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Multi-effect distillation applied to an industrial case study

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Abstract

An industrial separation system consisting of four pressure-staged distillation columns has been studied to see if multi-effect integration can be applied to any two columns in the sequence. Shortcut equations and $V_{\min}$-diagrams have been used for screening purposes to find the columns with the highest potential for energy savings. The most promising case has then been further studied using rigorous simulation tools to verify the results from the shortcut approach. Three cases have been simulated: a non-integrated base case (existing), a multi-effect indirect split arrangement (ISF) and a multi-effect prefractionator arrangement (PF). The results showed that when considering the existing number of stages available the ISF arrangement was the best, however when considering infinite number of stages the PF arrangement was the best (as expected).

Keywords: Energy saving; Process integration; Multi-effect distillation; Prefractionator

1. Introduction

Multi-effect (also called pressure-staged) distillation means that the column pressures are adjusted such that the cooling (energy removal) in one column can be used as heating (energy input) in another column.

The separation of a hydrocarbon feed into four products using four sequential distillation columns have been studied in this paper to see if any of the four columns are suitable for heat integration by using a multi-effect prefractionator arrangement.

Multi-effect integration of prefractionators has been considered in the literature by authors like Cheng and Luyben [2] and Emtir et al. [12], who demonstrated that this arrangement can have high energy savings. In terms of industrial examples there is no knowledge of the multi-effect *prefractionator* arrangement being used. There are, nevertheless, examples of other multi-effect arrangements in use. Examples in literature includes a binary multi-effect distillation described by O'Brien [10], the feed-split arrangement presented by Gross et al. [6] and the forward-integrated indirect split arrangement (ISF) for the methanol–water separation as described by Engelien et al. [3].

In this revamp case study we investigate if the multi-effect prefractionator arrangement can be implemented in an industrial context. Three separation tasks from a gas processing facility are investigated, in order to see if an integrated prefractionator arrangement can be suitable for an industrial application.

The methods presented in Engelien and Skogestad [4] are applied in order to screen the three cases based on minimum vapour flowrate criteria. Also the required pressure levels for multi-effect integration was calculated for each case. From these preliminary calculations a candidate for integration was identified for which further rigorous simulations were carried out to compare energy consumption, pressure and temperature levels for the new multi-effect system with that of the existing distillation arrangement. Finally an exergy analysis was made in order to determine the efficiencies of the different arrangements.

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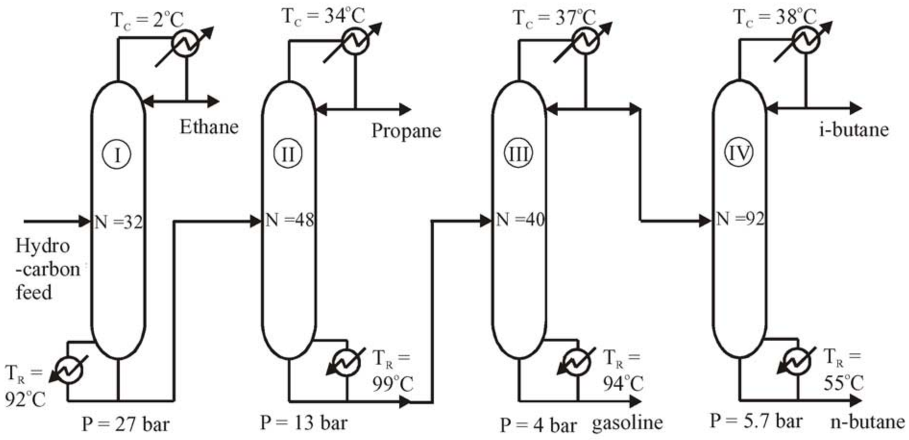


Fig. 1. Existing column arrangement.

