

Comparison of Energy Consumptions and Total Annual Costs Between Heat Integrated and Thermally Linked Distillation Sequences

C. Gildardo Hernández-Gaona and S. Hernández*

Universidad de Guanajuato; Facultad de Química;
Noria Alta s/n; Guanajuato, Gto., 36050 México
E-mail: hernasa@quijote.ugto.mx

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This paper presents a comparative analysis of energy consumption and total annual cost for the separation of ternary mixtures of hydrocarbons for different feed compositions. The separation schemes considered include two conventional distillation sequences, two thermally coupled distillation schemes, and two distillation sequences with heat integration. The results regarding energy consumptions indicate that the distillation sequences with heat integration can reduce the energy demands between 20 and 40 % in contrast to the direct and indirect distillation sequences; furthermore, energy savings achieved in the thermally coupled distillation schemes are up to 30 % with respect to conventional schemes. When the total annual costs are compared, the thermally coupled distillation sequences can achieve savings 10 % higher than the heat integrated distillation sequences; that is because the heat integrated distillation sequences require higher operational pressures than the conventional and thermally coupled distillation sequences. Also, because of the levels of operational pressure used in the heat integrated distillation schemes, they require additional utilities with the corresponding cost increase.

Keywords:

Distillation, energy integration, thermally coupled distillation

Introduction

The total annual cost (TAC) in the case of distillation trains is dominated by the steam vapour supplied to the reboilers and the cooling water used in the condensers. As a result, many researchers are interested in developing distillation schemes which are able to reduce the energy demands in the reboilers. Two approaches can be mentioned. The first one uses energy integration and the second one introduces thermal links between the distillation columns. *Annakou* and *Mizsey*¹ and *Emtir et. al.*² have reported TAC savings around 40 % for the separation of ternary mixtures using heat integrated distillation sequences. Also, for the case of the typical thermally coupled distillation sequences, for example, thermally coupled distillation with side columns and the Petlyuk column, savings in energy consumption of 30 % can be expected as reported by *Triantafyllou* and *Smith*,³ *Hernández* and *Jiménez*,^{4,5} *Rév et. al.*,⁶ and similarly savings in capital can be obtained as reported by *Kaibel*.⁷ Despite the theoretical energy and TAC savings predicted for complex distillation sequences, these have not been used extensively in the industry because of possible control problems. Fortunately, some researchers have reported that energy savings can be achieved without potential control problems.^{8,9}

In this work we compare the energy savings and total annual costs of conventional distillation sequences, heat integrated, and thermally coupled distillation sequences for the separation of ternary mixtures of hydrocarbons.

Cases of study

We have explored the energy consumption and the TAC for six distillation sequences for the separation of two ternary mixtures of hydrocarbons: Mixture I (n-pentane, n-hexane and n-heptane) and Mixture II (n-butane, isopentane and n-pentane) for the three compositions indicated in Table 1. These compositions have been selected because the energy savings for thermally coupled distillation sequences depend strongly on the amount of the intermediate component; as a result, we have selected compositions with low or high content of the intermediate component. The sequences studied were the two conventional distillation sequences shown in Figures 1 and 2, the two heat integrated distillation sequences drawn in Figures 3 and 4 and, finally, the two thermally coupled distillation sequences shown in Figures 5 and 6. The two thermally coupled distillation sequences shown in Figures 5 and 6 have been selected, because they can be obtained directly from the retrofit of the conventional distillation sequences. The design and optimisation of all se-

*Corresponding author

Table 1 – Feed compositions in molar fraction.

Component	Feed F1	Feed F2	Feed F3
A	0.33	0.45	0.3
B	0.33	0.1	0.4
C	0.34	0.45	0.3

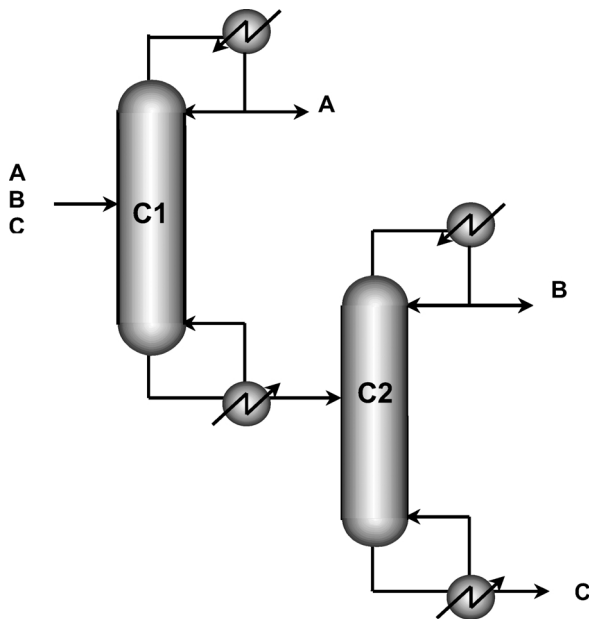


Fig. 1 – Direct distillation sequence (DS)

