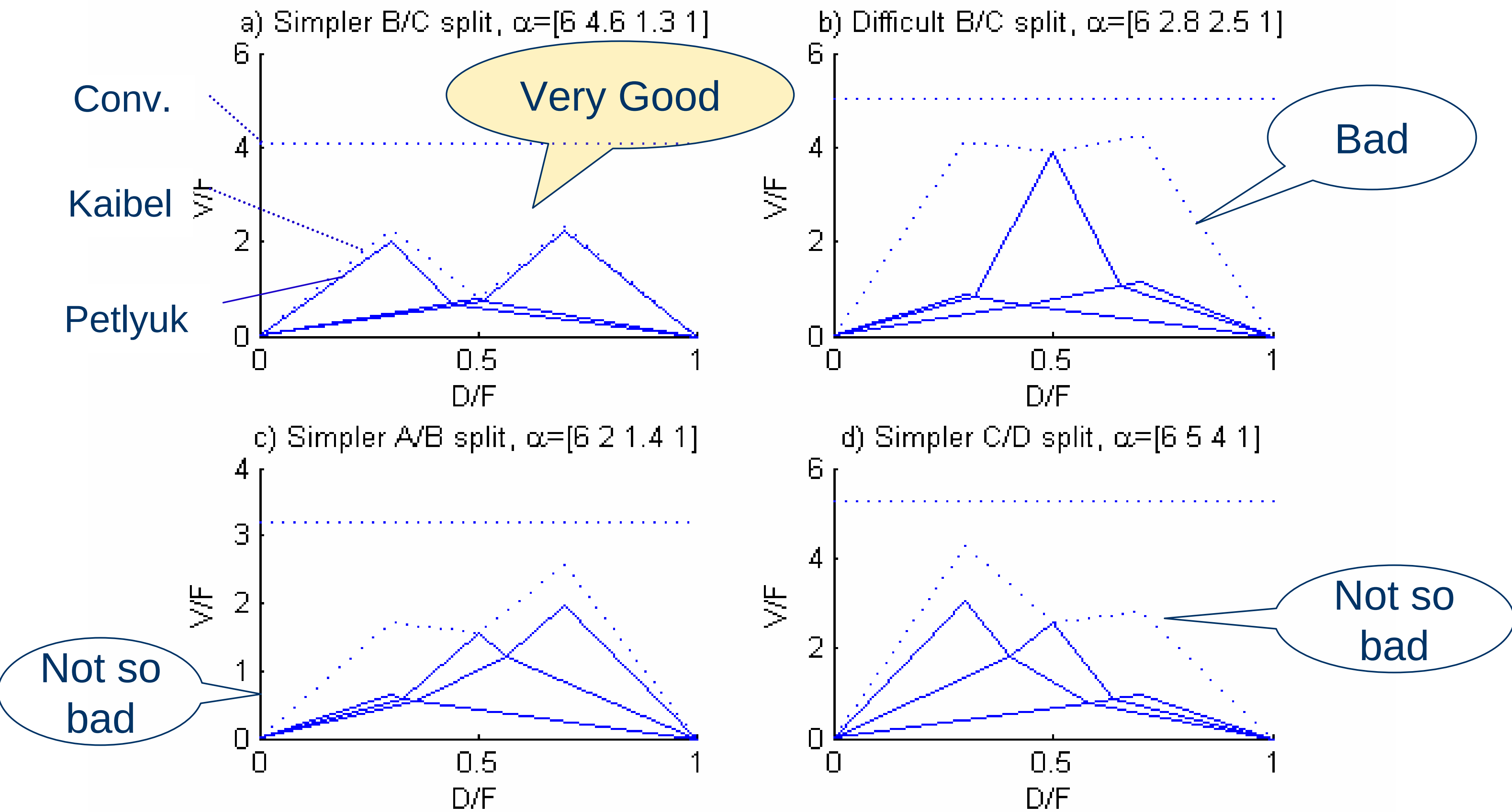


Exact analytical expressions
by the Underwood equations

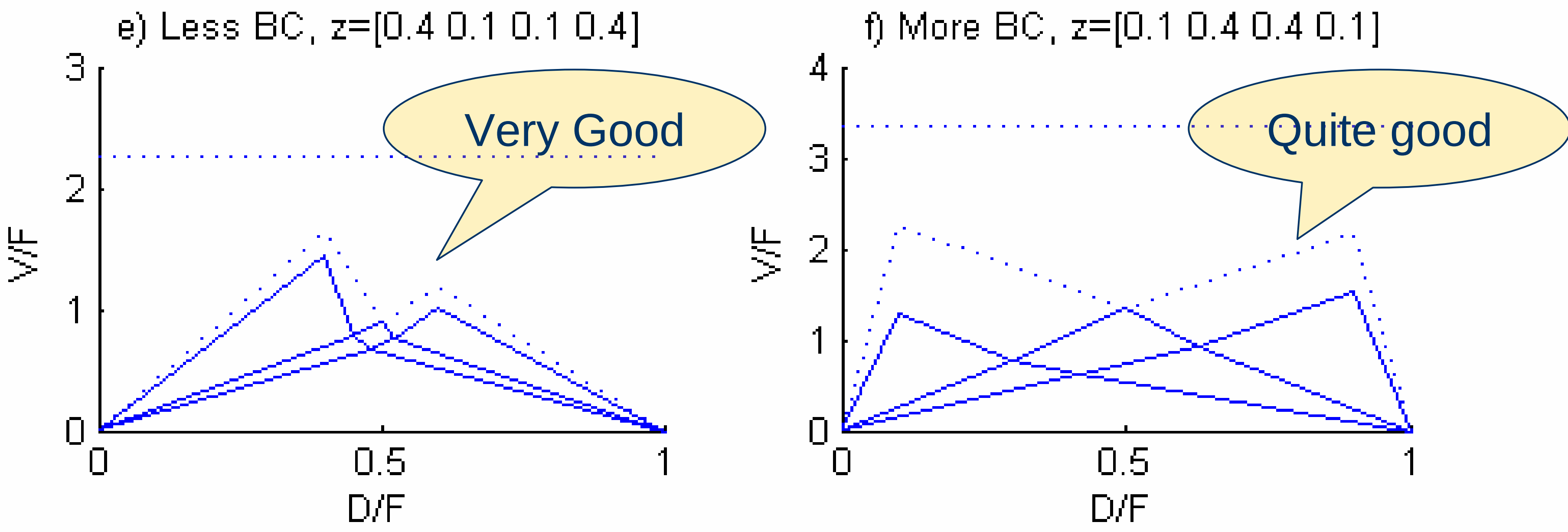
V_{min}-diagram for the Kaibel column



