Optimal operation of a Petlyuk Distillation Column: Energy Savings by Over-fractionation

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by

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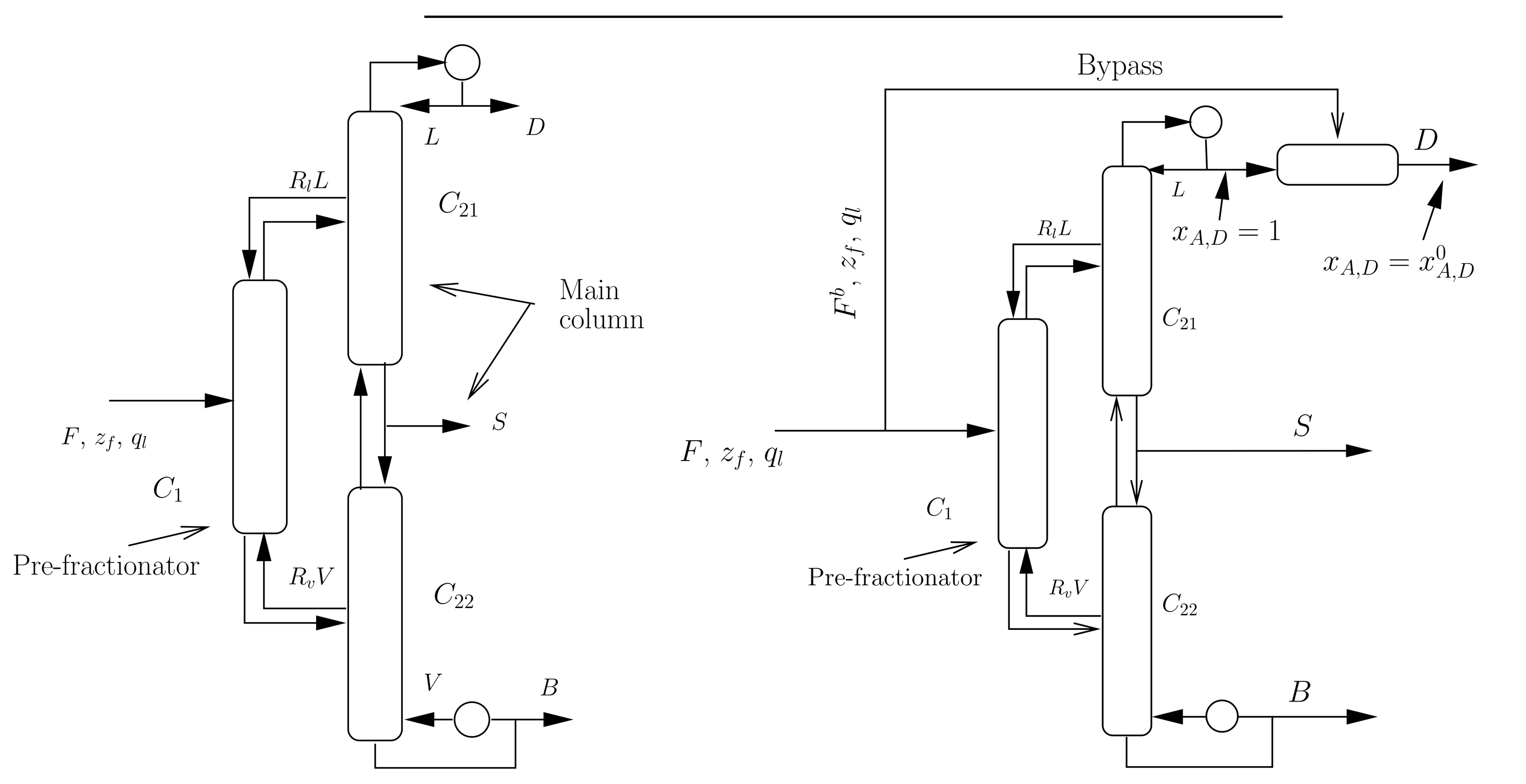
Abstract

This work shows the unexpected result that over-fractionating one of the product streams in a Petlyuk distillation column may be optimal from a energy point of view. Analytic expressions for the potential energy savings are derived using the Underwood equations. The energy savings by over-fractionation may be further increased by bypassing some of the feed and mixing it with the over-fractionated product to meet product specifications. Normally, the energy savings are small, so the main significance of our results is to point out that over-fractionating is optimal in some cases.

