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Reduction of Energy Demand of Pressure-Swing Distillation by Splitting Feed between High- and Low-Pressure Columns

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By pressure-swing distillation (PSD), if the composition of the fresh feed is between the azeotropic ones at the column pressures applied, the feed can be introduced into either of the columns, resulting in two column sequences: HP1-LP2 when feeding into the high-pressure column (HPC) and LP1-HP2 when the feed enters the low-pressure column (LPC). In the present work, a new column sequence (HP+LP) is proposed to reduce the energy demand of the process, where the feed is split and introduced into both columns simultaneously. The energy demand, total annual cost (TAC) and CO_2 emission of the sequences are compared for the separation of the minimum-boiling azeotropic mixture acetone-methanol by rigorous simulation performed by the professional flow-sheet simulator ChemCAD. First, HP1-LP2 and LP1-HP2 are studied without optimisation, and the effect of feed splitting on the energy demand is investigated without changing any geometrical or operational parameters. Subsequently, TAC of the three sequences are minimised by a genetic algorithm (GA), and finally, partial Heat Integration (PHI) is applied to the cases studied. Without optimisation, LP1-HP2 is clearly more advantageous both in terms of energy demand and TAC. The lowest energy demand, with or without PHI, is reached by the optimised HP+LP sequence. It also has the lowest TAC with PHI, but the optimised HP1-LP2 has a lower TAC (by 1.2 %) if PHI is not applied. However, the differences in TAC values of the optimised processes are low.

1. Introduction

Pressure-sensitive azeotropic mixtures are commonly separated by pressure-swing distillation (PSD), which does not require the addition of a new component, but whose main drawback is its high energy demand. The mixture is separated in a two-column system where the columns operate at different pressures. The configuration of the system depends on the feed composition (z) and on whether the concentration of the lighter component (having a lower boiling point) in the azeotrope (x_{az}) increases or decreases on the increase of the pressure. If the feed composition is not between the azeotropic ones at the pressures of the columns, it can only be introduced into a given column. Between the azeotropic compositions, the feed can be introduced into any column. By the HP1-LP2 configuration, the feed enters the high-pressure column (HPC); by LP1-HP2, the low-pressure one. One of these column sequences will be superior in terms of energy demand and/or total annual cost (TAC), depending on the feed composition. Near $x_{az,LP}$, HP1-LP2 has the lowest energy demand, while near $x_{az,HP}$, LP1-HP2.

In this work, a new column configuration (HP+LP) is proposed where the feed is split between the LPC and HPC. The underlying hypothesis is that by splitting the feed, lower energy demand (and TAC) can be obtained than by either of the conventional column sequences. To our best knowledge, this configuration was not studied yet in the literature.

The energy demand of PSD systems can be reduced by performing Heat Integration (HI) of the columns: the top vapour of HPC is used to heat the reboiler of LPC. In the case of partial Heat Integration (PHI), the heat offered by the condensation of the vapour is not equal to the heat duty of the reboiler of LPC, and either an auxiliary condenser or an auxiliary reboiler is needed. By modifying the operational parameters of the columns, full Heat Integration (FHI) can be achieved where the two heat duties are equal.

The TAC of the PSD process can be considerably reduced by optimising the values of the geometrical (e.g. number of trays) and operational parameters of the columns. Since the cost of heating is a substantial part of TAC, minimisation of the latter generally also leads to a reduction of the energy demand. Metaheuristic optimisation methods, such as genetic algorithms (GA), are capable of approaching the global optimum without requiring the calculation of derivatives, which makes it possible to couple them to professional flow-sheet simulators. Álvarez et al. (2021) used a GA to minimise the TAC of the separation of the minimum boiling azeotropic mixture ethyl acetate-ethanol without HI. Ferchichi et al. (2022) optimised by a GA the separation of the maximum boiling water-ethylenediamine not only without HI but with PHI and FHI, as well.

