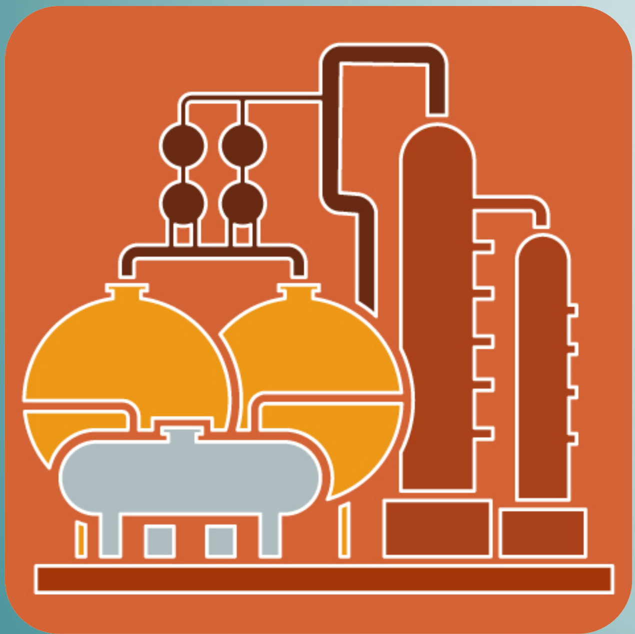
Chemical Process Design / Diseño de Procesos Químicos

Topic 7. Process synthesis: distillation sequences



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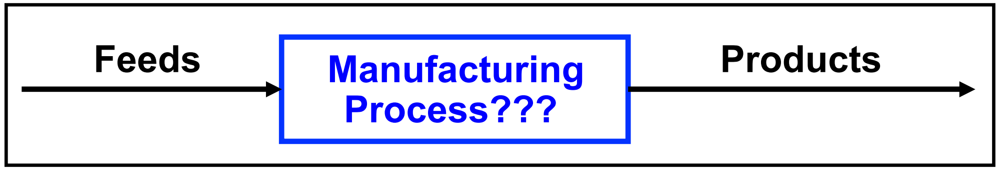
1.- Process synthesis



How to derive "optimal" configuration of a process or subsystem
→ Topology ≡ Which Units?, How to interconnect?

Main Approaches to Process Synthesis

Heuristics

Rules of thumb, quickly understood, easily used, practical method yielding approximate results (e.g. remove thermally unstable, corrosive or chemically reactive components early in the distillation sequence).

Physical insights (perceptions, ideas):

Narrow down the alternative designs very considerably (e.g. given a minimum temperature approach, the exact amount for minimum utility consumption can be predicted prior to developing the network structure).

Systematic search:

Total enumeration, tree search, superstructures (SEN or STN superstructure of distillation) or problem abstraction

Optimization:

Explicit procedure for deriving the configuration (e.g. transshipment model (MILP) for stream matching).

2.- Synthesis of distillation sequences

- **Given multicomponent feed separate into N high priority products. Assume: Ideal behavior, Splits near 100% recovery.**
  - 3 components: A, B, C → 2 sequences (direct, indirect) (*)
  - 4 components: A, B, C, D → 5 sequences (*)
  - Increase n° components → Increase nº sequences →

→ N° flowsheets = [2 (N – 1)]! / [(N – 1)! (N)!]

- **Other alternatives:**
  - **Petlyuk column** (1 condenser,1 reboiler, lowest level of energy, most energy efficient) **(*)**
  - **Side Stream Columns** (1 condenser, 2 reboilers) **(*)**
  - **Extractive Distillation (*)**