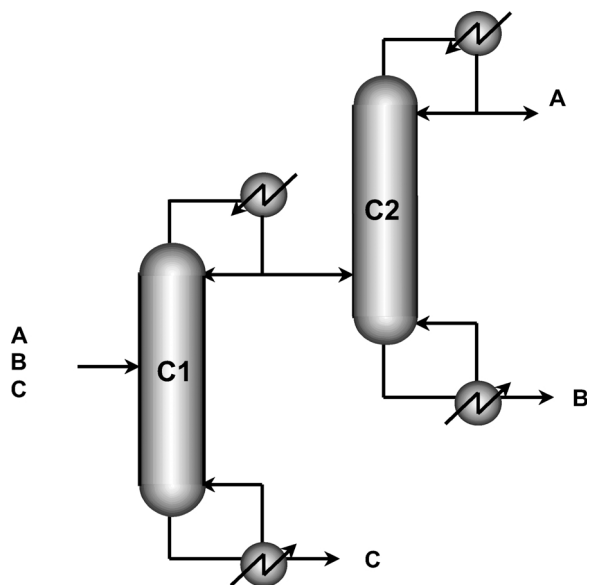


Fig. 2 – Indirect distillation sequence (IS)

quences were obtained through the use of Aspen Plus 11.1.™

The designs of the conventional distillation sequences were obtained through the use of the short

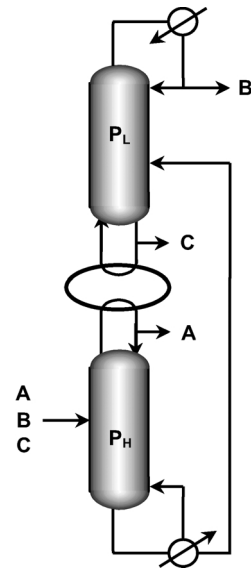


Fig. 3 – Direct heat integrated distillation sequence (DSI)

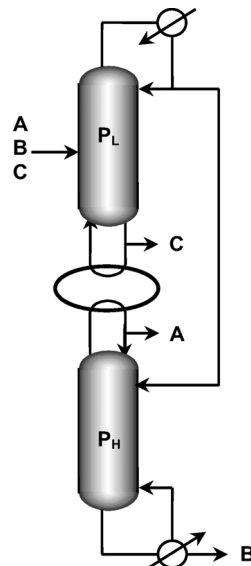


Fig. 4 – Indirect heat integrated distillation sequence (ISI)

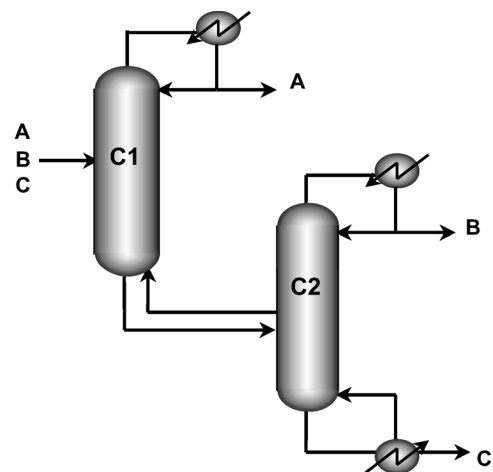


Fig. 5 – Direct thermally coupled distillation sequence (DTCDS)

