Improved Analysis and Understanding of the Petlyuk Distillation Column

by

Ivar J. Halvorsen and Sigurd Skogestad

Norwegian University of Science and Technology (NTNU)
Department of Chemical Engineering

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Email: Sigurd.Skogestad@chembio.ntnu.no, Ivar.J.Halvorsen@ecy.sintef.no
Web: http://www.chembio.ntnu.no/users/skoge http://www.chembio.ntnu.no/users/ivarh

Motivation and Objectives

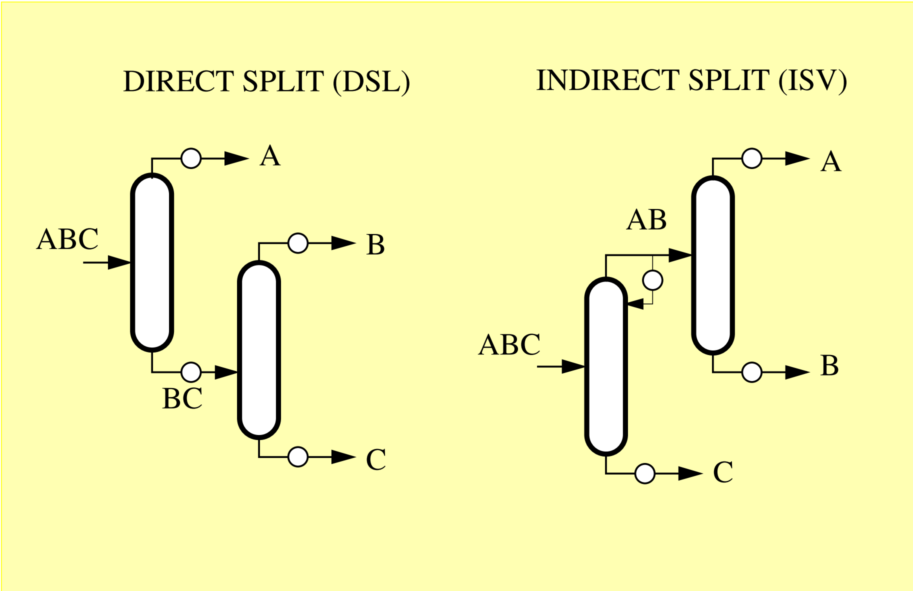
- The Petlyuk Arrangement can save large amounts of energy- and also capital costs (A typical number of 30% is reported, but up to 50% is possible)
- It is 50 years since Wright's patent (1949)
- It is 25 years since Petlyuk presented the energy savings results (1965)
- Usage of Petlyuk arrangement is still limited. Why?
- Usual reasons given: “Difficulties in design and difficulties in control?”

Objective:

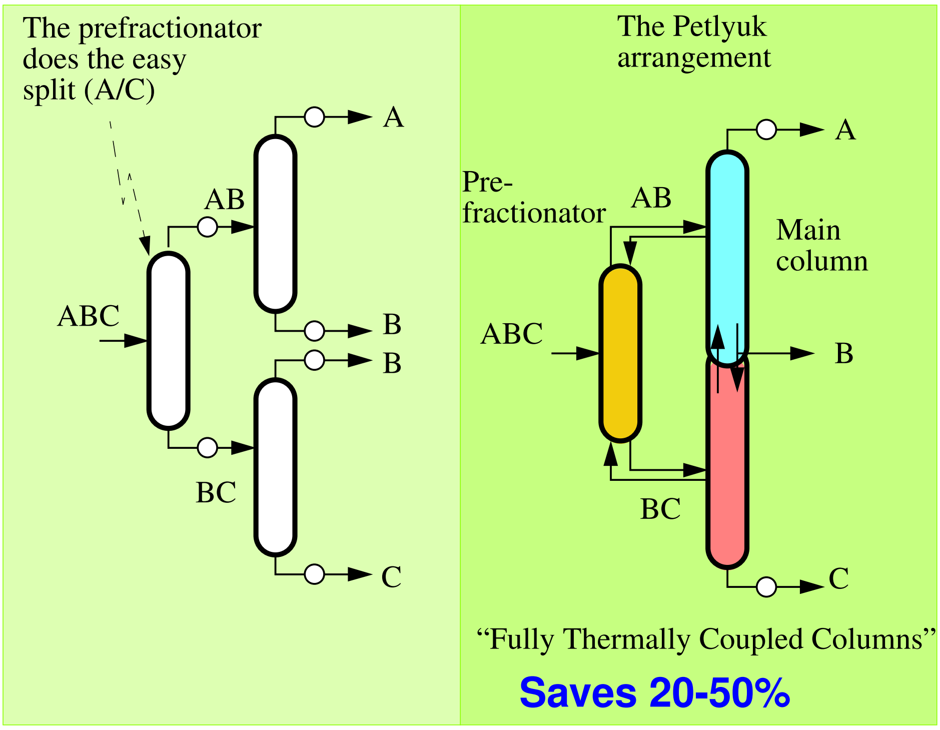
- Understand how the energy usage is affected by disturbances, manipulative variables and product purity specifications.
- Focus on operation.