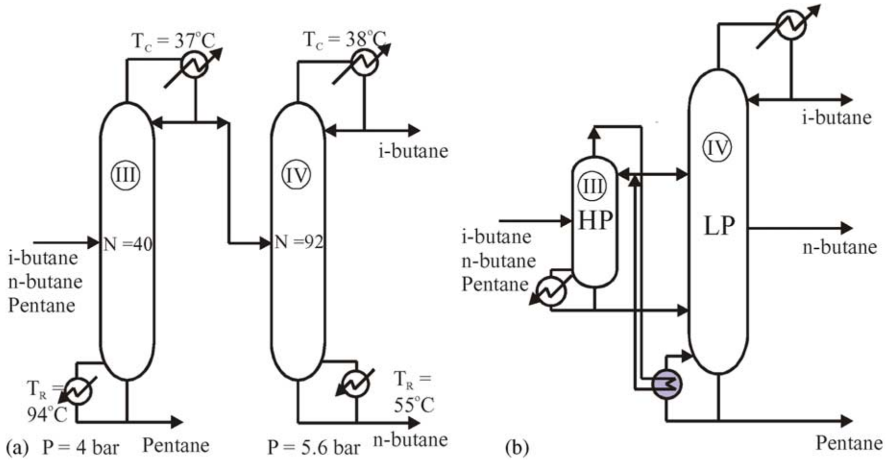


Fig. 2. Multi-effect integration of two columns (Case 3): (a) existing indirect split (IS) arrangement; (b) multi-effect prefractionator (PF) arrangement with forward integration.

2. Systems studied

We consider the separation of a light hydrocarbon mixture into five products: ethane, propane, *i*-butane, *n*-butane and gasoline (pentane). The four two-product columns presently used for this task are denoted I, II, III and IV in Fig. 1. The present pressure and temperature levels are indicated in the figure. An example of a multi-effect integration of Columns III and IV is shown in Fig. 2. This is only one possibility as there are three adjacent pairs of columns that are candidates for being replaced by multi-effect prefractionator arrangements in a possible revamp of the plant:

- *Case 1*. Columns I and II for the separation of ethane, propane and butane (+higher).
- *Case 2*. Columns II and III for the separation of propane, butane and gasoline.

Table 1
Feed, product and relative volatility data

	Case 1	Case 2	Case 3	Product composition
Ethane ($\alpha = 10.0$)	0.3742 A	0.005	1.44e−12	0.9142
Propane ($\alpha = 7.98$)	0.3697 B	0.6212 A	0.005	0.9870
i-Butane ($\alpha = 3.99$)	0.0491 C	0.0827 B	0.2137 A	0.9723
n-Butane ($\alpha = 3.0$)	0.1122 C	0.1889 B	0.5070 B	0.9881
n-Pentane ($\alpha = 1.0$)	0.0607 C	0.1022 C	0.2742 C	0.8414
Feed flowrate (kmol/h)	3228.01	1917.14	714.12	–
Temperature (°C)	49.05	59.42	50.89	–

- *Case 3*. Columns III and IV for the separation of *i*-butane, *n*-butane and gasoline.

The feed data for all three cases are given in Table 1.

3. Minimum vapour flowrate—shortcut calculations

The first task is to determine if any of the three cases are suitable for integration using multi-effect distillation. Shortcut methods have been used to calculate the minimum vapour flow requirement for each of the separations. Simple flash calculations have also been made to determine the required pressure levels.

For simplicity the mixtures have been taken as ternary mixtures for the shortcut calculations. Hydrocarbons of C5 or higher have therefore been assumed to be *n*-pentane and the small presence of CO_2 in the feed to Column (I) has been neglected. Further, in the shortcut simulations for Case 1 the small amounts of *i*-butane and *n*-pentane have been lumped together as *n*-butane. For Case 2 the *i*-butane and *n*-butane have been considered to be *n*-butane. The ternary feeds to each case are marked in Table 1 as A, B and C. The specifications of the five products are given in the right hand column. Also given is the relative volatility of each component, relative to the heaviest component considered; *n*-pentane. These relative volatilities are found from literatures [9,11]. For the shortcut analysis the relative volatilities have been assumed to be independent of pressure, but this assumption is relaxed later when studying the most promising alternative in more detail. In addition the analysis assumes sharp splits, liquid feeds, constant molar flows.

The $V_{\min}$-diagram gives the minimum energy requirements (in terms of vapour flow V) as a function of the distillate fraction $\eta = D/F$ for the first column in a two-column sequence. Engelien and Skogestad [4] show how to draw the $V_{\min}$-diagram and how to use it to compare the multi-effect prefractionator arrangement with other multi-effect systems and the existing non-integrated direct split (Cases 1 and 2) and indirect split (Case 3) arrangements. We can also compare the $V_{\min}$ to that of the Petlyuk arrangement, which is the best of the adiabatic systems [7,8].

