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Optimization of Conventional and Energy-integrated Distillation Configurations at Different Feed Conditions

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The steady-state design and rigorous simulation of conventional distillation configurations and several energy-integrated configurations has been studied for ternary mixture separation. The studied configurations are optimized rigorously based on total annual cost as the economic objective function. The energy-integrated distillation configurations are compared with conventional configurations to find the maximum achievable total annual cost savings. Changing feed conditions is considered as one of the optimization variables by investigating different states of feed conditions; feed at 15.5 °C temperature, liquid at bubble point and vapor at dew point. The investigated configurations are conventional direct and indirect separation sequence, heat-integrated direct sequences, Petlyuk column, heat-integrated sloppy sequence, and double heat-integrated sloppy sequence. Optimization results indicate that saving in energy and total annual cost of the configurations is affected by the states of the feed conditions.

1. Introduction

Distillation units are the most widely used technique for the separation of fluid mixtures in chemical and petrochemical industry. It is known that distillation is used for the separation of about 95% of all fluid separations in the chemical industry, and that around 3% of the total energy consumption in the world is used in distillation units (Hewitt et al 1999). The main disadvantage of the distillation is its high-energy requirement. As a result, new distillation sequences are emerging in order to reduce or improve the use of energy so that, there are several techniques which used to overcome this problem like integration of the distillation column with the overall processes which can give significant energy saving, e.g. Smith and Linnhoff (1988), Mizsey and Fonyo (1990), but these kinds of improvements can be limited. There are different configurations or distillation schemes that can be applied to get more energy saving, like integration of distillation columns with forward or backward heat integration, side-stripper, side-rectifier, fully thermally coupled distillation column (Petlyuk column) or dividing-wall column, heat-integrated of sloppy sequence, and double heat integration sequence. Energy-integrated distillation schemes give a great promise of energy savings up to about 70%. In addition to saving energy, which are accompanied by reduced environmental impact and site utility costs; there is also a possibility for reduction in capital costs.

Theoretical studies, e.g. Petlyuk et al. (1965), Stupin and Lockhart (1972), Fonyo et al. (1974), Stichlmair and Stemmer (1989), Annakou and Mizsey (1996), Dunnebier and Pantelides (1999), Emtir et al. (2001), Kolbe and Wenzel (2004) have shown that the column coupling configurations are capable of achieving typically 28-33 % of energy savings compared with the best conventional scheme. In addition, the coupling configuration can also be achieved with the so-called dividing-wall column (Kaibel 1987). By this arrangement, reduction in capital cost can be expected through the elimination of the prefractionator column shell (but not the column internals). Emtir et al. (2003) compared five different energy integrated schemes, among them the forward and backward integrated prefractionator arrangement, with a non-integrated direct split sequence. The study compared the total annual costs (TAC) and the controllability of the different schemes. In terms of TAC they found that the backward integrated direct split configuration has the maximum savings of 37%. The integrated prefractionator arrangements have similar savings of 34% for the forward-integrated case and 33% for the backward-integrated case.

2. Aim of the study

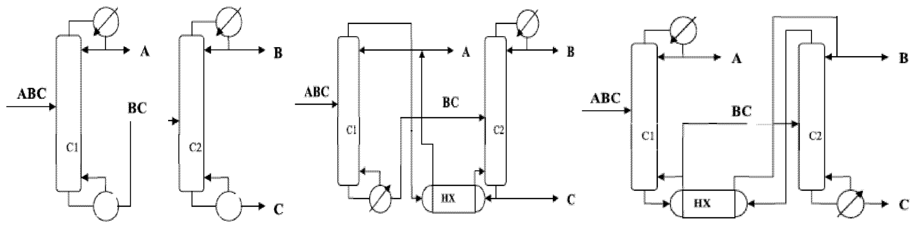
The aim of this study is to investigate different energy-integrated distillation configurations and compare them to each other and to the best conventional distillation configuration based on energy consumption and total annual cost evaluation, this comparative design includes the effect of feed condition; liquid state, saturated liquid, and saturated vapour on the saving potential of the studied configurations. For the final selection both the economic performance and the energy saving should be taken into account. Therefore, the schemes are optimized over the objective function of minimum total annual cost (TAC_{min}).