Introduction: 3-component separation:

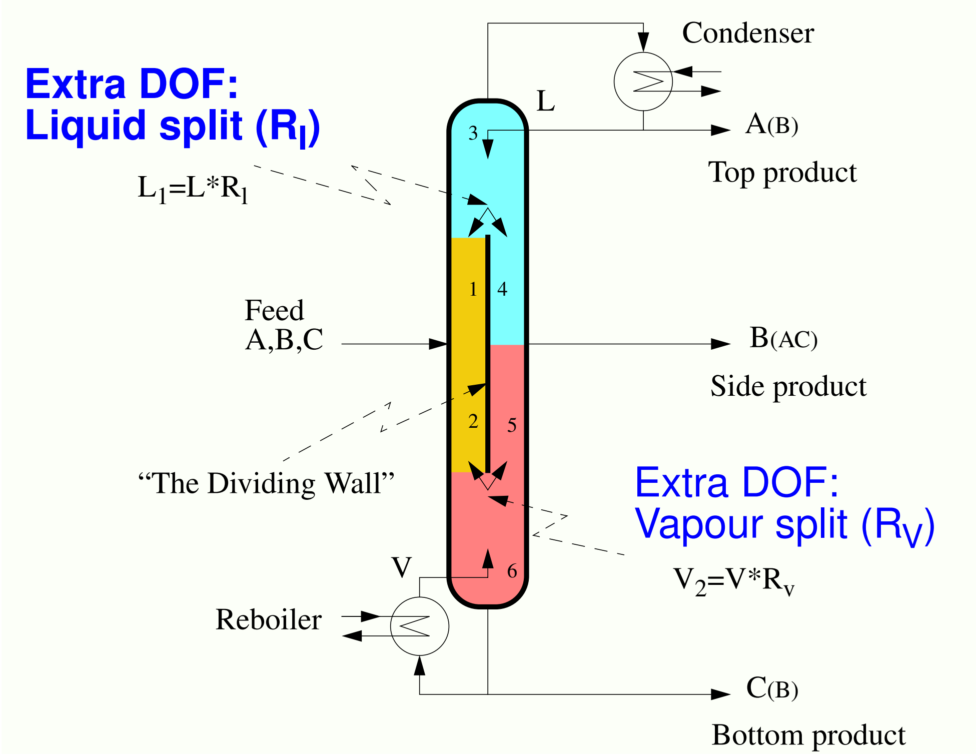
Conventional configurations:



Prefractionator Arrangements:



"Petlyuk" in a single shell: The Dividing Wall Column:



Minimum Energy for the Petlyuk Column

Very simple minimum boilup expression (Fidkowski 1986, Westerberg 1989):

$$V_{min}^{petlyuk} = max\left(\frac{\alpha_A z_A}{\alpha_A - \varphi_1} - (1-q), \frac{\alpha_C z_C}{\varphi_2 - \alpha_C}\right) \tag{1}$$

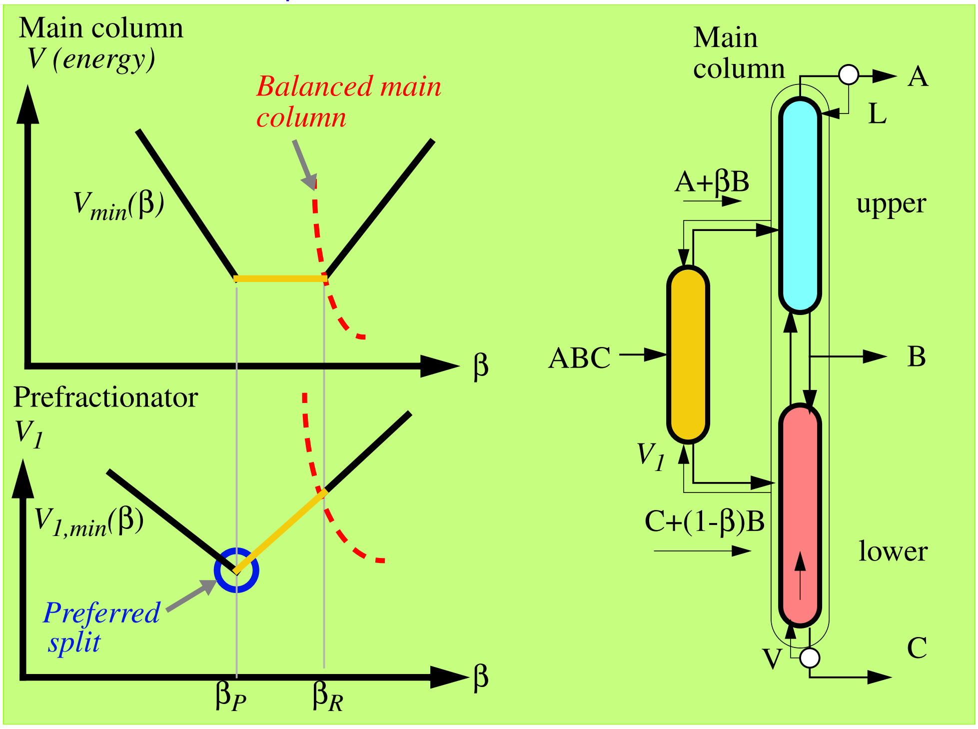
Underwood roots (φ) from:

