Efficient use of energy in distillation sequences

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[>>COnCEPT]
Computer Optimization of Chemical Engineering Processes and Technologies

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Introduction

In a growing energy consumption world, energy efficiency has become mandatory. Furthermore, the climate emergency has highlighted the necessity to replace fossil fuels with renewable energy sources. Nevertheless, the direct utilization of many of these energy sources requires, at least partially, the electrification of chemical processes.

It is not uncommon the claim that distillation must be substituted by other, more efficient separation technologies [1]. The main reason is based on the fact that distillation vaporizes a mixture in the reboiler and then liquifies a vapor stream in the condenser. However, Agrawal and Tumbalam Gooty [2], have shown that distillation can be much more efficient than what intuition seems to suggest.

Different alternatives have been proposed to increase the energy efficiency in distillation. If we are dealing with a single separation we can consider alternatives like multi-effect distillation, and intermediate heat exchangers either in the rectifying or in the stripping section [3], pre-fractionations, internally heat integrated distillation columns (HIDiC) and heat pump assisted distillation (Vapor recompression, Mechanical or Thermal Vapor recompression -VRC- or bottom flashing arrangements) [4]. In multicomponent distillation, the number of alternatives increases because we can integrate the alternatives for heat integration between different columns with those of a single column and the alternatives for column sequencing inherent in multi-component distillation.

In this work, we show that the systematic and simultaneous implementation of some heat integration alternatives like direct reboiler condenser heat exchange, implementation of vapor (re)compression cycles, leverage of heat in high-pressure steam utilities at lower pressure/temperatures, multiple effect distillation, etc. can eventually produce considerably reductions in energy and total annualized cost and at the same time, contribute to the electrification of chemical plants. While none of these alternatives is new, they are rarely simultaneously implemented in a distillation sequence, however, we show that there is great potential in the synergic effects of implementing simultaneously some of them.

Algorithm

We propose an approach that sequentially tries to improve efficiency in a non integrated selected configuration:

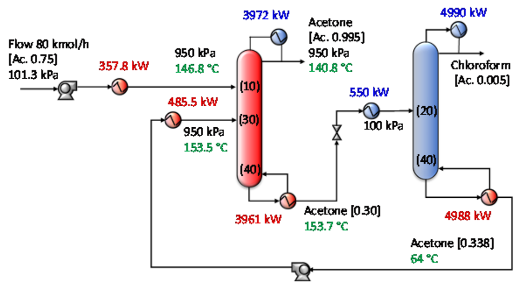
1. Select the best sequence of not heat integrated distillation columns. If we are considering a zeotropic mixture we can use any of the approaches based on mathematical programming to get the optimal configuration [5]
2. Consider the possibility of heat integration with the rest of the process.
3. For each column in the sequence, we determine the lower and upper pressure limits. The pressure determines which are the highest and lowest temperatures in each column.
   - The change of temperature (pressure) allows the development of strategies for direct heat integration between condensers and reboilers of different columns [6]
   - The limits in pressure and temperature allow for determining the possibility of **multi-effect distillation** which has a special interest in difficult separations.
4. If the sequence requires heat at very different temperatures, it is possible to recover energy from the exhausted high-temperature utility to use them at lower temperatures.
5. The use of intermediate heat exchangers (reboilers in the stripping section and condensers in the rectifying section) can, in some cases, reduce the condenser/reboiler heat duties, which can be substituted with cheaper utilities. Besides, these new heat exchangers can eventually be used in the heat integration strategy. [3]
6. Heat pump-assisted configurations [4] (vapor compression, mechanical or thermal vapor recompression, absorption heat pumps, bottom flashing, etc.) can be implemented not only between the condenser and reboiler of a given column but between different heat exchangers (source and sinks of heat).

Example

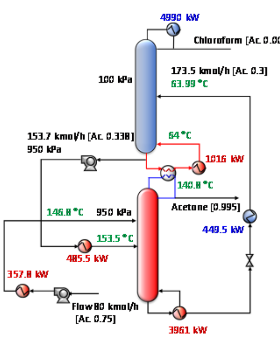
To illustrate some of the characteristics of the proposed algorithm we consider the separation of a mixture of Acetone and Chloroform using pressure swing distillation (PSD). The objective is to obtain each product with a purity of at least 0.995 mol fraction. The following Table shows the data for the example.