3. Case study

This study is devoted towards separation of benzene/toluene/m-xylene (BTX) ternary mixture by continuous distillation at high product purity of 99.9 mol % which is market demand. The feed composition to be separated consists of (25/50/25) mixture at atmospheric pressure and total flow rate of 100 kgmol/hr. Different feed conditions are investigated; feed at 15.5 °C temperature, saturated liquid and saturated vapor. HYSYS. simulation is used for rigorous modelling in all studied systems with the following assumptions: UNIQUAC thermodynamic model is used, pressure drop across distillation columns is taken 5 Kpa, pumping is not considered in cost calculations, maximum internal flows are 75 to 80% of the flooding, and exchange minimum approach temperature (EMAT)= 10°C. In this study the total cost for each configuration is assumed to be the sum of utility costs (steam and cooling water) and equipment costs (purchase and installation). Detailed utility cost data are extracted from Emtir et al. (2001).

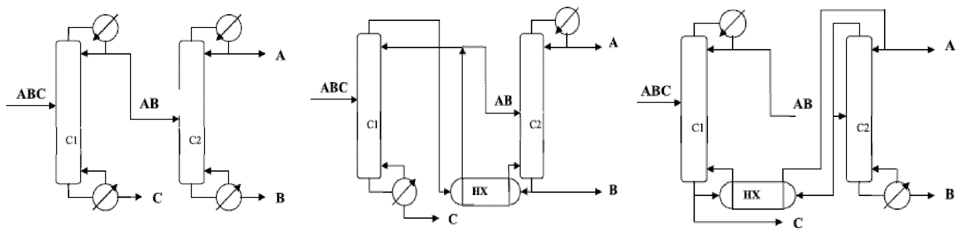
4. Studied configurations

Throughout this work A, B, and C denote the light, intermediate, and heavy components, respectively. The impurities are symmetrically distributed in the middle product stream. The studied distillation configuration are showing below: direct sequence without heat integration (D), direct sequence with forward heat integration (DQF), direct sequence with backward heat integration (DQB), indirect sequence without heat integration (I), indirect sequence with forward heat integration (IQF), indirect sequence with backward heat integration (IQB), sloppy sequence (S) known as prefractionator arrangement, sloppy with forward heat integration (SQF), sloppy with backward heat integration (SQB), Petlyuk column (SP), and sloppy with double heat integration (SQD); have been investigated.



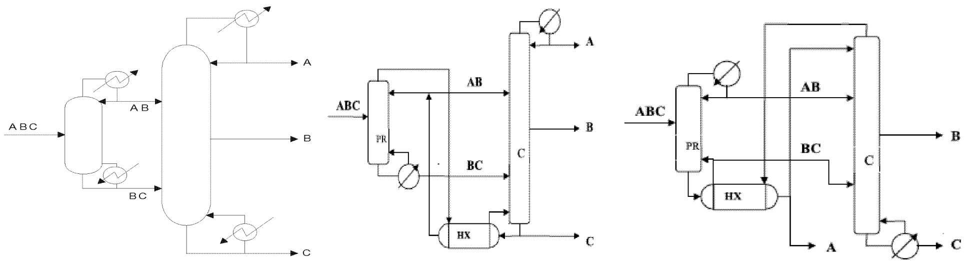
(D) (DQF) (DQB)