Fulgueras et al. (2016) studied the separation of the minimum-boiling azeotropic mixture acetone-methanol. The composition of the feed (50 mol% acetone) was between the azeotropic ones at the given pressures (1.01 and 10.1 bar); therefore, it was possible to introduce it into either column. Instead of a rigorous optimisation procedure, the numbers of trays and the reflux ratios were selected based on shortcut calculations; then, by rigorous simulation, the optimal feeding locations were determined by minimising the reboiler duties. The total reboiler duty of LP1-HP2 was by 29.5 % lower than that of HP1-LP2 without Heat Integration and by 32.7 % lower when PHI was applied.

The novelty of this work is the proposal of a new column configuration (HP+LP) previously not studied in the literature. The new configuration is applied for the separation of the equimolar water-ethylenediamine mixture, studied by Fulgueras et al. (2016). Our aim is to determine the reduction of the energy demand and TAC that can be achieved by using feed splitting compared to the conventional configurations. TAC of the process is minimised for each column configuration (LP1-HP2, HP1-LP2 and HP+LP) by a GA coupled to a flow-sheet simulator. The optimisation variables are the numbers of trays, feeding locations, reflux ratios and, in the case of feed splitting, the splitting ratio. Subsequently, partial heat integration is applied to the optimal non-heat integrated processes, and the environmental impact of the processes studied is evaluated by calculating CO_2 emission values.

2. Vapour-liquid equilibrium

Acetone (A) and methanol (B) form a pressure-sensitive minimum boiling azeotrope (Figure 1) at both pressures (1.01 and 10.1 bar) applied by Fulgueras et al. (2016). The vapour-liquid equilibrium was described by the NRTL model with the binary interaction parameters B_{AB}=87.8485 K, B_{BA}=123.661 K and α=0.3008. At 1.01 bar, the azeotrope has a (calculated) boiling point of 55.3 °C and contains x_{Az}=78.3 mol% A. At 10.1 bar, the boiling point is 134.4 °C and x_{Az}=37.7 %. Therefore, the composition of the feed (z=50 %) is between the two azeotropic ones. The change in x_{Az} is considerable, which shows that PSD can be applied for the separation of the mixture. The mixture has a Bancroft point at around 5 bar (Fulgueras et al., 2016): below this pressure A, above it, B has the lower boiling point of the two components.

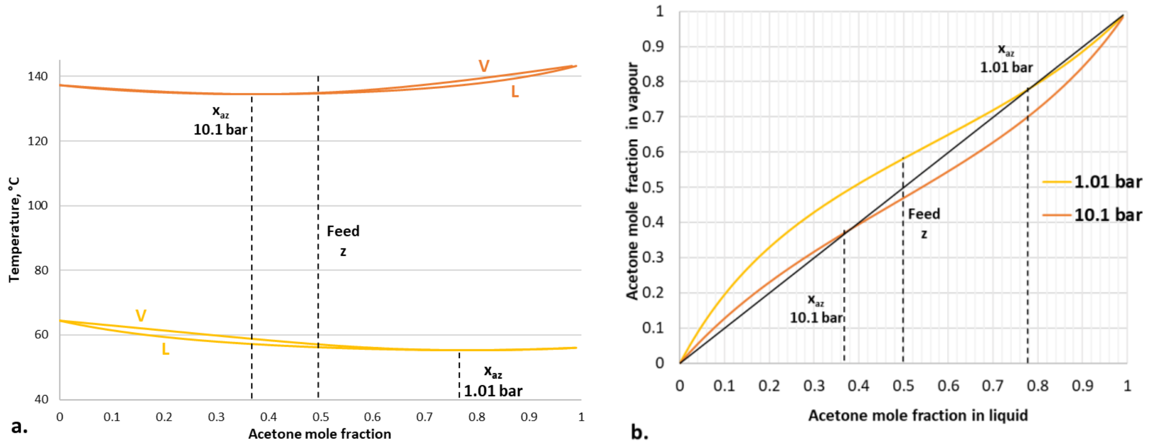

Figure 1: Equilibrium diagrams of the mixture acetone(A)-methanol(B) at 1.01 and 10.1 bar: a. boiling and dew point curves, b. y-x curves.