$$\frac{\alpha_A z_A}{\alpha_A - \varphi} + \frac{\alpha_B z_B}{\alpha_B - \varphi} + \frac{\alpha_C z_C}{\alpha_C - \varphi} = (1-q) \tag{2}$$
$$\alpha_A > \varphi_1 > \alpha_B > \varphi_2 > \alpha_C$$

Assumptions:

- Infinite number of stages
- Constant relative volatility
- Constant molar flows
- Sharp product splits (pure products)

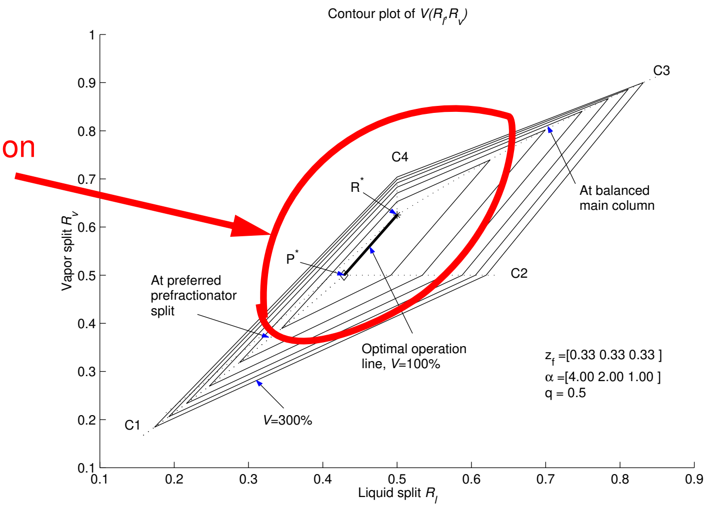
Minimum energy: Operation in the flat region between the *preferred split* in prefractionator and a *balanced main column*



Solution surface for boilup (*V*) as a function of the remaining DOFs (R_l,R_V) for sharp splits $V(R_l,R_V)$:

Our Contribution:

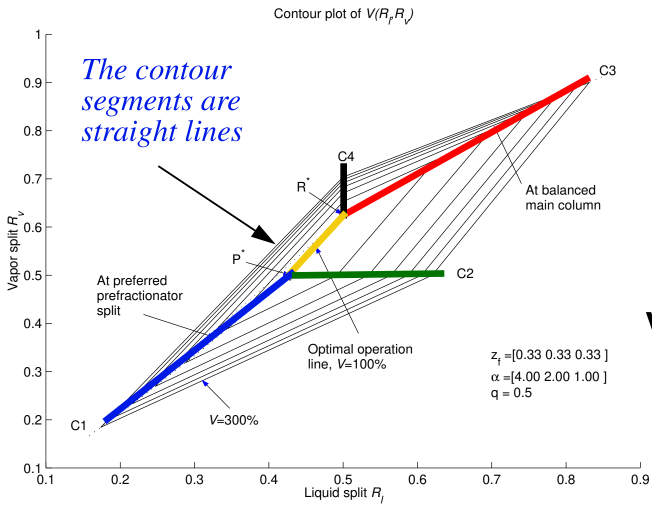
Extended the expression to operation outside the flat region



The energy consumption increase rapidly when the operation is not exactly at the minimum energy region (which is on PR).

Important: When PR is large, one DOF (R_l *or* R_V) may be kept constant!!!