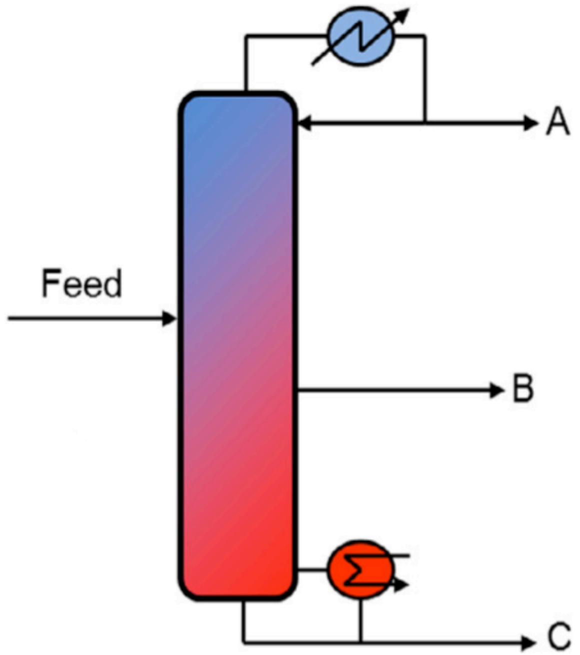
- **If several technologies exist for separation (adsorption, extraction, other distillations), there are more alternatives.**

Distillation → 14 flowsheets

N = 5 → **→ N° flowsheets = {[2 (N – 1)]! / [(N – 1)! (N)!]} S^{N-1}**

3 technologies (S) → 1134 flowsheets.

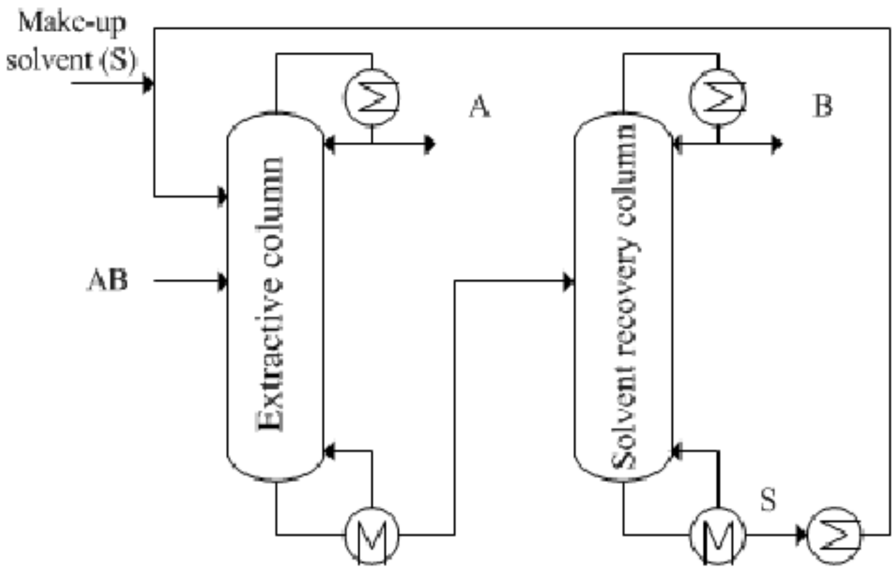
Side Stream Column



Long, N.V.D.; Minh, L.Q.; Nhien, L.C. & Lee, M. (2015): *«A novel self-heat recuperative dividing wall column to maximize energy efficiency and column throughput in retrofitting and debottlenecking of a side stream column»*. Applied Energy, 159. Pp. 28-38.

- **Offer a cost-effective way of producing three products from a single column:**
  - Limited purity of the intermediate component product stream is a problem.
  - A high-purity side stream might require large reflux ratios and a large number of stages, as well as larger associated energy requirements (Long *(et al.),* 2015).