3. Process description

The fresh feed (Fulgueras et al., 2016) is equimolar and has a flow rate of F=540 kmol/h. Its pressure is 2.5 bar, and it is a subcooled liquid at 47 °C. The separation is performed in two-column PSD systems with different column sequences. The top pressures of the columns are 1.01 (LPC) and 10.1 bar (HPC), respectively. The pressure drop of the columns is neglected. In the conventional column sequences, the fresh feed is introduced either into the HPC (HP1-LP2) or into the LPC (LP2-HP1). A is obtained in the bottom product of the HPC (W_{HP})

with a purity of 99.4 mol%, while B in that of the LPC (W_{LP}) with a purity of 99.5 mol%. The distillate of each column (D_{HP} and D_{LP}) has a composition close to the azeotropic one at the pressure of the column, and it is fed (recycled) to the other column. Therefore, the column where the fresh feed is introduced has a second feed, the recycled stream. The two feeds can be united or introduced separately into the column in an order determined by their relative composition.

In the column sequence proposed here (HP+LP), the fresh feed is divided into two parts, F_{HP} and F_{LP}, which are introduced into the respective column (Figure 2). The splitting ratio of the fresh feed, defined as $SR=F_{HP}/(F_{HP}+F_{LP})$, presents an additional degree of freedom compared to the conventional sequences. By HP+LP, both columns have two feeds. Since D_{LP} contains more A and D_{HP} less A than the fresh feed, both streams are introduced below F_{HP} and F_{LP}, respectively.

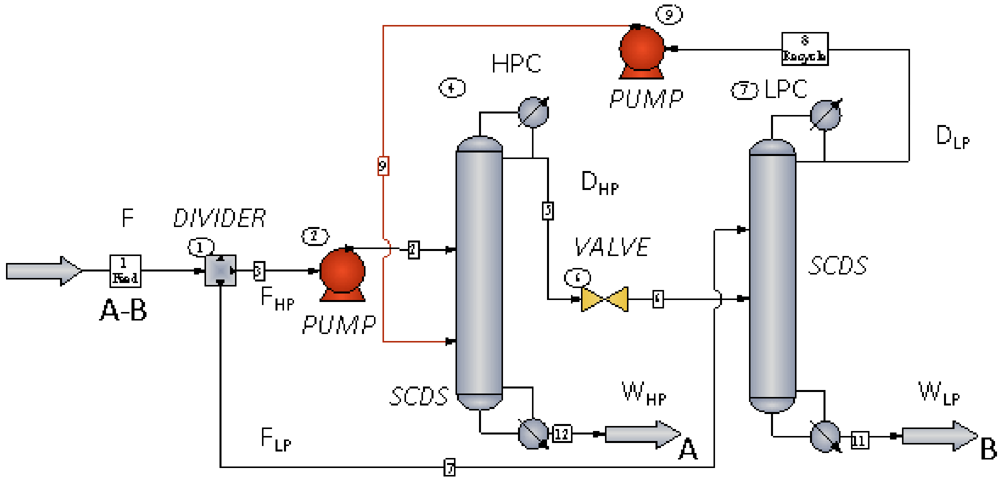

Figure 2: Flow-sheet of the HP+LP sequence without Heat Integration

Since the top temperature of HPC is higher than the bottom temperature of LPC, partial Heat Integration (PHI) can be applied, where the top vapour of HPC is used to heat the reboiler of LPC. Depending on the magnitude of the condenser duty of HPC ($Q_{c,HP}$) and the reboiler duty of HPC ($Q_{r,HP}$), either an auxiliary condenser is needed to completely condense the top vapour ($Q_{c,HP}>Q_{r,HP}$) or, if the heat offered by the top vapour is insufficient ($Q_{c,HP}<Q_{r,HP}$), an auxiliary reboiler must be applied. In all the cases studied here, an auxiliary reboiler is needed.

4. Calculation method

ChemCAD model of the HP+LP sequence is presented in Figure 2. Unit 4 and Unit 7 are the HPC and LPC, respectively (SCDS columns). The non-heat integrated processes of Fulgueras et al. (2016) are considered as the base cases.