COMPUTATION OF THE ENERGY CONSUMPTION OUTSIDE THE FLAT REGION: $V(R_l,R_V)$



PR: Minimum energy region

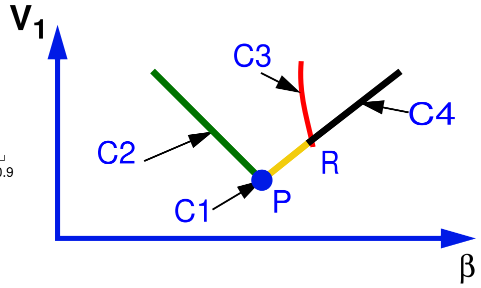
***Characteristic corner edges*:**

C1: At preferred split

C2: Left branch of $V_{1,min}(\beta)$

C3: Balanced main column

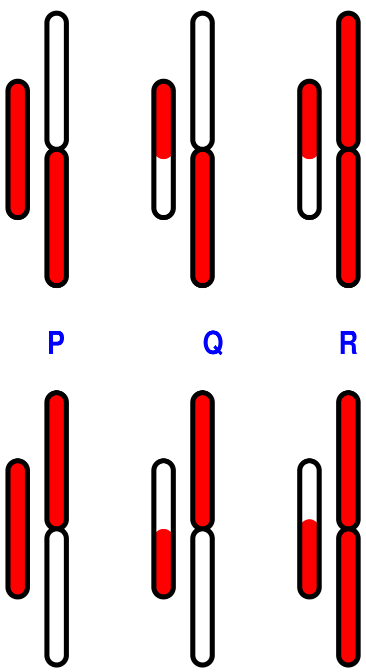
C4: Right branch of $V_{1,min}(\beta)$



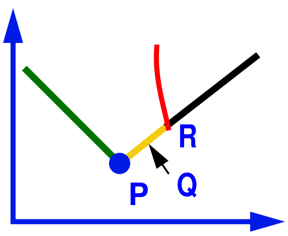
Column sections at minimum reflux for 3 main cases:

: Over-refluxed

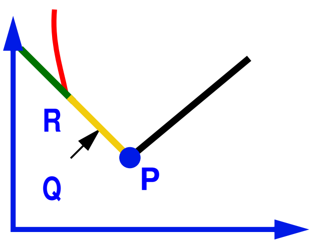
: Minimum reflux



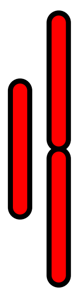
Case 1: $\beta_P<\beta_R$



Case 2: $\beta_P>\beta_R$

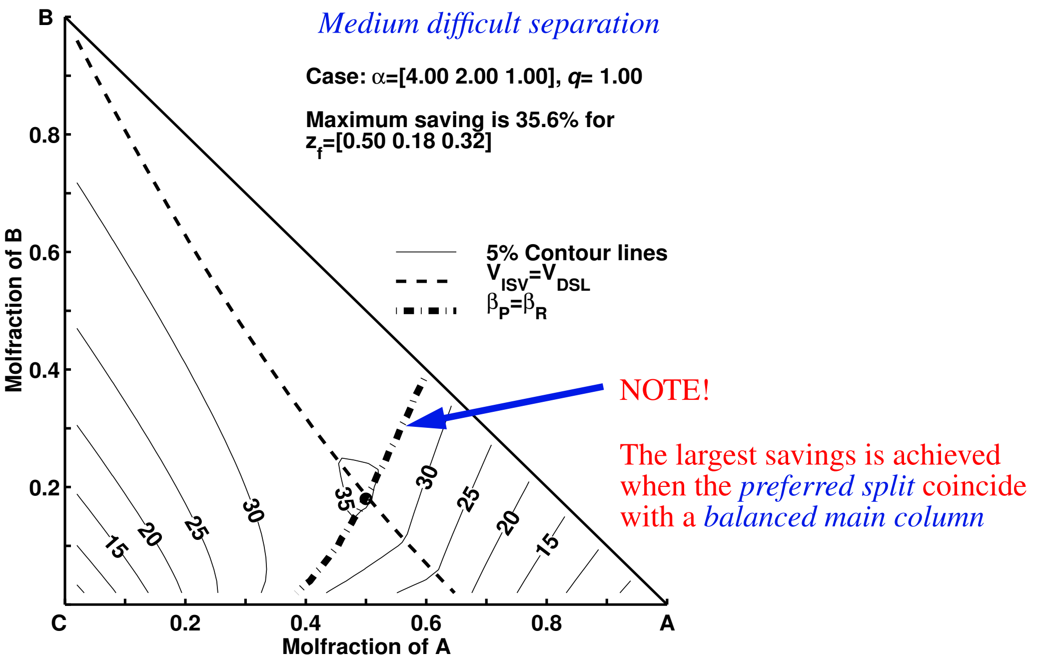


Case 3: $\beta_P=\beta_R$



P=Q=R

Contour plot of theoretical savings as function of feed composition compared to the best of the conventional configurations.



Important observations for high purity operation of the Petlyuk column:

2-point on-line optimization is required in the following situations:

- For operation close to the boundary region
  In particular for difficult separations

1-point on-line optimization is sufficient:

- For operation further away from the boundary, but note that the control strategies may be different dependant on the particular side.

No optimizing control is required:

- For very small feed variations and other disturbances
  (impossible in practice)
- Can be sufficient for easy separations
  (But then the potential savings are small!)