Components	Composition (mol fraction)		
Acetone	0.75	Feed Flow	80 kmol/h (5872 kg/h)
Chloroform	0.25	Pressure	101.3 kPa
Cold Utilities	Cost ($/kW y)	**Hot Utilities**	Cost ($/kW y)
water (20-15 ºC)	11.4	LP Steam (~2 bar 120 ºC)	277.5
		HP Steam (~10 bar 180 ºC)	292.18

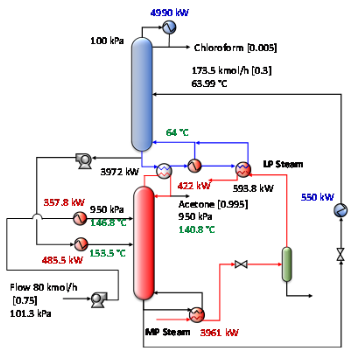
Thermodynamics NRTL (default Aspen-HYSYS parameters)
Electricity 0.067 $/kWh
interest = 10% in 10 years
Cost estimation based on correlations by (Turton et al., 2013)



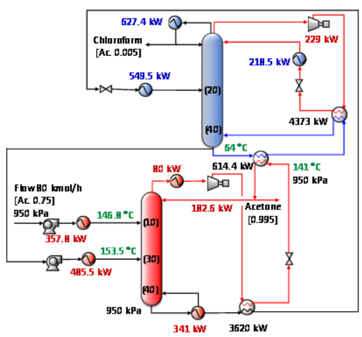
Base case. Total Module Cost (TMC) k$ 1,710. Total utilities cost (TUC) 2,907.1 k$/y; Cost of Manufacturing (COM) 3900.3 k$/y. Total annualized Cost (TAC) **4198.7 k$/y**



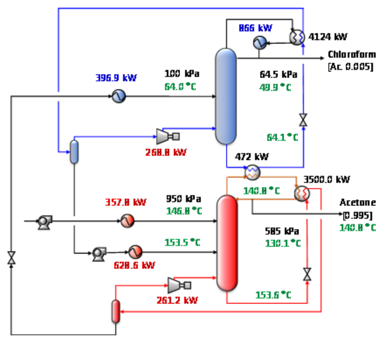
Direct HP-LP columns heat integration.
TUC: 1585.7 k$/y COM: 2281.7 k$/y.
TAC = 2579.8 k$/y



Direct HP-LP columns heat integration + exhaust MP Steam recovery
TUC: 1433.7 k$/y COM: 2094.7 k$/y.
TAC = 2392.8 k$/y



Two heat integrated Vapor Recompression Cycles
TUC: 646 k$/y COM: 1521.8 k$/y.
TAC = 2176.3 k$/y



Direct HP-LP columns heat integration + two bottom flashing cycles
TUC: 637 k$/y COM: 1510.7 k$/y.
TAC = 2165 k$/y

we have shown that it is possible to increase the efficiency of distillation columns by sequentially and iteratively adding different alternatives of heat integration. While no one of those alternatives is new, the simultaneous consideration of all/some of them can produce an impressive increase in energy efficiency that is reflected in a considerable reduction in total costs.

We have illustrated the procedure with the separation of a mixture of acetone and chloroform using pressure swing distillation. The systematic consideration of different available alternatives allows for reducing the energy cost by an impressive 78% when compared with a non-heat integrated based case or 59.8% compared with a base case using only direct heat integration. In terms of TAC, reductions are around 48% and 16.1% respectively.

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References

1. Engineering National Academies of Sciences and Medicine. A research agenda for transforming separation science. Washington, DC: The National Academies Press; 2019
2. Agrawal, R., Tumbalam Gooty, R., 2020. Misconceptions about efficiency and maturity of distillation. AIChE J. 66, 2–4.
3. Bandyopadhyay, S., Malik, R.K., Shenoy, U. V., 1998. Temperature-enthalpy curve for energy targeting of distillation columns. Comput. Chem. Eng. 22, 1733–1744.
4. Kiss, A.A., Flores Landaeta, S.J., Infante Ferreira, C.A., 2012. Towards energy efficient distillation technologies – Making the right choice. Energy 47, 531–542.
5. Nallasivam, U., Shah, V.H., Shenvi, A.A., Huff, J., Tawarmalani, M., Agrawal, R., 2016. Global optimization of multicomponent distillation configurations: 2. Enumeration based global minimization algorithm. AIChE J. 62, 2071–2086.
6. Caballero, J.A., Grossmann, I.E., 2006. Structural Considerations and Modeling in the Synthesis of Heat-Integrated−Thermally Coupled Distillation Sequences. Ind. Eng. Chem. Res. 45, 8454–8474.

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