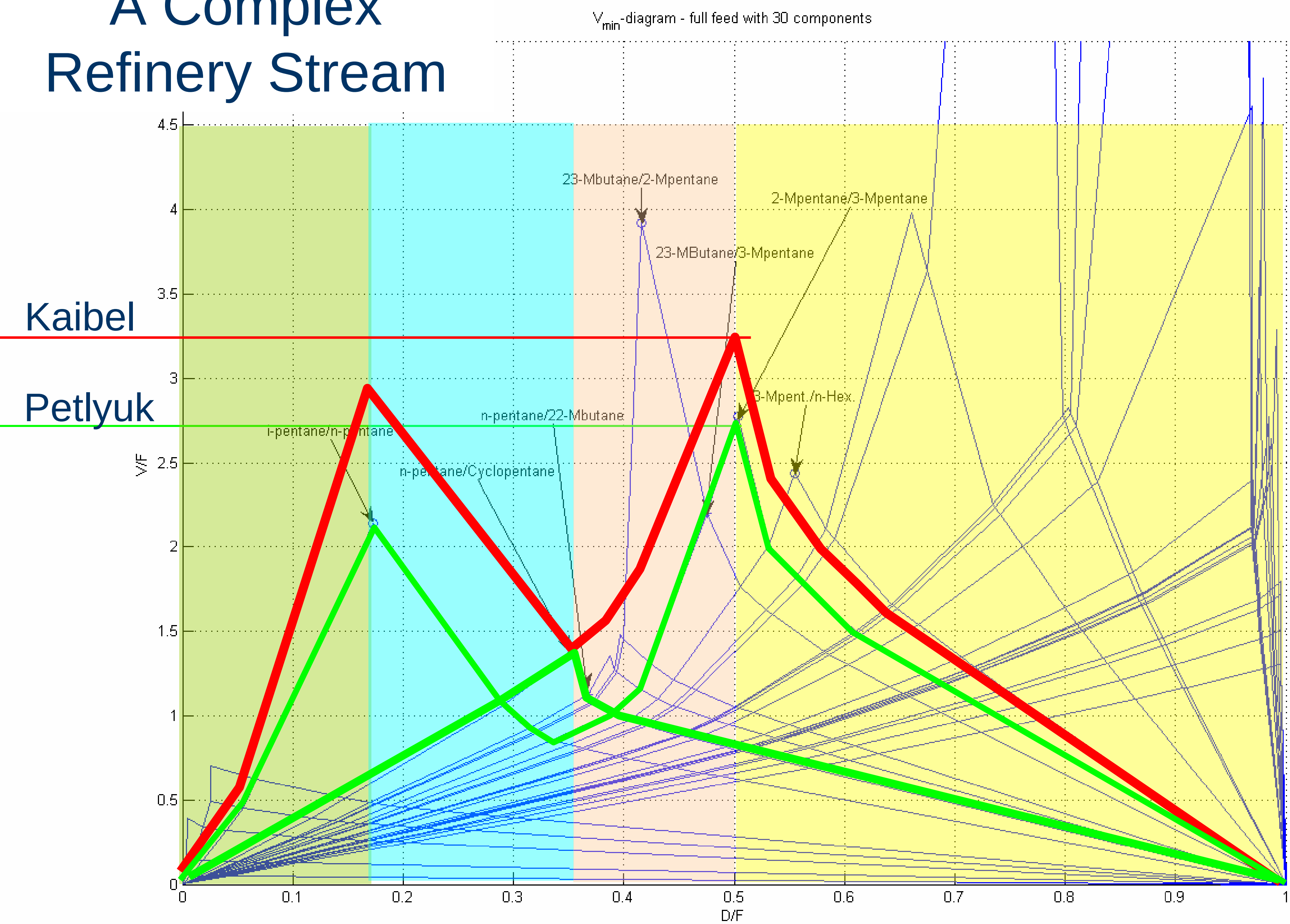
Assessment by the V_{min}-diagram



Assessment by the *Vmin*-diagram...



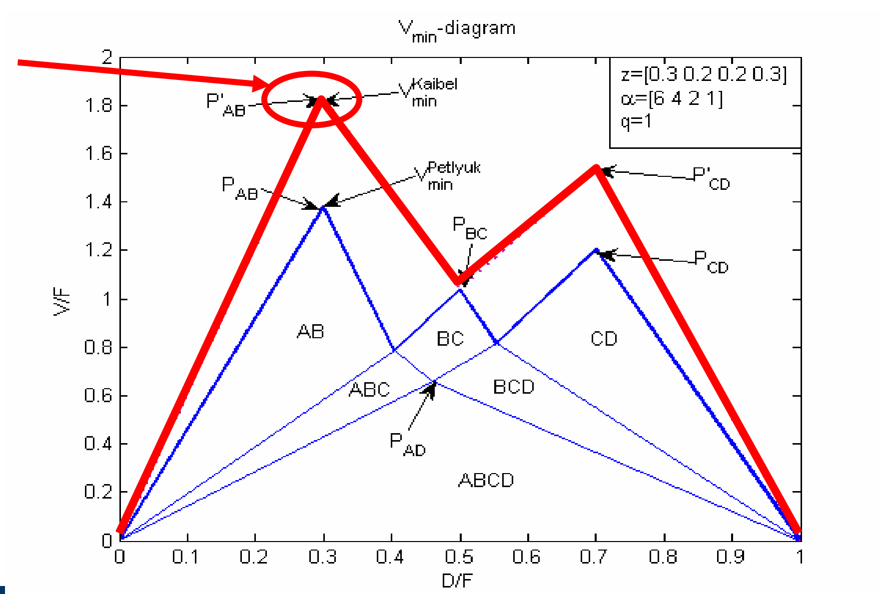
A Complex Refinery Stream

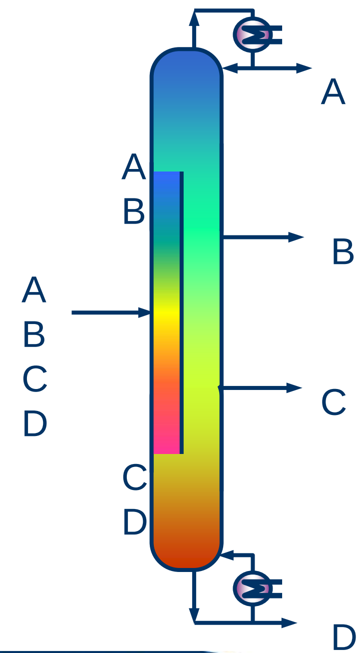