Computing: Very simple analytic functions, realized in Matlab:

The minimum energy solution is just a function of α, z and q

- $V_{min}=f(\alpha,z,q)$ at the operating points P*=f(α,z,q), R*=f(α,z,q)
- P* and R* are defined by the degrees of freedom (R_l,R_v)
  (Which fully determines all internal flows)

The most complex operation is computing the Undewood roots,
(finding the roots of a 3.rd order polynomial)

Example: Each triangular plot shown is computed at ~1200 grid points in z.
CPU-time is < 10 seconds on 200MHz Pentium CPU.

The full solution surface f(V,R_l,R_v,α,z,q)=0 is computed via the corner points:

- Ci=$f_i(V,\alpha,z,q)$, for $V>V_{min}$, (i=1-4)
- An arbitrary operating point
- V=f(Rl,Rv,α,z,q)=f(R_l,R_v,C1,C2,C3,C4)
- Note that we get a full solution surface for every set of α,z,q

Summary of Underwood's Equations for Minimum Energy Calculations

Feed equation gives common "V_{min}"-roots φ

$w_{i,F}=Fz_{i,F}$

F,z,q

V^T-V^B=$(1-q)F$

"Top section"

$w_{i,T}$

$$V^T = \sum_i \frac{\alpha_i w_{i,T}}{(\alpha_i - \phi)}$$

$$(1-q) = \sum_i \frac{\alpha_i z_i}{(\alpha_i - \varphi)}$$

"Bottom section"

$w_{i,B}$

$$V^B = \sum_i \frac{\alpha_i w_{i,B}}{(\alpha_i - \psi)}$$

$w_{i,B}=w_{i,T}-Fz_{i,F}$

Top and bottom equations has the "real" - roots ϕ and ψ

Underwood:
When one or more pairs ϕ_i, ψ_{i+1} coincide, then $\phi_i = \psi_{i+1} = \varphi_i$, and
$V=V_{min}$

Usage:
1. Compute φ from "feed eq"
2. Specify 2 DOF variables.
3. Use every "active" φ-root in "top or bottom" eq. and compute V_{min} and all recoveries

Note: "Active" roots are between the distributed components

Visualisation of minimum energy and component distribution for the ternary example (feed components ABC)