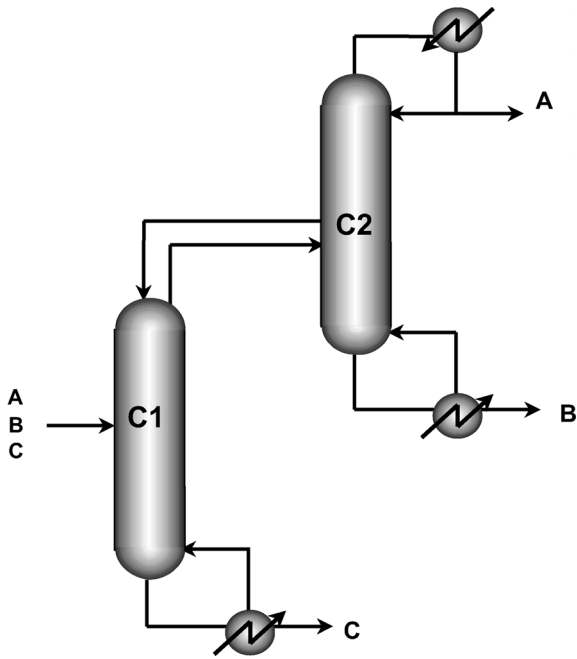


Fig. 6 – Indirect thermally coupled distillation sequence (ITCDS)

cut method of Fenske-Underwood-Gilliland and then optimised by using rigorous steady state simulation with design specification of purities of 0.987, 0.98 and 0.986 for stream products A, B and C, respectively. All distillation sequences studied meet the design specifications indicated above.

The designs of the heat integrated distillation sequences were derived from the conventional distillation sequences. It is important to say that, in the case of the direct distillation sequence with heat integration (Figure 3, DSI), the pressure of the first column must be high enough to boil up the bottoms

of the second column. Also, the pressure in the second column permits the use of cooling water. Similarly, in the indirect distillation sequence with heat integration (ISI) shown in Figure 4, the pressure in the second column must be such that the overhead products can boil up the bottoms of the first column.

The design and optimisation of the thermally coupled distillation sequences, indicated in figures 5 and 6, are clearly more complicated, because of the recycle streams or thermal links. If one considers the direct thermally coupled distillation sequence (DTCDS) of figure 5, the recycle stream of vapour from the second column to the bottom of the first column eliminates the reboiler, because the heating required is supplied by direct mass contact. This recycle stream of vapour should be varied until the minimum energy requirement is detected. The design and optimisation of the indirect thermally coupled distillation (ITCDS) drawn in Figure 6 can be obtained in a similar way, but a liquid recycle stream from the second column to the top of the first column is needed, and the condenser is removed. Again, in order to detect the minimum energy consumption, this recycle stream must be varied.

Results

Energy savings

Tables 2 and 3 show the energy optimisation of the DTCDS for mixture I for feeds F1 and F3, as representative results. We have only considered the heat duty supplied to the reboilers for this compari-

Table 2 – Search for optimal design of DTCDS, Mixture I, Feed F1

Mixture I			
F1			Graph
33	33	34	
F_V			Q_{RT}
kmol h ⁻¹			kW
56.3			876.9
56.8			831.2
57.9			800.5
59.0			790.8
61.3			787.4
61.7			788.1
62.4			789.2
63.6			792.3
68.1			810.7

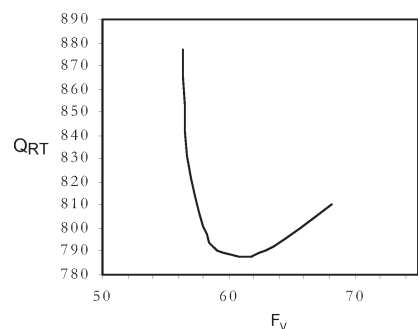
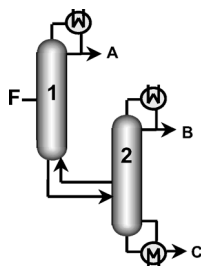


Table 3 – Search for optimal design of DTCDS, Mixture I, Feed F3

F3		Mixture I			Graph
30	40	$\frac{F_V}{\text{kmol h}^{-1}}$	$\frac{Q_{RT}}{\text{kW}}$		
		57.7	847.5		
		58.1	840.2		
		59.0	831.8		
		61.3	825.1		
		63.6	829.4		
		65.8	836.1		
		68.1	846.5		

Table 4 – Search for optimal design of ITCDS, Mixture I, Feed F3

F3		Mixture I				Graph
30	40	$\frac{F_L}{\text{kmol h}^{-1}}$	$\frac{Q_{R1}}{\text{kW}}$	$\frac{Q_{R2}}{\text{kW}}$	$\frac{Q_{RT}}{\text{kW}}$	
		34.1	524.2	294.2	818.3	
		36.3	540.0	227.3	767.3	
		37.5	548.1	216.8	764.9	
		38.6	556.3	209.9	766.2	
		39.7	564.5	204.8	769.3	
		40.9	572.8	201.0	773.9	
		43.1	589.5	195.4	784.9	
		45.4	606.3	191.4	797.7	

son, because the energy required in the reboiler dominates the total energy consumption in distillation columns. The graphs included in the Tables indicate that, in fact, the energy consumption in the DTCDS depends strongly on the recycle stream. For that reason, the vapour recycle stream must be varied until the minimum energy consumption is achieved. Table 4 contains the search for the optimum energy demand of ITCDS; in this case the liquid recycle stream must be changed until the optimum energy demand is obtained. When mixture II was analysed, the optimisations curves were very similar to those contained in Table 5.