1 Introduction

- The Petlyuk distillation column, see Figure 1(a), with a pre-fractionator (C_1) and a main column (C_{21} and C_{22}), is an interesting alternative to the conventional cascade of binary columns for separation of ternary mixtures. The potential savings are reported to be of approximately 30% in both energy and capital cost [4].
- It is well known that if the products have different economic value, it may be economically optimal to over-fractionate the low value product in order to produce more of the more valuable products.
- Here we intend to show that we in fact can **save energy** by over-fractionating one of the product streams.
- It is known from literature that for a conventional binary distillation column, bypassing a portion of the feed to the products does not affect the energy demand to produce the specified products [2].



(a) Petlyuk Column (b) Petlyuk Column with bypass (Case 1)

Figure 1: Sketch of the Petlyuk column without (a) and with bypass (b)

2 System description

- **Feed** F consist of 3 components (A,B and C):
  - Composition: $\mathbf{z_f} = [z_A\ z_B\ z_C]^T$
  - Liquid fraction: q_f
  - Relative volatility: $\alpha = [\alpha_A\ \alpha_B\ \alpha_C]^T$
- **Products**
  - **Distillate**, flow D, $x_D = [x_{A,D}\ x_{B,D}\ x_{C,D}]^T$
  - **Side-stream**, flow S, $x_S = [x_{A,S}\ x_{B,S}\ x_{C,S}]^T$
  - **Bottom-stream**, flow B, $x_B = [x_{A,B}\ x_{B,B}\ x_{C,B}]^T$
- **Operational objective:** Minimize energy consumption (minimize boilup (V)) with given minimum purity:

$$\min_{\mathbf{u}} V(\mathbf{u}) \quad (1)$$

$$x_{A,D} \geq x^0_{A,D},\ x_{B,S} \geq x^0_{B,S},\ x_{C,B} \geq x^0_{C,B} \quad (2)$$

  - $\mathbf{u} = [L\ V\ S\ R_l\ R_v]^T$ is the vector of steady-state degrees of freedom (manipulated inputs).
  - $x^0_{i,j}$ is the minimum fraction of the main component $i \in \{A,B,C\}$ in each product stream $j \in \{D,S,B\}$.

3 V_{min}-diagram and Underwood equations

- The V_{min}-diagram, see Figure 3(a), is a graphical representation of the energy requirements in distillation columns [3] and is based on the Underwood equations [5].
- Assumptions: **(1):** Constant molar flows. **(2):** Constant relative volatility. **(3):** Infinite number of stages.
- For a three-product column it can be shown that the minimum energy diagram for the Petlyuk column with sharp splits maps the V_{min} diagram for the pre-fractionator C_1 operated at the preferred split [3].
- Same diagram applies for non-sharp splits, and the minimum boilup is given by eq. (3)

$$V^{Petl}_{T,min} = \max(V^{D/SB}_{T,min}, V^{DS/B}_{T,min}) = \max(V^{C_{21}}_{T,min}, V^{C_{22}}_{B,min} + (1-q_f)F) \quad (3)$$

where

$$V^{C_{22}}_{B,min} = -B\left[\frac{\alpha_A(1-x_{C,B})}{\alpha_A-\theta_B} + \frac{\alpha_B(x_{C,B})}{\alpha_B-\theta_B}\right] \qquad V^{C_{21}}_{T,min} = D\left[\frac{\alpha_A x_{A,D}}{\alpha_A-\theta_A} + \frac{\alpha_B(1-x_{A,D})}{\alpha_B-\theta_A}\right] \quad (4)$$

where $\theta_A = \theta_A(\mathbf{z_f}, q_f, \alpha)$ and $\theta_B = \theta_B(\mathbf{z_f}, q_f, \alpha)$ are the Underwood roots carried over from C_1 to C_{21} and C_{22} respectively.