Extractive Distillation

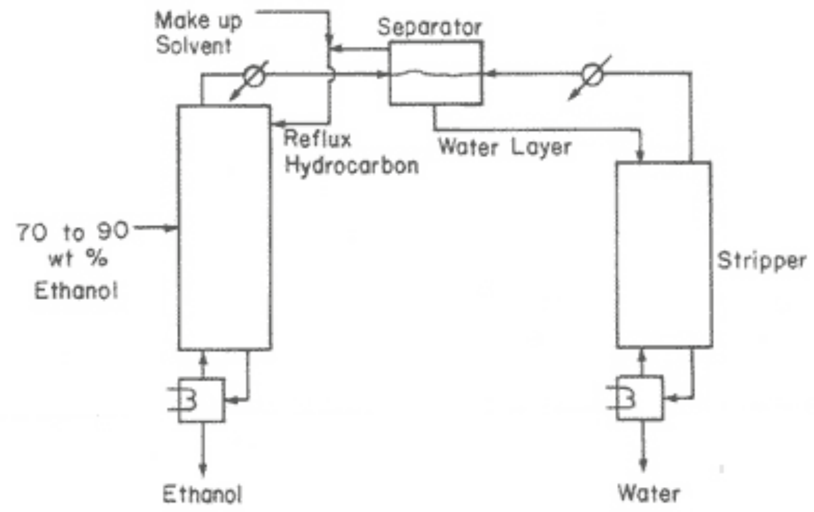


Nhien *(et al.)* (2014): *«Application of mechanical vapor recompression to acetone-methanol separation»*. International Journal of Chemical Engineering and Applications, 5, 3 (2015-2018).

- **Extractive distillation (ED) is used in the industry for the separation of mixtures with similar relative volatilities and azeotropes, for example the separation of:**
  - Hydrocarbons with close boiling points.
  - The recovery of aromas or fragrances.
  - Aqueous alcohol solutions.
  - Ether and alcohol mixtures.
  - Methylal and methanol mixtures.

Anokhina, E. & Timoshenko, A. (2015): «Criterion of the energy effectiveness of extractive distillation in the partially thermally coupled columns». Chemical Engineering Research and Design, 99. Pp. 165-175.

Azeotropic Distillation



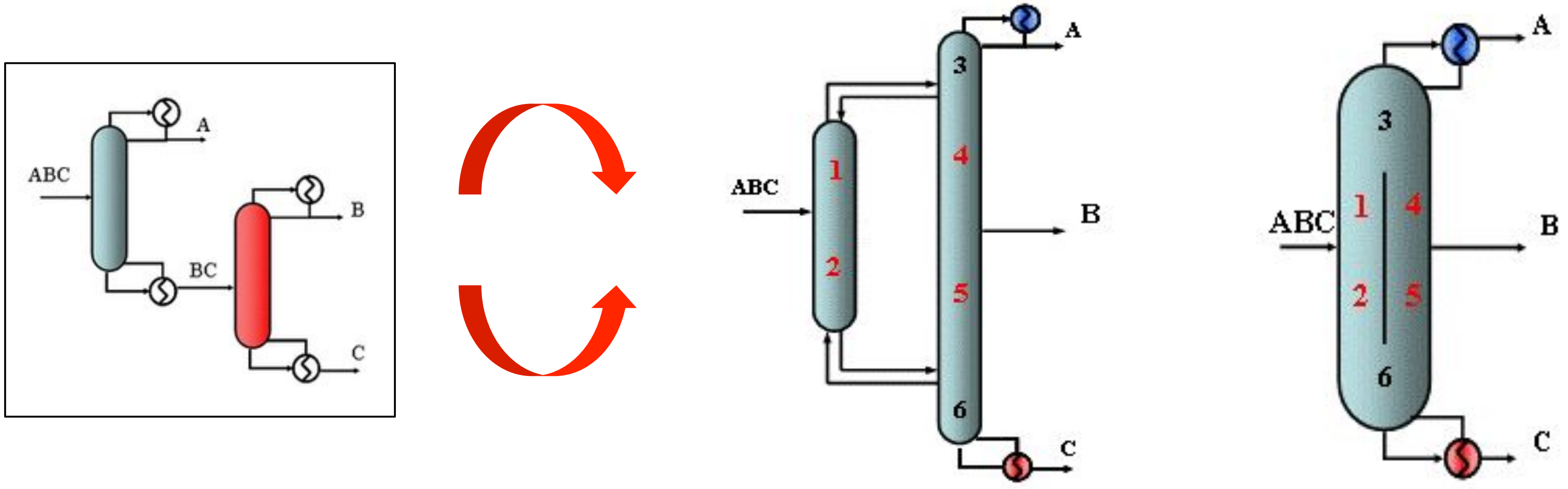
http://www.hyper-tvt.ethz.ch/distillation-azeotropic.php.

The ethanol-water mixture can be broken using Pentane as the entrainer. This produces the formation of a heterogeneous ternary azeotrope.