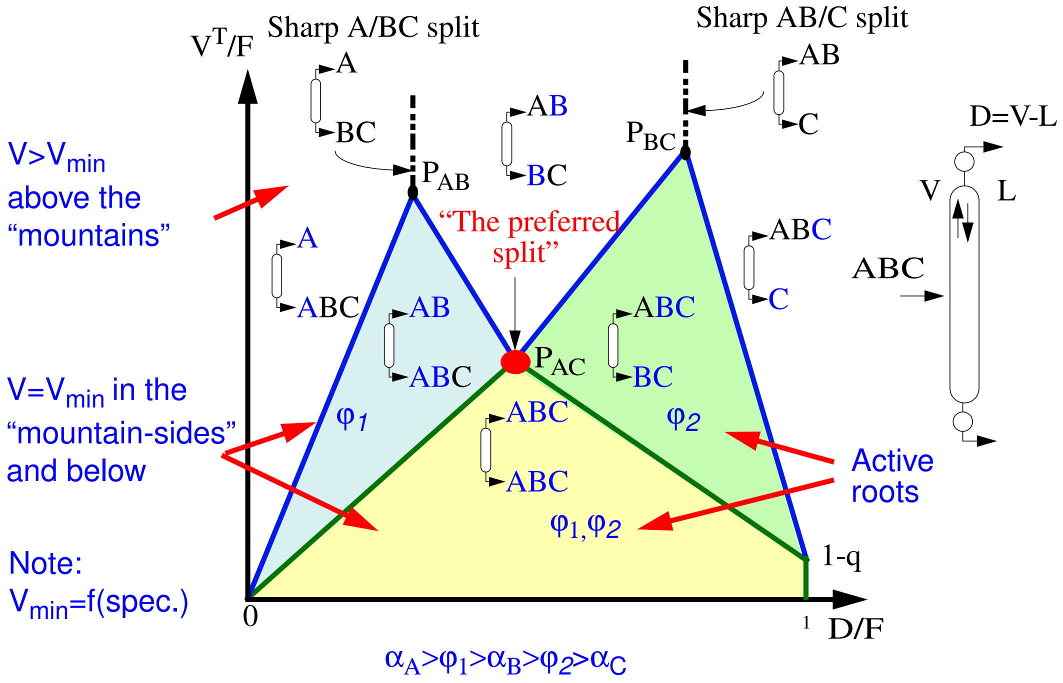
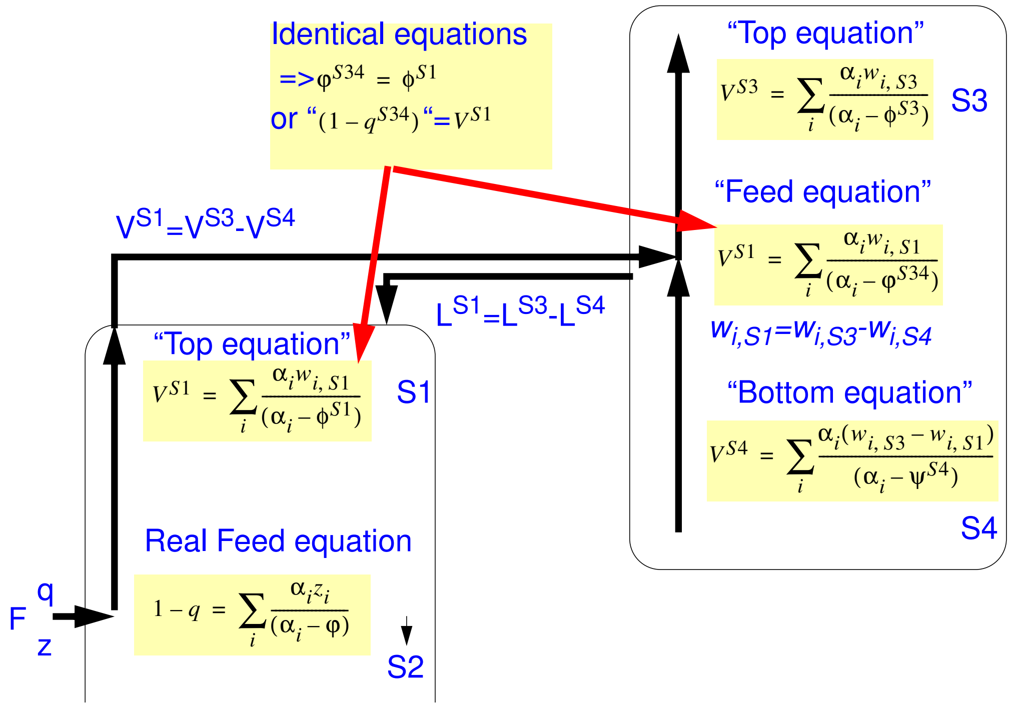
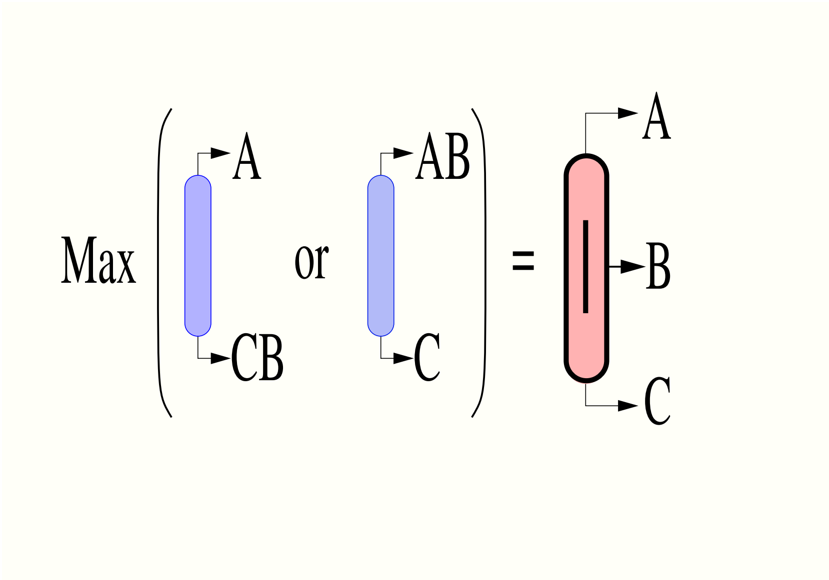