- Three cases of operation [3]:
  - **Case 1:** C_{22} is limiting: Separation B/C is the most difficult separation (peak C_{22} is above peak C_{21}).
  - **Case 3:** C_{21} is limiting: Separation A/B is the most difficult separation, as illustrated in Figure 3(a).
  - **Case 2:** Balanced main column: Required vapor load are equal.
- **Important:**
  - **Case 1** with $x_{C,B}$ constant: Minimum boilup proportional to B.
  - **Case 3** with $x_{A,D}$ constant: Minimum boilup proportional to D

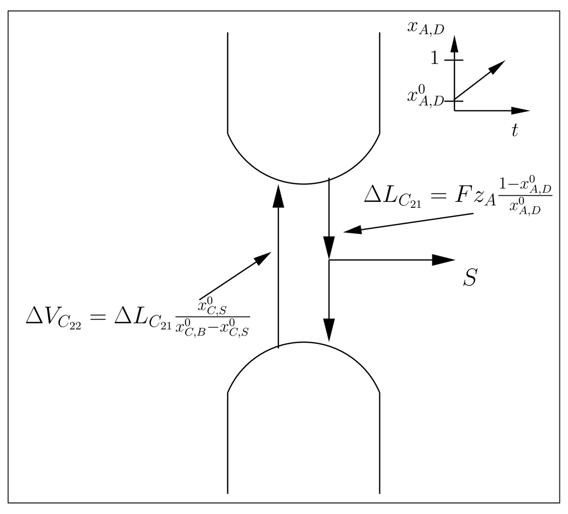
4 Energy savings by over-fractionation

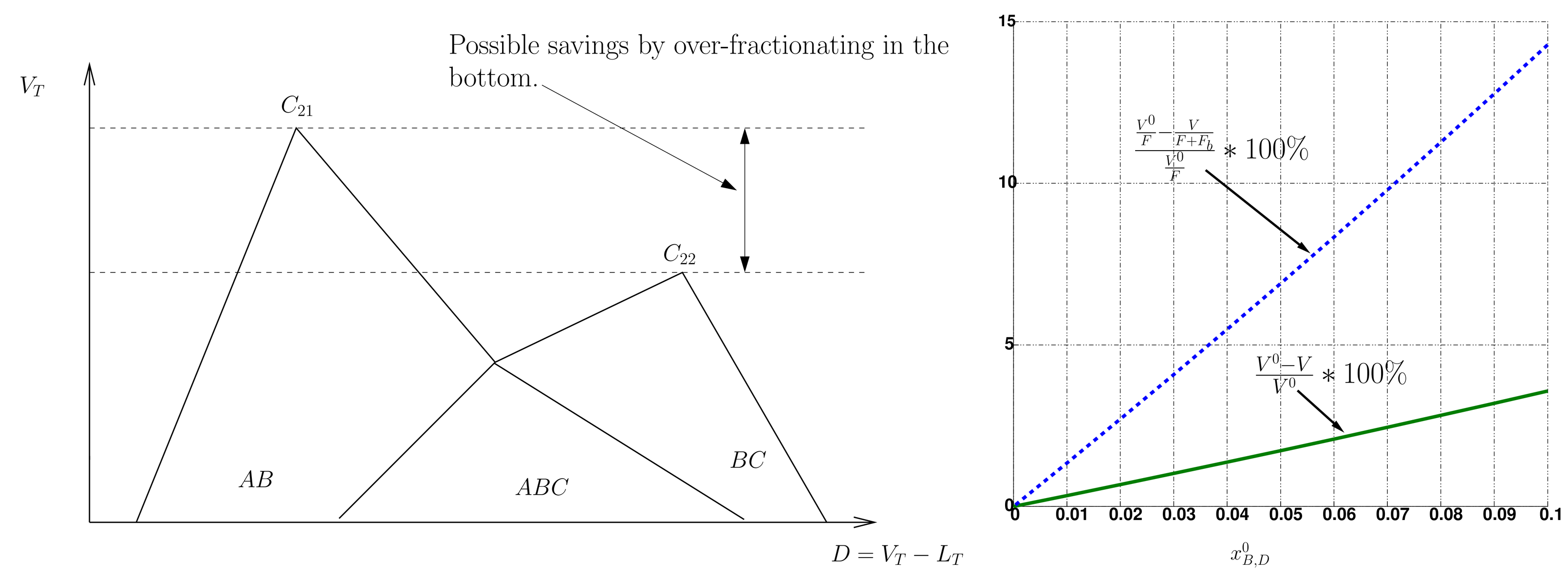
- Based on the material balance of the column, explicit expressions for B and D are derived [1].
- **Case 1 (Case3) :** Energy savings ($E_S = \frac{V_0 - V}{V_0}$) when increasing the purity from $x^0_{A,D}$ ($x^0_{C,B}$) to $x_{A,D}$ ($x_{C,D}$)