By both sequences, the top pressure of HPC is P_{HP}=10.1, and that of LPC is P_{LP}=1.01 bar. By HP1-LP2 (case H-NHI0), the number of theoretical trays in the base case is N_{HP}=42 (including the total condenser and the partial reboiler) for HPC, while N_{LP}=26 for LPC. The fresh feed is introduced onto stage f_{HP}=22 of HPC (counted from the top), while W_{HP} enters LPC on stage f_{LP}=21. The recycle stream (D_{LP}) is mixed to the fresh feed ($f_{rec}=f_{HP}$).

By LP1-HP2 (case (L-NHI0)), N_{HP} equals 29 and N_{LP} is 34. The fresh feed is mixed with D_{HP} and introduced to stage $f_{LP}=f_{rec}$=18. D_{LP} is fed to stage f_{HP}=19 of the HPC.

The different column sequences without and with Heat Integration are compared with each other and with the NHI process by calculating the values of an economic indicator, the total annualised cost (TAC, \$/y) and an environmental one, the CO_2 emission generated by the process. The CO_2 emission of the process is calculated by considering the emissions related to the production of heating steam.

TAC is calculated from the total capital cost (TCC, \$) of the equipment and the total energy cost (TEC, \$/y):

$$TAC = \frac{TCC}{PBP} + TEC \tag{1}$$

where PBP is the length of the payback period, here 3 years. The above formula is commonly used for the economic evaluation of distillation processes (e.g. by Li et al., 2016). TCC includes the cost of the columns and the heat exchangers (condensers, reboilers and eventually the integrated heat exchanger for PHI). The energy cost is that of the heating steam. LP steam (4 bar) with a price of 7.78 $/GJ is used for heating LPC, MP steam (11 bar) with 8.22 $/GJ for HPC. A detailed description of the cost and CO_2 emission calculation method can be found in Ferchichi et al. (2022).

Subsequently, the influence of splitting the feed between the columns is studied. The initial value of SR, corresponding to no splitting, is 1.0 by HP1-LP2 and 0.0 by LP1-HP2, respectively. SR is then varied without changing any other geometrical or operational parameters to find its optimal value where the sum of the reboiler heat duties ($Q_{r,HP}$+$Q_{r,LP}$) is minimal. The resulting processes are denoted as S-NHI1a (obtained by using the parameters of H-NHI0) and S-NHI1b (obtained by using the parameters of H-LHI0).

The TAC of the three sequences is then minimised by an elitist genetic GA written in VBA under Excel. The optimised processes are denoted as H-NHI2, L-NHI2 and S-NHI2. The parameters of the GA: mutation probability: 5 %, crossover probability: 70 %, population size: 30, number of generations: 100. To calculate the results necessary for the calculation TAC, the algorithm calls ChemCAD for each individual. The optimisation variables are the numbers of trays (N_{HP}, N_{LP}), the feeding locations (f_{HP}, f_{LP}, f_{rec}), and the reflux ratios (R_{HP}, R_{LP}). Additionally, by the HP+LP sequence, SR is also an optimization variable, and the number of feeding locations increases by one (f_{HP}, f_{LP}, $f_{rec,HP}$, $f_{rec,LP}$). As it can be seen from the list of optimization variables, the intercolumn stream(s) (D_{LP} and D_{HP}) are not mixed with the fresh feed but introduced separately to the column(s). The following ranges of the optimisation variables (Table 1) are used: Range 1 for H-NHI2, Range 2 for L-NHI2 and Range 3 for S-NHI2.

Table 1: Ranges of the optimisation variables for GA

	N_{HP}	f_{HP}	$f_{rec,HP}$	N_{LP}	f_{LP}	$f_{rec,LP}$	R_{HP}	R_{LP}	SR
Range 1	20-60	2-12	15-30	20-60	3-20	-	0.5-7	0.75-5	-
Range 2	45-70	10-40	-	20-60	3-20	15-30	2-7	0.75-5	-
Range 3	20-60	2-12	15-30	20-60	3-20	10-50	0.5-7	0.75-5	0-1

Partial Heat Integration is applied to all the NHI processes without changing any geometrical or operational parameters. Since $Q_{c,HP}$ is lower than $Q_{r,LP}$ in all the cases, an auxiliary reboiler is needed to provide the missing heat duty (Q_{aux}). The resulting processes are denoted by changing NHI to PHI in their names.