- **Azeotropic distillation is a method used to modify the equilibrium of complex mixtures in order to separate their components.**
- **Usually two different kinds of azeotropic distillation are distinguished:**
  - Binary systems which form a heterogeneous azeotrope.
  - Binary systems which form a homogeneous azeotrope. In this case an entrainer or solvent is added in order to form an azeotrope with one or both of the components. The system then becomes ternary.

2.- Synthesis of distillation sequences

Petlyuk column   Dividing wall column



http://iq.ua.es/~jose/DestilacionAcoplamientoTermico/Separacion_tres_componentes.html.

Petlyuk column

The Petlyuk arrangement consists of a prefractionator coupled to the main column, using two recycle streams.

Dividing wall columns (DWCs)

Split the middle section of a single vessel into two sections by inserting a vertical wall. DWCs represent a typical example of process intensifi-cation since they can bring significant reductions in both capital investment and energy costs of up to 30%.

2.- Synthesis of distillation sequences

General Heuristics for Distillation

- **Remove the most corrosive components first.**
- **Remove products as distillate.**

Heuristics for sequencing Distillation trains (priority order)

- **H1: forbidden splits:**
  a) Don't use distillation if $\alpha_{lk/hk} < 1.05$
  b) If $(\alpha - 1)_{extractive\ distillation} / (\alpha - 1)_{regular\ distillation} < 5$ → Use ordinary distillation.
  c) If $(\alpha - 1)_{l\text{-}l\ extraction} / (\alpha - 1)_{regular\ distillation} < 12$ → Use ordinary distillation.
  d) Consider absorption if refrigeration is needed.
- **H2: use the next separation of components that have the highest $\alpha_{lk/hk}$ → easiest first, most difficult last**
- **H3: remove the most abundant component first**
- **H4: if α´s or concentrations are not very different → Direct sequence**
- **H5: remove mass separation agent in next column**
- **H6: favor sequences that do not "Break" desired products**

Apply rules in Decreasing Order of Priority.

3.- Examples of distillation synthesis (Practical Chapter)

a) Demonstration of H4 rule: if α´s or concentrations are not very different → Direct sequence.

- Assume A, B, C equimolar mixture, feed liquid and similar $\alpha_{L/K}$

b) Application of Heuristics. Problem 18.10 (Biegler, Grossmann and Westerberg, 1997): using the heuristics, propose separation sequences for the following problem.

- Separate a mixture of six components *ABCDEF* into products *A, BDE, C*, and *F*.
- Use either of two methods in developing your sequences
  - Distillation, method I. Component volatility order *ABCDEF.*
  - Extractive distillation, method II. Component volatility order A*CBDEF.*
- Component amount (kmols/hr). *A:* 4.55, *B:* 45.5, *C*: 155.0, *D:* 48.2, *E:* 36.8 and *F: 18.2.*
- Relative volatilities of the key species:
  Method m I: *A/B*: 2.45, *BIC:* 1.55, *CID:* 1.03, *E/F: 2.50.*
  Method m II: *CIB:* 1.17, *CID: 1.70.*

c) Analysis of the Petlyuk Column (Energy Integration).

4.- Further Reading and References

- Biegler, L.; Grossmann, I. & Westerberg, A. (1997): *«Systematic methods of chemical process design»*. Prentice Hall.

- Doherty, M. & Malone, M. (2003): *«Conceptual design of distillation systems»*. 1st Ed. Tata McGraw-Hill Education.

- Douglas, J.M. (1988): *«Conceptual design of chemical processes»*. McGraw-Hill.

- Peter, M.; Timmerhaus, K. & West, R. (2005): *«Plant design and economics for chemical engineers»*. 5ª Ed. McGraw-Hill.

- Seader, J.D. & Westerberg, A.W. (1977): *«A combined heuristic and evolutionary strategy for synthesis of simple separation sequences»*. AIChE Journal, 23. P. 951.

RELEVANT TO LEARNING

- To distinguish between the different Approaches to derive “optimal” configuration of a process or subsystem.
- Superstructures of distillation.
- Application of Heuristics.