Using the relative volatility data and the simplified feed compositions in Table 1 minimum vapour flow ($V_{\min}$) diagrams for each of the three cases were plotted in Figs. 3–5. For clarity the feed composition and relative volatility used are given in each of the diagrams. The results for some other sequences are summarised in Table 2.

The following savings are found for the integrated prefractionator arrangement, compared with the existing arrangement:

- *Case 1* (Fig. 4). 43.3% savings.
- *Case 2* (Fig. 5). 37.2% savings.
- *Case 3* (Fig. 6). 55.3% savings.

We see that Case 3 has the highest savings. For Case 3 the other multi-effect arrangements also give relative high savings of 28 and 26% for the indirect and direct multi-effect arrangements, respectively.

From the $V_{\min}$-diagram we can also find how the prefractionator column should be operated in order to achieve the highest energy savings. The value of η_{optimum} corresponds to $V_{\min,\text{PF/PB}}$. The value of η_{optimum} can be used as a starting point for further rigorous simulations.

As shown by Engelien and Skogestad [4] the $V_{\min}$-diagrams also indicate how the columns are unbalanced. From Figs. 3–5 it can be seen that for all cases the lower section of the main column has “excess” vapour. For the purpose of a retrofit we may then consider using a relatively short section below the sidestream. This would leave more stages for the more difficult separation in the upper section above the sidestream. Alternatively, if the number of stages in the column is sufficient the excess vapour could be utilised by taking out the sidestream as vapour, which can then be used to provide heat elsewhere in the process (if necessary). This could lead to a reduction of the energy consumption of the overall plant.

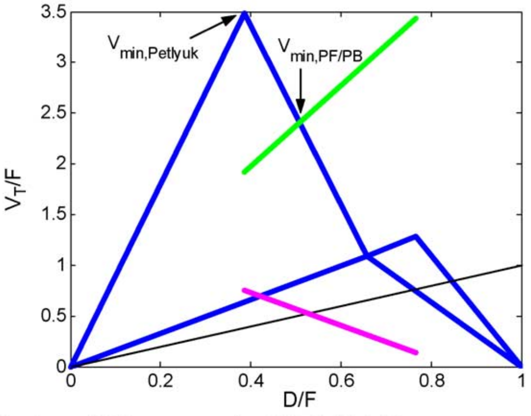
3.1. Column pressure levels

The pressure levels in the columns were found from flash calculations using the recoveries found from the $V_{\min}$-diagrams. For integrated prefractionator arrangements there are two possible types of integration; a forward integration (PF) and a backward integration (PB). In Table 3 we have calculated the pressure levels required in both the PF and the PB arrangements.

For Cases 2 and 3 the temperature of the overhead condenser was assumed to 20 °C, so that the existing cooling liquid (seawater) can be used. For Case 1 in the original flow-

Table 2
Minimum vapour flowrate and percentage improvement for different integrated arrangements (α independent of pressure).

	Case 1		Case 2		Case 3	
	$V_{\min}/F$	%	$V_{\min}/F$	%	$V_{\min}/F$	%
Direct split	4.23	0.0	1.63	0.0	3.38	−0.2
Indirect split	4.33	−2.2	1.69	−3.76	3.38	0.0
Multi-effect direct split (DSF/DSB)	3.48	17.7	1.17	28.1	2.49	26.4
Multi-effect indirect split (ISF/ISB)	3.43	19.0	1.16	28.5	2.42	28.4
Petlyuk	3.48	17.7	1.17	28.1	2.49	26.4
Multi-effect prefractionator (PF/PB)	2.40	43.3	1.02	37.2	1.51	55.3

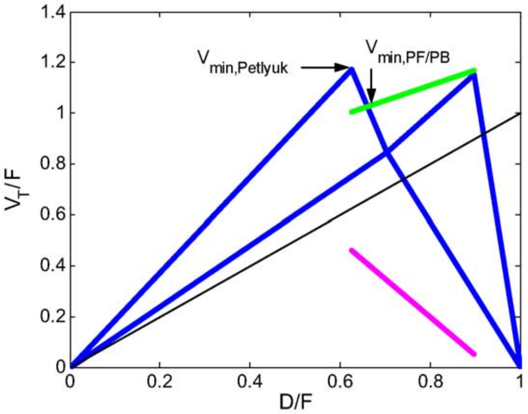


Feed composition:	
ethane	0.3856
propane	0.3811
butane	0.2333

Relative volatility:	
ethane	3.33
propane	2.66
butane	1.00

Saving of PB compared withDS:43.3 %

Fig. 3. $V_{\min}$-diagram for Case 1 (α independent of pressure).