Figure 1: direct sequence with possible heat integration



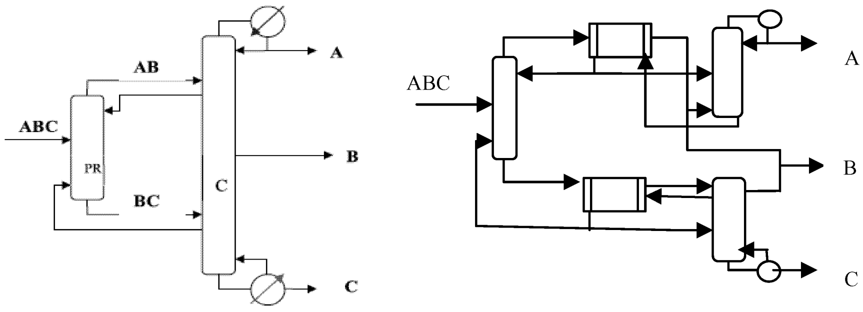
(I) (IQF) (IQB)

Figure 2: Indirect sequences with possible heat integration



(S) (SQF) (SQB)

Figure 3: Sloppy sequences with possible heat integration



(SP) (SQD)

Figure 4: Petlyuk and double heat integration sequences.

The studied configurations are simulated rigorously by HYSYS and the results of simulation are exported to Microsoft Excel where the final cost calculations for optimization are executed. Moreover, detailed column and heat exchanger costs are calculated using the default column and heat exchanger sizing from rigorous simulation. The sizing of distillation columns and heat transfer equipments requires the determination of flow rates, temperatures, pressures, and heat duties from the flow sheet of mass and energy balance, and these quantities can then be used to determine the capacities needed for the cost correlation. In addition, the concept of material pressure factor (MPF) is used to evaluate particular instances of equipment beyond a basic configuration. This concept is an empirical factor developed by Biegler et al (1997) as part of the costing process. For each column system, the pressure, number of trays and feed location are considered as the optimization variables; they are manipulated until the optimal design is found for minimum total annual cost. Optimization variables can be more in case of additional feeds, draws or recycle streams are present. In every run, design parameters (optimization variables) are changed, specifications and optimality are checked. The process simulations are stopped when the global optimal system design is achieved.

5. Results and discussion

Considering the feed entering the studied distillation systems as liquid phase, the entire studied configurations are evaluated for energy consumption and TAC saving as compared to the base case (D). The results are shown in Figure 5 and summarized as follows:

- Direct sequence with backward heat integration (DQB) shows maximum saving values of 45 % in energy in addition to 26 % of TAC saving
- Sloppy with backward heat integration gives high energy saving 44 % and 21 % in TAC.
- Double heat integration (SQD) has slight advantages in energy and TAC savings over Petlyuk column due to its lower operating cost.
- In the liquid state Petlyuk column gives low energy and TAC saving compared to other distillation schemes; 16 %, 11 % respectively.
- Indirect sequence with backward heat integration (IQB) indicates inferior savings in both of energy and TAC which is attributed to the wide gap in temperatures between heat source and heat sink, and use of high pressure steam in distillation system.

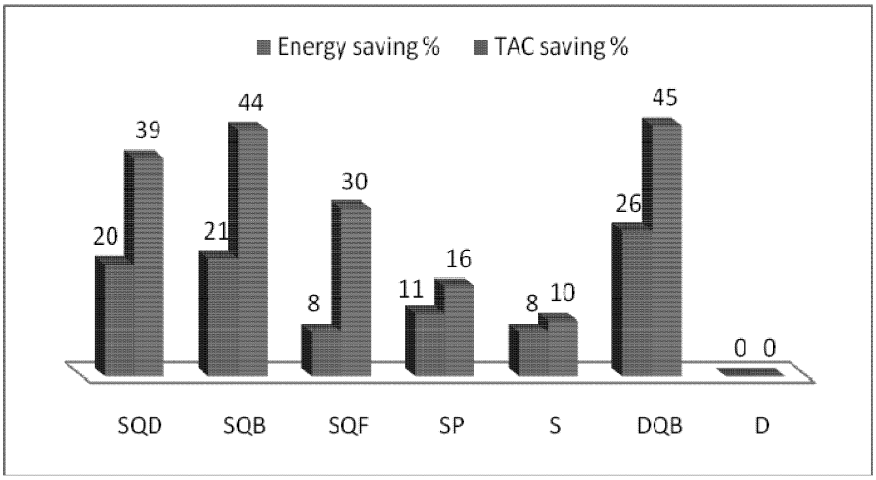


Figure 5: Energy and TAC saving compared to base case (D) at liquid state

The effect of changing feed conditions is indicating important factor on total energy savings of distillation configurations, Table 1 shows the comparative results of D, DQB, SP, and SQD distillation configurations.