$$\textbf{Case 1:}\ E^{C_{22}}_S = \frac{\frac{1}{x^0_{A,D}} - \frac{1}{x_{A,D}}}{\frac{z_C}{z_A}\frac{1}{x^0_{C,S}} + \frac{1}{x^0_{A,D}} - \frac{1}{z_A}} \qquad \textbf{Case 3:}\ E^{C_{21}}_S = \frac{\frac{1}{x^0_{C,B}} - \frac{1}{x_{C,B}}}{\frac{z_A}{z_C}\frac{1}{x^0_{A,S}} + \frac{1}{x^0_{C,B}} - \frac{1}{z_C}} \quad (5)$$

- Approximate savings without bypass:
  - **Case 1:** $E_S \approx x^0_{C,S} x^0_{B,D}$ **Case 2:** $E_S \approx x^0_{C,S} x^0_{B,B}$

- **Physical explanation (Case 1):**
Energy savings is possible since **(1)** by over-fractionating in the top component B is moved from the distillate to the side-stream, see Figure 2 for an illustration. **(2)** Without violating the constraint in the side-stream, component C may now be moved from the bottom stream to the side-stream. **(3)** Since the boilup is proportional to the amount of bottom product eq.(4), the energy input is reduced.
- **Physical explanation (Case 3):**
Same as Case 1, but now with over-fractionating in the bottom.





(a) V_{min} diagram for Case 3

(b) Energy saving when increasing purity from $x^0_{A,D}$ to $x_{A,D}$ for z_f = (0.5 0.3 0.2), α = (9 3 1)^T, q_f = 1, $x^0_{B,B}$ = 0.03 and $x^0_{C,S}$ = 0.1 with (dashed) and without (solid) bypass.

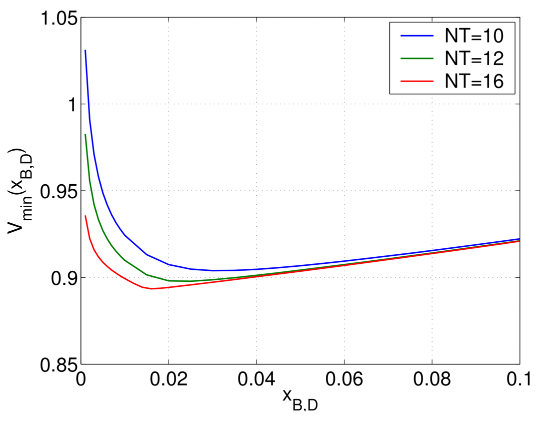
Figure 3: V_{min} and energy savings for for Case 3.

5 Additional savings using bypass

- Over-fractionating one of the products makes it possible to bypass some of the feed to the product to fulfill the composition constraint, reducing the energy input further, see Figure 1(b).
- Amount of bypass when over-fractionating to pure products ($x_{A,D} = 1$ or $X_{C,B} = 1$):
  - **Case 1:** $F^{C_{22}}_B = D_{|(x_{B,D}=0)} \frac{x^0_{B,D}}{1 - x^0_{B,D} - z_A}$ **Case 3:** $F^{C_{21}}_B = B_{|(x_{B,B}=0)} \frac{x^0_{B,B}}{1 - x^0_{B,B} - z_C}$
- **But**: Introduces a component (C or A) into the product (D or B) that normally is not present
- Figure 3(b) illustrate the potential savings, for a specific case. Up to **4%** energy savings without bypass and **13%** energy savings with bypass.

6 Confirmation of results for finite number of stages

- Simulations carried out to verify the results. Assumptions model:
  - Constant relative volatility. Finite, equal number of stages in each section. Constant molar flows.
  - $z_F = [0.5\ 0.3\ 0.2]$, $\alpha = [9\ 3\ 1]$, $q_f = 1$, $x^0_{B,S} = 0.9$, $x^0_{C,B} = 0.97$
- Simulation confirms that one may save energy when the column has sufficient number of stages. Results also confirmed using HYSYS®.



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Conclusions

- Optimal from a energy point of view to over-fractionate one of the streams in the Petlyuk distillation column.
- Additional savings possible if bypassing some of the feed to the over-fractionated product.
- Explicit expressions for the achievable energy savings derived based on the Underwood equations assuming infinite number of stages.
- Energy savings possible due to different vapor load demands in the two main column sections.
- Results have been confirmed for finite number of stages.

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