Conclusion

- 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

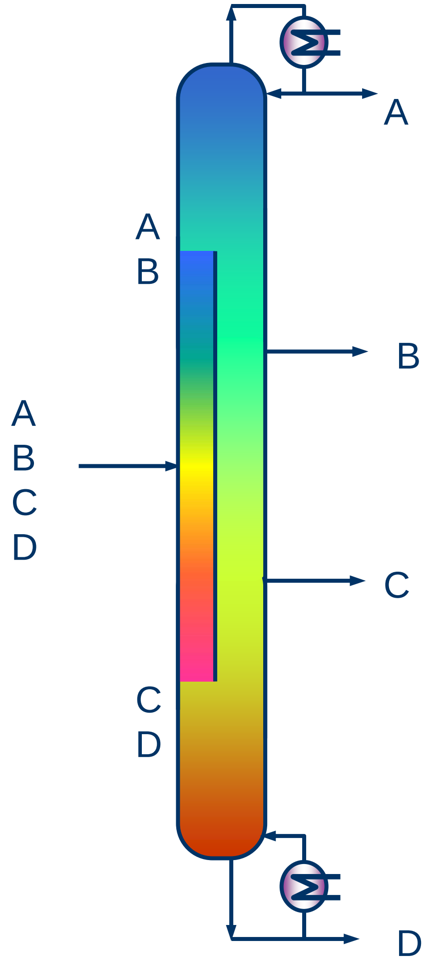




The Kaibel column
Summary

- 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