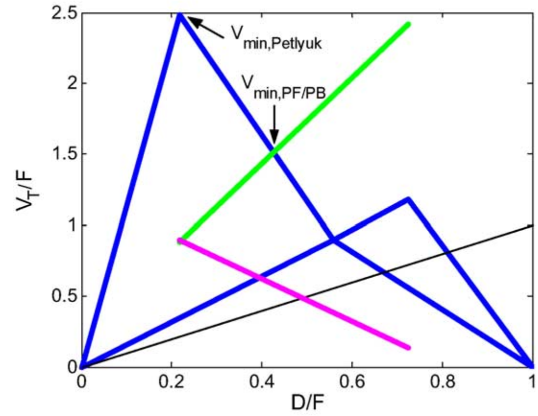


Feed composition:	
propane	0.6262
n-butane	0.2716
n-pentane	0.1022

Relative volatility:	
propane	7.98
n-butane	3.00
n-pentane	1.00

Saving of PF compared with DS:37.2 %

Fig. 4. $V_{\min}$-diagram for Case 2 (α independent of pressure).



Feed composition:	
i-butane	0.2188
n-butane	0. 5070
n-pentane	0. 2742

Relative volatility:	
i-butane	3.99
n-butane	3.00
n-pentane	1.00

Saving of PF compared with IS: 55.3 %

Fig. 5. $V_{\min}$-diagram for Case 3 (α independent of pressure).

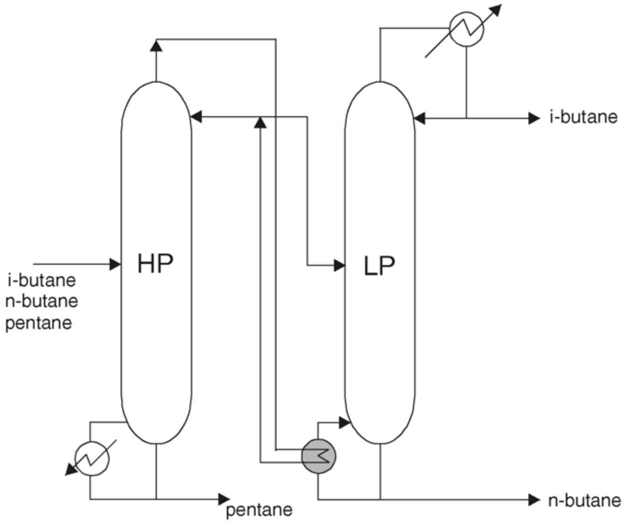


Fig. 6. Multi-effect indirect split arrangement with forward integration (ISF).

sheet a refrigerant is used in the condenser of the de-ethaniser. For this case the temperature corresponding to using the same coolant has been used for both the PF and PB integrated cases.

Further, a 10 °C temperature difference was assumed between the distillate and bottom stream from the integrated reboiler/condenser and sharp products from the main column was assumed. The concentrations for the prefractionator were found from the optimum product split, η, in Figs. 3–5. The calculated pressure levels for both forward and backward integration are summarised in Table 3. Note that for these shortcut calculations the pressure drops in the columns have been neglected.

It can be seen from Table 3 that to integrate the columns for Cases 1 and 2 in a multi-effect fashion would required very high pressure levels. Due to this and the fact that Case 3 has the highest energy savings, these cases were eliminated from further investigation. The rest of the study focuses on Case 3, which, in terms of energy savings and preliminary pressure levels shows potentials for energy integration.

In terms of pressure levels the results in Table 3 indicate that the PB arrangement might be a more suitable arrangement for this separation task than the PF arrangement. However, there are indications that the forward-integrated arrangement is easier to control [1,5]. Also, we believe that the forward-integrated arrangement would be easier in terms of start-up. As the heat input is to the first column this can be started up first, e.g. by using a total reflux approach, then when the first column is up and running it will be relatively easy to start the second up. The backward-integrated arrangement would be more difficult.

Table 3
Pressure levels in integrated columns (from flash calculations)

	Case 1		Case 2		Case 3	
	PF	PB	PF	PB	PF	PB
Prefractionator	153.0	19.2	8.32	8.01	14.0	2.55
Main column	25.1	104.6	66.0	35.37	3.0	6.74

Pressures in bar.