The energy savings for the separation of the mixture I are shown in Table 6. As we can see, both heat integrated distillation sequences have savings

around 40 % for all feed compositions. In contrast, the thermally coupled distillation sequences present energy savings between 10 and 30 %. When the mixture II was considered (Table 7), energy savings around 30 and 20 % were obtained for DSI and ISI, respectively. For the thermally coupled distillations sequences, the savings were significantly lower than those obtained in mixture I, except for ITCDS in feed F2 where the saving was around 45 %. This energy saving is obtained because in the case of thermally coupled distillation sequences, big energy savings are achieved, when the amount of the intermediate component is low.

Regarding the energy savings, we can conclude that the heat integrated distillations sequences require less energy consumption than conventional and thermally coupled distillation sequences.

Table 5 – Search for optimal design of DTCDs, Mixture II, Feed F1

Mixture II					
F1			F_V	Q_{RT}	Graph
33	33	34	(kmol/h)	(kW)	
			138.5	1850.8	
			139.4	1830.1	
			140.7	1823.2	
			145.3	1823.5	
			147.6	1824.3	
			149.8	1827.1	
			152.1	1829.7	
			154.4	1835.3	
			156.6	1835.6	

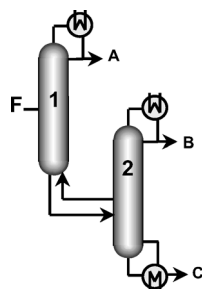


Table 6 – Energy savings for the separation of mixture I

Feed	Energy savings	
	DSI	DTCDs
F1	42.6%	11.7%
F2	44.3%	9.8%
F3	42.3%	14.0%
Feed	ISI	ITCDs
F1	39.5%	20.6%
F2	37.6%	17.0%
F3	43.1%	31.6%

Table 7 – Energy savings for the separation of mixture II

Feed	Energy savings	
	DSI	DTCDs
F1	30.3 %	6.3 %
F2	25.8 %	5.7 %
F3	38.4 %	16.5 %
Feed	ISI	ITCDs
F1	19.0 %	11.9 %
F2	16.2 %	44.7 %
F3	22.0 %	18.1 %

TAC savings

For the case of mixture I, the TAC results indicate that, in general, thermally coupled distillations sequences present savings between 15 and 25 % with respect to the conventional and heat integrated distillation sequences. Table 8 presents the design variables required to calculate the TAC using standard equations for the separation of the mixture I, feed F1 using the direct distillation sequences. When mixture M2 is considered, the DSI and ITCDS present savings around 25 % and 14 %, respectively, in comparison with conventional distillation sequences. It can be noted, that the TAC savings are lower than the energy savings in the heat integrated distillation sequences, because higher operational pressures are required in order to guarantee feasible heat integration in the columns.

Conclusions

The energy demands and the TAC of conventional distillation sequences, integrated distillation sequences, and thermally coupled distillation sequences for the separation of ternary mixtures of hydrocarbons, have been studied by using rigorous steady state simulations. The results about energy demands indicate that, in general, the distillation sequences with energy integration can have the best energy savings in contrast to, both, conventional and thermally coupled distillation sequences, but these energy savings are achieved at expenses of higher operational pressures and then more expensive forms of energy. When the TAC was studied, the thermally coupled distillation sequences outperformed conventional and integrated distillation se-

Table 8 – Relevant design variables for TAC calculations for the direct distillation sequences, for mixture I, feed F1