5. Results

First, the results without HI (NHI) are presented, then those with applying PHI.

5.1 No Heat Integration (NHI)

First, the reproduction of the results of Fulgueras et al. (2016) is intended. By using the same numbers of trays, feeding locations and reflux ratios as Fulgueras et al. (2016), it is possible to obtain similar heat duty values, with the highest difference being 5.7 % ($Q_{r,LP}$ of H-NHI0, Table 2). The TAC values shown for Fulgueras et al. (2016) are calculated by using the column diameters calculated here. Fulgueras et al. (2016) found that the LP1-HP2 had a lower total reboiler heat duty. The same is true for the TAC values, as well: L-NHI0 has a TAC lower by 28 % than H-NHI0. Both TCC and TEC are lower by 12 and 29 %, respectively. These results can be explained by the lower intercolumn flow rates.

Subsequently, the splitting of the feed is studied. Starting from H-NHI0, on the decrease of SR from 1.0 to 0.0, the sum of the reboiler heat duties decreases almost linearly (Figure 3). The lowest heat duty is thus reached by introducing the total amount of the feed into LPC (S-NHI1a), leading to an LP1-HP2 sequence (SR=0), although with different geometrical and operational parameters than L-NHI0. By S-NHI1a, the total reboiler heat duty (and thus TEC) is reduced by only 2.7 % compared to that of H-NHI0 (Table 3). $Q_{r,HP}$ decreases, while $Q_{r,LP}$ increases considerably following the changes in the internal flows of the columns (hinted at by the change in D_{HP} and D_{LP}). The column diameters change in a similar manner. These effects lead to a higher decrease in TCC (9.7 %). As a result, TAC is by 3.5 % lower. However, the total reboiler heat duty L-NHI0 is much lower (by 26 %) than that of S-NHI1a. TCC is also lower (by 13 %); thus, the TAC of L-NHI0 is lower by 25 %.

Table 2: Reproduction of the results of Fulgueras et al. (2016) (NHI processes without feed splitting)

Case	H-NHI0 (SR=1)				L-NHI0 (SR=0)			
	Fulgueras et al. (2016)		Present work		Fulgueras et al. (2016)		Present work	
Parameter	HPC	LPC	HPC	LPC	HPC	LPC	HPC	LPC
N	42	26	42	26	29	34	29	34
f	22	21	22	21	19	18	19	18
f_{rec}	22	-	22	-	-	18	-	18
Di (m)	2.90	3.98	2.90	3.98	2.59	2.90	2.59	2.90
T_c (°C)	134.5	55.4	134.5	55.4	134.4	55.5	134.4	55.4
T_r (°C)	143.8	66.7	143.4	64.3	143.8	66.7	143.4	64.3
R	1.26	3.98	1.26	3.98	4.13	1.72	4.13	1.72
D (kmol/h)	762.3	493.0	738.1	468.4	280.9	551.9	267.0	537.3
Q_c (kW)	12,909	21,440	12,444	20,356	10,910	13,141	10,320	12,816
Q_r (kW)	15,840	19,590	15,476	18,464	12,480	12,660	11,958	12,325
TCC (10^5 \$)	33.54		32.92		26.15		25.76	
TEC (10^5 \$/y)	88.64		84.95		63.06		60.90	
TAC (10^5 \$/y)	99.81		95.93		71.78		69.49	