Table 1: Comparative result at different feed conditions

Sequence	Liquid state				Saturated liquid				Saturated vapor			
	D	DQB	SP	SQD	D	SQD	SP	SQD	D	DQB	SP	SQD
Heating load (MW)	2.12	1.17	1.78	1.29	1.87	1.18	1.43	1.00	1.68	1.2	1.3	1
TCC($/yr*$10^5$)	0. 79	0. 83	0.96	0.96	0.79	0.79	0.85	0.86	0.92	0.78	1.09	1.04
TOC ($/yr*$10^5$)	5.41	3.78	4.53	3.99	4.83	3.69	3.68	3.84	4.48	3.89	3.49	3.97
TAC ($/yr*$10^5$)	6.19	4.61	5.49	4.95	5.62	4.48	4.53	4.7	5.4	4.67	4.58	5.01
Energy %	0	44.8	16	39.2	0	36.9	23.5	46.5	0	28.6	22.6	40.5
TAC %	0	25.5	11.3	20	0	20.3	19.4	16.4	0	13.5	15.2	7.2

6. Conclusions

The state of feed conditions plays important role on the optimization ranking of distillation configurations, DQB configuration is showing higher energy saving for feed entering at liquid state, this due to the recycling of the energy added to change the phase of the feed inside the configuration system, where as in case of Petlyuk column its more effecient to supply the feed at saturated liquid phase because there is no significant energy recycling. SQD configuration is indicating the highest energy saving, but due to increasing the preussures of the integrated columns which is leading to utilization of high pressure steam causing its TAC saving to drop down.

7. References

Annakou, O. and P. Mizsey, 1996, Ind. Engng. Chem., 35, 1877.

Dimian, A.C., Eds., 2003, Integrated Design and Simulation of Chemical Processes. Elsevier, Amsterdam.

Dunnebier, G. and C.C. Pantelides, 1999, Ind. Eng. Chem. Res., 38, 162.

Emtir, M., E. Rev, and Z. Fonyo, 2001,. Applied Therm. Eng., 21, 1299-1317.

Emtir, M., Mizsey, P., E. Rev, and Z. Fonyo, 2003,.Chem. Biochem. Eng. Q., 17(1), 31-42.

Fonyo, Z., J. Szabo, and P. Foldes, 1974, Acta Chimica Academia, 82, 235.

Hewitt, G., Quarini, J. and Morell, M., 1999, Chem. Eng, 21 Oct.

Kaibel, G., 1987,.Chem. Engng. Technol., 10, 92.

Kolbe, B. and S. Wenzel, 2004, Chemical Engineering and Processing, 43, 339.

Mizsey, P. and Z. Fonyo, 1990, Computers and Chemical Engineering, 14, 1303.

Petlyuk, F. B., V. M. Platonov, and D. M. Slavinskii, 1965, Int. Chm. Engng., 5, 561.

Smith, R. and B. Linnhoff, 1988, Trans. IChemE., 66, 195.

Stichlmair, J. and A. Stemmer, 1989, Chemical Engineering Technology, 12, 163.

Stupin, W. J. and F. J. Lockhart, 1972, Chemical Engineering Progress, 68, 71.

Biegler, L. T., Grossmann, I. E. and Westerberg, A. W., Eds., 1997, Systematic Methods for Chemical Process Design, Prentice-Hall, NJ.