In light of the control issues it was decided to focus the further study on Case 3 in terms of the forward-integrated prefractionator arrangement. The integrated arrangement for Case 3 is shown on the right-hand side in Fig. 2.

4. Rigorous column simulations

After identifying Case 3 as a suitable candidate for integration, further investigations were made using a commercial rigorous simulations program (HYSYS).

The shortcut calculations indicate that the integrated prefractionator arrangement should give approximately 55% improvement in energy consumption, compared with the non-integrated indirect split (IS) arrangement. In addition to the integrated prefractionator arrangement another multi-effect arrangement has been considered. The second best multi-effect arrangement, according to Table 2, is a multi-effect integrated indirect split system. The improvement for this system should be around 28% compared with the non-integrated arrangement. The forward-integrated indirect split (ISF) system (see Fig. 6) was selected based on the same arguments that were made when selecting the PF system.

For the simulations the pressure levels were adjusted so that a 10 °C temperature difference was achieved for the integrated reboiler/condenser. This gave a pressure of 19.5 bar in the top of the HP column and 4.17 bar in the LP column for the PF-prefractionator arrangement. The deviation from pressure levels in Table 3 is due to impure products. For the multi-effect indirect split arrangement in Fig. 6 the pressure level is lower with 8 bar in the HP column and 5.2 bar in the LP column.

The energy consumption's for the original base case (IS), the integrated prefractionator (PF) and the integrated indirect split system (ISF) have been found from rigorous simulations. The number of stages in the columns was taken to be the same as the existing number of stages (see Fig. 2a).

From the results presented in Table 4, it can be seen that for the multi-effect prefractionator arrangement (PF) there is an improvement in energy consumption of about 28.6%, compared with the base case. The multi-effect indirect split (ISF) arrangement has an even higher energy saving, at about

Table 4
Rigorous calculations of energy consumption for Case 3 using existing number of stages

	Base case	ISF	PF
Q_{B1} (MW)	3.853	7.183	8.951
Q_{C1} (MW)	5.464	8.359	8.267
Q_{B2} (MW)	8.682	8.359	8.267
Q_{C2} (MW)	8.735	8.678	10.700
$Q_{B,total}$ (MW)	12.535	7.183	8.951
% Energy improvement	–	42.7	28.6

Table 5
Rigorous calculation of energy consumption for Case 3 using a very large number of stages

	Base case	ISF	PF
Q_{B1} (MW)	3.962	6.929	5.309
Q_{C1} (MW)	5.564	8.097	4.608
Q_{B2} (MW)	8.349	8.097	4.608
Q_{C2} (MW)	8.403	8.419	7.068
$Q_{B,total}$ (MW)	12.311	6.929	5.309
% Energy improvement	–	43.7	56.9

42.7%. Interestingly, the energy savings of the ISF arrangement are higher than the savings indicated by the shortcut calculations in Table 2. This is because in the shortcut equations we have assumed sharp splits for simplicity, whereas for the rigorous simulations the actual product compositions have been used.

On the other hand for the prefractionator arrangement (PF) the energy savings of 28.6% are significantly lower than the 55.3% indicated by the shortcut calculations in Table 2. However, the shortcut calculations give the minimum energy for infinite number of stages. To confirm that the changes in energy savings for the PF arrangements is due to the number of stages a comparison was made for infinite number of stages (in practice a very large number of stages were used). The results are shown in Table 5. From this it can be seen that for infinite number of stages the integrated prefractionator arrangement has a 56.9% improvement compared with the base case, whereas the integrated indirect split arrangement has a 43.7% improvement. By comparing Tables 4 and 5 we see that the ISF arrangement shows little improvement with the increased number of stages, indicating that the existing number of stages already is sufficient for the separation and it is close to the minimum vapour flow target. The PF arrangement shows significant improvement as the number of stages is increased. The results for the PF at infinite number of stages are in good agreement with the $V_{\min}$ calculated from the shortcut equations (Table 2).

5. Number of stages

From the above results it is clear that the main column of the prefractionator arrangement requires more stages than a conventional column to achieve the potential energy savings. This is seen in Table 4 as the ISF arrangement has higher energy savings than the PF arrangement with the existing number of stages.