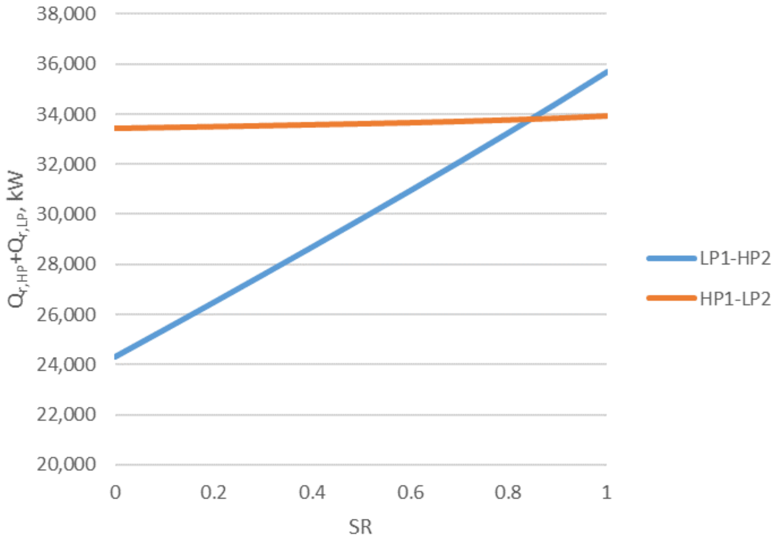

Figure 3: Influence of SR on the total reboiler heat duty (no Heat Integration)

Starting from L-NHI0, the increase of SR (from 0.0) leads to a considerable, almost linear increase in the total reboiler heat duty (Figure 3). Therefore, S-NHI1b is identical to L-NHI0. These results indicate that without changing the geometrical parameters and the reflux ratios, splitting the feed is not advantageous.

Finally, the three sequences are optimised by GA (Table 3). By the HP1-LP2 sequence (H-NHI2), N_1 decreases by 7 and N_2 increases by 6 compared to the non-optimised process (H-NHI0). The fresh feed is introduced very close to the condenser of HPC, showing that mixing the fresh feed and the recycle is far from the optimal. The flow rates of the intercolumn streams increase slightly (by 2.5-4 %). The reflux ratios and thus the heat duties decrease to a great extent. The highest decrease is observed by R_1 (it is one-sixth of that of H-NHI0). These changes reduce TEC by 39 %. At the same time, TCC is lower by 13 %. By the optimisation, TAC is decreased very importantly, by 36 %.

Table 3: Results of the S-NHI1a process and the optimised NHI processes

Case	S-NHI1a (SR=0)		H-NHI2		L-NHI2		S-NHI2	
	Feed splitting based on H-NHI0		HP1-LP2 optimised		LP1-HP2 optimised		HP+LP optimised	
Parameter	HPC	LPC	HPC	LPC	HPC	LPC	HPC	LPC
N	42	26	35	31	45	38	38	39
f_i	22	21	3	17	29	16	4	14
f_{rec}	22	-	22	-	-	21	21	28
Di (m)	1.98	4.11	2.74	4.11	2.59	2.90	2.74	4.11
T_c (°C)	134.8	55.4	134.5	55.4	134.4	55.4	134.5	55.4
T_r (°C)	143.4	64.3	143.3	64.3	143.4	64.3	143.4	64.3
SR	0.0		1.0		0.0		0.370	
R	1.26	3.98	0.199	2.03	2.97	1.82	1.20	1.75
D (kmol/h)	342.6	612.9	756.9	487.6	247.9	518.2	445.5	516.2
Q_c (kW)	5,699	26,588	6,774	12,917	7,415	12,804	7,293	12,386
Q_r (kW)	7,579	25,853	9,854	10,976	9,005	12,362	9,454	12,369
TCC $(10^5\ \$)$	29.74		28.36		27.81		30.73	
TEC $(10^5\ \$/y)$	82.62		52.18		53.38		52.12	
TAC $(10^5\ \$/y)$	92.54		61.64		62.65		62.36	

By optimising the LP1-HP2 sequence (L-NHI2), N_1 is increased to a great extent (by 16), while N_2 only slightly (by 4) compared to L-NHI0. Unlike H-NHI2, the fresh feed is introduced relatively close to the other feed of LPC. The column diameters are unchanged. The flow rate of the intercolumn streams decrease slightly (by 3.6-7.2 %). There is a considerable decrease in R_1 and the heat duties of HPC (e.g. $Q_{r,HP}$ is lower by 25 %), while a slight increase can be observed in the case of LPC (except for $Q_{c,LP}$). Because of the increase in the numbers of trays, TCC increases by 8.0 %. However, the decrease of TEC (by 12 %) leads to a 9.8 % lower TAC. The decrease of TAC reached by optimisation is thus much lower in the case of LP1-HP2, already having a lower TAC, than in the case of HP1-LP2.