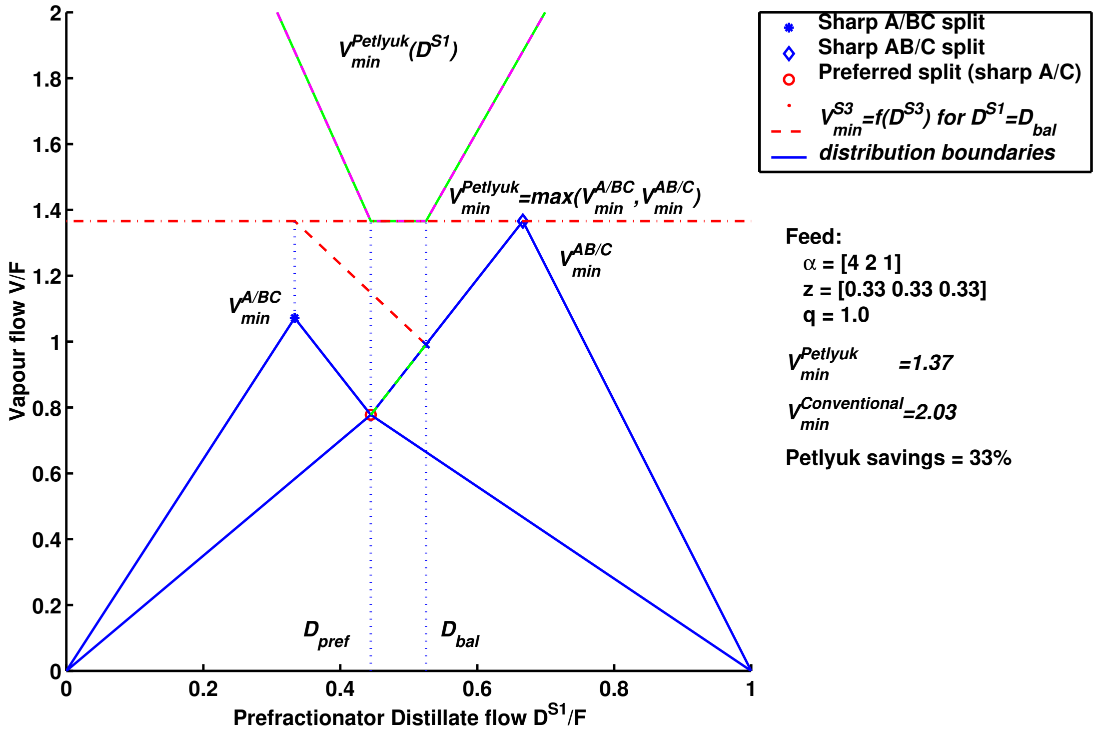
Illustration of how Underwood roots carry over to the next column through the full thermal coupling



Very simple computation of V_{min} for Petlyuk column



Example: Application to a 3 product Petlyuk Column:



Feed:
α = [4 2 1]
z = [0.33 0.33 0.33]
q = 1.0

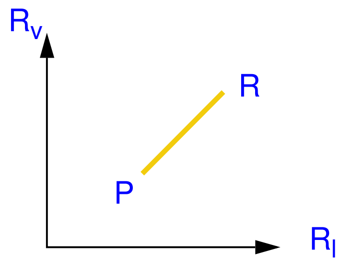
$V^{Petlyuk}_{min}=1.37$

$V^{Conventional}_{min}=2.03$

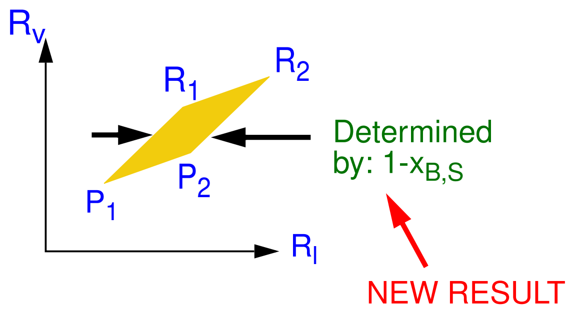
Petlyuk savings = 33%

Non-pure side-stream =>
Flat region is extended to a parallelogram

Sharp split $x_{B,S}=1$



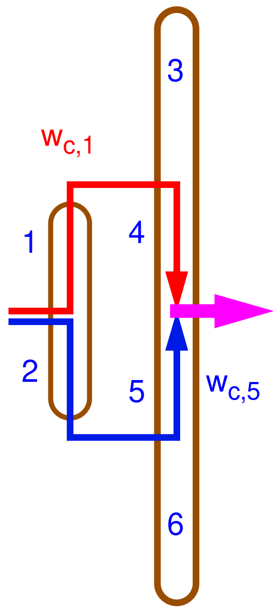
Non-sharp split $x_{B,S}<1$



Direction 1 (PR): Depends on “Preferred split” - “Balanced main column”

Direction 2 (12): Depends on side-stream purity ($1-x_{B,S}$)

Why optimum is flat due to side-stream impurity:



Case: Ternary feed (A,B,C)
Assume lower main column is at V*min* ($\beta_P<\beta_R$)

Look at the path for C from feed to side-stream:

Assume constant amount if impurity (C) in S

$w_{C,S}=w_{c,1}+w_{c,5}$=constant at specification

$\Rightarrow \Delta w_{c,1}=-\Delta w_{c,5}$

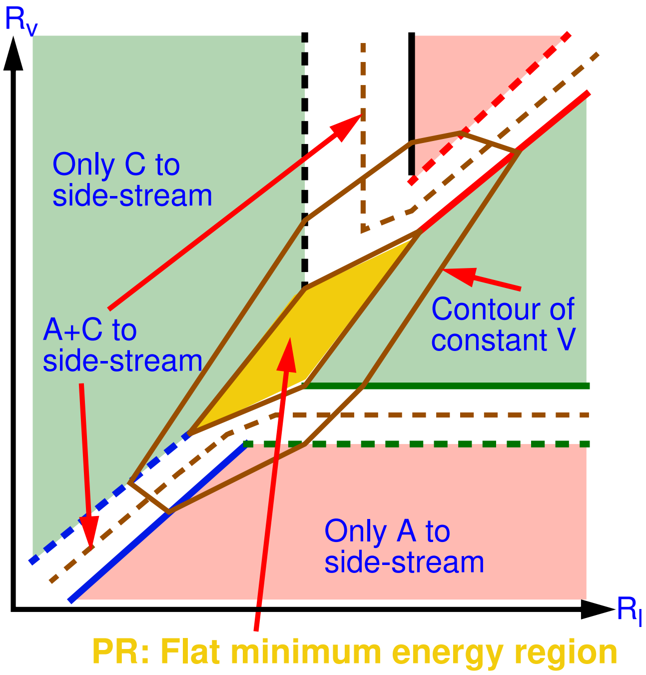
At optimum, only Underwood root φ_2 is active since only B and C is distributed in 5,6 and 2!

Implies $\Delta V_2(\Delta w_{c1})=-\Delta V_5(\Delta w_{c1})$ (φ_2 “carry over”)

$\Delta V_6=\Delta V_2+\Delta V_5=0$

Boilup (V_6) is constant and independent of “path”

ENERGY CONSUMPTION:
$V(R_l,R_v)$ for constant product purity and NON-sharp splits



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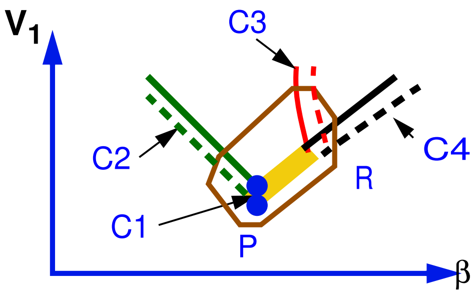
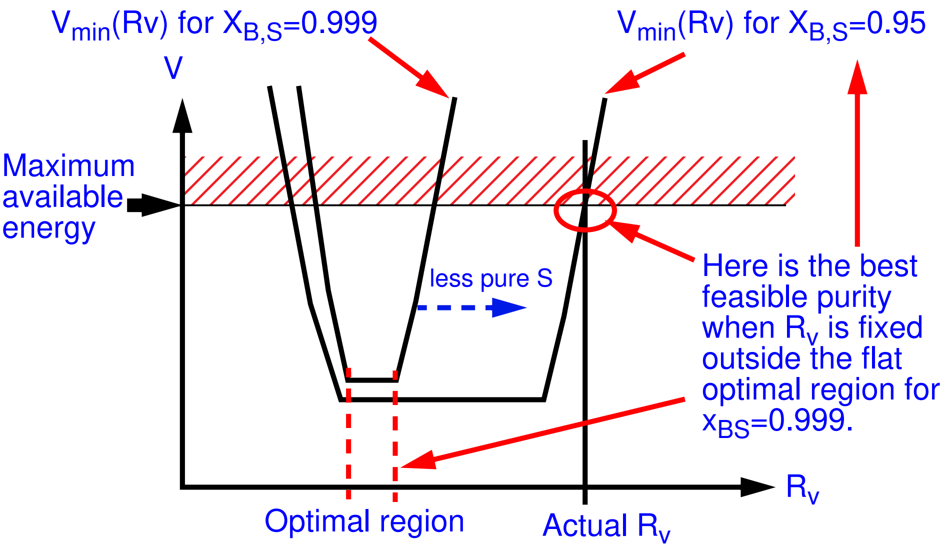


Main symptoms of non-optimal operation:

1. $V >> V_{min}$
2. $x_{B,S}$ << Specified, see illustrating example:



Can we do better than the plain Petlyuk column?

YES!

One part of the main column is usually over-refluxed => Need less energy

Can take out the “extra” energy in many different ways:

- Extract heat at the side-stream outlet (or extract S as vapour)
- Extract heat from the feed (decrease q)
- Use a condenser at the prefractionator top
- Use a separate reboiler for the prefractionator
- Cooler/heater in the middle of the main column
- Etc.

  .....
- Use the best practical solution

Principle=>Try to run all sections at their local V_{min} simultaneously (“P=R”)

Conclusion

New results:

- Analytic expressions for the solution surface $V(R_l,R_v)$ outside the optimal region
- Extension of the computations to non-sharp product splits
- Understanding of the parameters that determine the extent of the optimality region in the two main directions.
- Use of Underwood equations to quickly find V_{min} for Petlyuk column with just a glance at the graphical D-V diagram.
- Handle general multicomponent feed mixtures. (N_c>3)
- Petlyuk columns and improved structures can save large amounts of energy
- High purity optimal operation is feasible