Design Variable	DS		DSI		DTCDS	
	C1	C2	C1	C2	C1	C2
T_D , °C	48.6	69.8	121.4	69.8	48.6	69.8
T_B , °C	102.8	110.3	177.2	110.3	102.8	110.3
p_D , kPa	144.8	101.4	888.1	101.4	144.8	101.4
p_B , kPa	179.3	135.8	922.6	135.9	179.3	135.9
D_C , m	0.61	0.73	0.44	0.74	0.64	0.92
H_C , m	18.3	18.3	18.3	18.3	18.3	18.3
R_R , Reflux Ratio	2.59	3.18	2.59	3.18	2.96	1.98
N_R , Rectifying stages	17.0	18.0	17.0	18.0	17.0	18.0
Q_R , kW	410.6	481.2	410.6	100.9	N/A	787.4
Q_C , kW	380.3	503.3	N/A	503.3	359.3	420.2
C_{STEAM} , \$ year ⁻¹	32,642.5	44,838.3	67,039.9	9,400.2	N/A	73,373.9
$C_{COOLING WATER}$, \$ year ⁻¹	11,367.8	15,043.5	N/A	15,043.5	10,738.6	12,560.9
C_{COLUMN} , \$	20,129.2	24,278.0	15,485.1	24,855.2	21,401.8	31,158.1
C_{STAGES} , \$	2,400.4	3,295.4	1,495.1	3,404.1	2,612.5	4,651.0
$C_{REBOILER}$, \$	16,380.7	18,160.7	16,380.7	1,475.5	N/A	25,012.8
$C_{CONDENSER}$, \$	11,669.5	8,164.1	N/A	8,164.1	11,245.4	7,261.0
$C_{HEAT EXCHANGER}$, \$	N/A	N/A	23,169.0	N/A	N/A	N/A
C_{IP} , \$	30,347.9	32,338.9	33,918.0	22,739.3	21,155.8	40,849.7
$C_{MAINTENANCE}$, \$ year ⁻¹	90.1	110.3	67.9	113.0	96.1	143.2
$C_{UTILITIES}$, \$ year ⁻¹	44,010.3	59,881.8	67,039.9	24,443.7	10,738.6	85,934.8
$C_{CAPITAL}$, \$ year ⁻¹	16,275.7	17,357.7	18,157.5	12,240.7	11,379.2	21,929.7
C_{TAC} , \$ year ⁻¹	137,525.4		121,881.7		129,982.2	
ENERGY SAVINGS, % year ⁻¹	N/A		42.60		11.70	
% OF SAVINGS IN TAC	N/A		11.40		5.50	

quences for the mixture I. The higher savings in TAC of the thermally coupled distillation sequences were obtained when the amount of the intermediate component in the feed was low.

ACKNOWLEDGEMENT

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Nomenclature

ABC – Ternary mixture

B_1 – Bottoms product 1

B_2 – Bottoms product 2

C1 – Distillation column 1

C2 – Distillation column 2

C – Cost, \$ year⁻¹

D – Diameter of the distillation column, m

D_1 – Distillate 1

D_2 – Distillate 2

F_V – Recycle vapour stream, kmol h⁻¹

F_L – Recycle liquid stream, kmol h⁻¹

H – Height of the distillation column, m

p_H – High pressure, kPa

p_L – Low pressure, kPa

Q_{R1} – Heat duty supplied to the reboiler of distillation column 1, kW

Q_{R2} – Heat duty supplied to the reboiler of distillation column 2, kW

Q_{RT} – Total heat duty supplied to the distillation sequence, kW

References

1. *Annakou, O., Mizsey, P.*, *Ind. Eng. Chem. Res.* **35** (1996) 1877
2. *Emtir, M., Mizsey, P., Rev, E., Fonyo, Z.*, *Chem. Biochem. Eng. Q.* **17** (1) (2003) 31
3. *Triantafyllou, C., Smith, R.*, *Trans. Inst. Chem. Eng. Part A* **70** (1992) 118
4. *Hernández, S., Jiménez, A.*, *Comp. Chem. Engng.* **23** (8) (1999) 1005
5. *Hernández, S., Jiménez, A.*, *Ind. Eng. Chem. Res.* **38** (1999) 3957
6. *Rév, E., Emtir, M., Szitkai, Z., Mizsey, P., Fonyó, Z.*, *Comp. Chem. Engng.* **25** (2001) 119
7. *Kaibel, G.*, *Proc. ESCAPE-12 (Computer Aided Process Engineering, 10)*, Eds. J. Grievink and J.V. Schijndel, Elsevier, Amsterdam 2002 pp. 9
8. *Segovia-Hernández, J. G., Hernández, S., Jiménez, A.*, *Trans. Inst. Chem. Eng. Part A* **80** (2002) 783
9. *Segovia-Hernández, J. G., Hernández, S., Jiménez, A.*, *ESCAPE-13 (Computer Aided Process Engineering, 14)*, Eds. A. Kraslawski and I. Turunen, Elsevier, Amsterdam 2003 pp. 521