By the optimised HP+LP sequence (S-NHI2), 37 % of the fresh feed enters HPC. The values of the other optimisation variables are between those of H-NHI2 and L-NHI2 with the exception of N_2 and R_2, which are very slightly above and below those of L-NHI2, respectively. The same is also true for the heat duty (except for $Q_{c,LP}$) and the flow rates of the intercolumns streams. Feed splitting thus has the effect of balancing out the load of the two columns.

By comparing the three optimised sequences, TCC is the lowest by L-NHI2 due to the lower column diameters and the highest by S-NHI2 because of the higher numbers of trays and diameters. TEC of H-NHI2 is lower than that of L-NHI2, because as D_{HP} is much higher, and since the distillate of HPC partially vaporises when its pressure is reduced before LPC, this leads to a decrease in $Q_{r,LP}$. The TEC of S-NHI2 is even lower, but the difference is only 0.12 %. In contrast to results without optimisation, the lowest TAC is obtained by H-NHI2. However, the differences between the sequences are not considerable: that of S-NHI2 is only by 1.2 %, and that of L-NHI2 is by 1.6 % higher.

5.2 Partial Heat Integration (PHI)

By the application of PHI (Table 4), an auxiliary reboiler is needed in all the cases.

Table 4: Results of the application of PHI

Case	SR	$Q_{r,HP}$ (kW)	Q_{rc} (kW)	Q_{aux} (kW)	TCC $(10^5\ \$)$	TEC $(10^5\ \$/y)$	TAC $(10^5\ \$/y)$
H-PHI0	1.0	15,476	12,444	6,020	32.53	54.59	65.43
L-PHI0	0.0	11,958	10,320	2,005	25.13	35.72	44.10
S-PHI1a	0.0	7,579	5,699	20,154	29.91	68.72	78.69
H-PHI2	1.0	9,854	6,774	4,202	28.11	35.66	45.03
L-PHI2	0.0	9,005	7,415	4,947	27.59	35.29	44.48
S-PHI2	0.370	9,454	7,293	4,076	30.44	34.32	44.47

By H-PHI0, TEC decreases by 36 %. TCC is only slightly changed (lower by 1.2 %), while TAC is by 32 %. Therefore, by applying PHI without any modification in the process parameters, a decrease in TAC similar to that by optimisation of the NHI process can be reached. By L-PHI0, both $Q_{r,HP}$ and the heat duty of the auxiliary reboiler (Q_{aux}) are much lower, leading to a decrease in TEC by 41 %. There is a decrease in TCC, as well (by 2.4 %), and TAC is reduced by 37 %. In this case, the application of PHI offers a greater reduction of TAC than the optimisation of the NHI process. In the case of S-PHI1a, PHI only decreases TEC by 17 % because the high difference between $Q_{c,HP}$ and $Q_{r,LP}$ results in a high Q_{aux} value. Moreover, TCC even increases (by 0.57 %) as a result of the lower temperature difference in the reboiler-condenser. The decrease in TAC is thus 15%.

By applying PHI to the optimised processes (H-PHI2, L-PHI2, S-PHI2), TEC is decreased to a similar extent (32-34 %) for all the processes. TCC increases slightly in all the cases, by 0.79-0.94 %. As a result, the reduction of TAC is also similar: 27 % by H-PHI2 and 29 % by both L-NHI0 and S-PHI2. Since the TAC values of the optimised NHI processes are close to each other, the differences between those of the PHI processes are also low. However, the order of the sequences changes with the application of PHI. While without HI, H-NHI2 has the lowest and L-NHI2 the highest TAC, with HI, S-PHI2 has the lowest and H-PHI2 the highest value. Nevertheless, TAC of H-PHI2 is only 1.3 % higher than that of S-PHI2, while the difference between L-PHI2 and S-PHI2 is negligible.

Interestingly, the lowest TAC is obtained not by applying PHI to one of the optimised NHI processes but to the non-optimised LP1-HP2 sequence (L-PHI0): it is by 0.83 % lower than that of S-PHI2. This can be explained by the fact that Q_{aux} is by far the lowest by L-PHI0.

5.3 CO_2 emissions

The CO_2 emissions of the processes are calculated (Table 5). By optimising the NHI processes, a reduction of 38 % (H-NHI2) and 16 % (L-NHI2) is reached. Among the NHI processes, the lowest emission is reached by the optimised process with feed splitting (S-NHI2). By the application of PHI, the CO_2 emission is reduced by 22-28 % with the exception of S-NHI1a where the decrease is only 13 %. The lowest CO_2 emission is reached by L-PHI2.

Table 5: The CO_2 emission of the processes studied

Case	CO_2 emission (kg CO_2/h)	Case	CO_2 emission (kg CO_2/h)
H-NHI0	1,348	H-PHI0	1,017
L-NHI0	990.0	L-PHI0	715.5
S-NHI1a	1,107	S-PHI1a	955.7
H-NHI2	837.6	H-PHI2	657.4
L-NHI2	827.4	L-PHI2	630.2
S-NHI2	825.9	S-PHI2	631.9

6. Conclusions

The novelty of the present work was the proposal of a new column sequence (HP+LP) to reduce the energy demand of such pressure-swing distillation processes where the composition of the feed is between the azeotropic ones at the pressures of the columns. In the conventional sequences, the feed is introduced either into the high-pressure column (HPC; HP1-LP2 sequence) or into the low-pressure column (LPC, LP1-HP2 sequence). In the new sequence, the feed is split and introduced simultaneously into both columns. The separation of a minimum-boiling azeotropic mixture, acetone-methanol, was studied by rigorous simulation using the professional flow-sheet simulator ChemCAD. First, the results of Fulgueras et al. (2016) were reproduced, who found that the LP1-HP2 had an energy demand by 29 % lower than the HP1-LP2 one. In addition to the energy demand, the total annual cost (TAC) and the CO_2 emission of the process were also evaluated in the present work. The TAC of LP1-HP2 without optimisation and without Heat Integration (L-NHI0) was by 28 % lower than that of HP1-LP2 (H-NHI0). Splitting feed without changing any other geometrical or operational parameters led to an LP1-NH2 sequence but with higher TAC.

The TAC of the three sequences (without Heat Integration) was then minimised by a genetic algorithm (GA). By HP1-LP2 (H-NHI2), TAC decreased considerably (by 36 %), while that of LP1-HP2 (L-NHI2) by 9.8 % only. As a result, the optimised HP1-LP2 had the lowest TAC value, although that of L-NHI2 was by 1.6 % higher only. Although TAC of the optimised HP+LP (S-NHI2) was between those of the conventional sequences, its energy demand was the lowest.

Partial Heat Integration (PHI) was applied to all the cases studied. By the non-optimised processes, it led to a decrease of TAC by 32-37 %, while in the case of the optimised one, to a decrease of 27-29 %. Among the heat integrated, optimised processes, HP+LP had both the lowest energy demand and TAC, although the TAC values were close to each other. However, the lowest TAC was obtained by applying PHI to L-NHI0. The lowest CO_2 emission was reached by the heat-integrated LP1-HP2 sequence (L-PHI2).

The columns of the new HP+LP sequence had more evenly balanced loads due to the splitting of the feed between the columns. The new sequence had lower energy demand (and thus CO_2 emission) than the conventional ones. Although the TAC of HP+LP was the lowest in the case of applying PHI, it was only the second-lowest if no HI was applied. However, it must be noted that the energy demand and TAC results of the three optimised sequences were very close to each other. Therefore, it would be useful to study feed splitting in another case study where the difference between the conventional sequences is greater to verify whether it can lead to a more considerable decrease in energy demand. Another possibility for the continuation of the work is to perform the optimisation of the heat integrated processes, as well, which will likely lead to a reduction of the heat duty of the auxiliary reboiler by increasing the condenser duty of HPC through decreasing the number of trays and/or increasing the reflux ratio of HPC.

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