In a distillation column there is a trade-off between the number of stages and the energy usage (vapour/reflux). This trade-off (see Fig. 7) is illustrated in many textbooks on distillation (e.g. [9]) and applies to conventional as well as to integrated arrangements. A more careful analysis reveals that the actual V approaches $V_{\min}$ for N approximately $2N_{\min}$ or larger. Here $N_{\min}$ is the infinite number of stages corresponding to infinite vapour flow, whereas $V_{\min}$ is the minimum vapour flow corresponding to infinite number of stages.

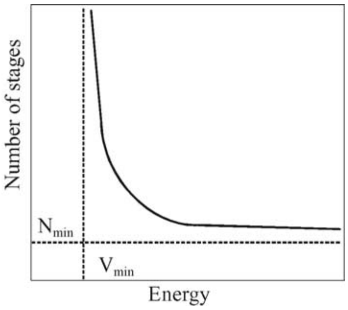


Fig. 7. Trade-off between energy usage (V) and number of stages (N).

Typically, if we were to operate a column at $2N_{\min}$ (a typical rule-of-thumb for design) then we are already within +20% of $V_{\min}$. At $3N_{\min}$ we are within about +2% of $V_{\min}$ and at $4N_{\min}$ we are within +0.2% of $V_{\min}$. The measure of $V_{\min}$ is therefore a good target for comparing energy as we are usually operating close to it. However, we cannot generally expect that a prefractionator arrangement (PF) will have enough stages if we base it on an existing conventional arrangement (DS or IS) as we did here. This follows since the existing column, which is designed for a two-product separation, is now required to do a three-product separation task. On the other hand, the number of stages will be sufficient for the ISF arrangement as illustrated in this paper.

The conclusion is that a revamp of a conventional arrangement (DS or IS) to a prefractionator arrangement (PF or PB) should be accompanied by an increase in the number of stages in the main column, for example by changing the column internals or packing.

6. Comparison in terms of thermodynamic efficiency

In addition to looking at the first law effects of the multi-effect distillation, where the *quantity* of energy is considered, it is also interesting to look at second law effects, where the *quality* of energy is determined. The latter is particularly interesting in a plant setting.

When integrating distillation columns by multi-effect we increase the pressure levels in order to integrate a condenser of one column with the reboiler of another column. This increase in pressure results in an increase of the temperature span between where the heat is supplied (reboiler) and where it is removed (condenser). This is illustrated in Fig. 8 where the temperature span between the reboilers and condensers is plotted against the required heat duties. This is, in terms of energy, the drawback of multi-effect integration.

As we can see from Fig. 8 the heat in the PF arrangement has to be supplied at a much higher temperature than the heat for the base case. The result of this is that if the required hot utility is supplied at the exact required temperature (+temperature difference to drive the heat transfer), then in the case of the PF arrangement we would degrade a higher quality

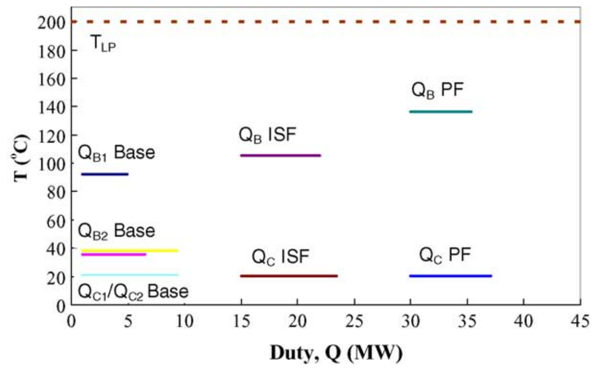


Fig. 8. Temperature/duty plot for infinite number of stages.

heat than in the other cases. The effect of this is seen clearly when comparing the *thermodynamic efficiency* of the three arrangements.

To find the thermodynamic efficiencies we calculate the *ideal minimal work* and the *total added work* for the three different distillation cases.

The ideal (reversible, minimum) work for the surroundings at constant T_0 is defined as

$$W_s^{id} \triangleq \Delta H - T_0 \Delta S \tag{1}$$

The enthalpy H and entropy S were found from the simulation for all streams and the ideal work was calculated. This ideal work needs to be compared with the actual work. In distillation, "work" is supplied indirectly through heating and cooling, which theoretically can be obtained from the surroundings by the use of heat pumps. Thus, the "actual" work W_s for any ideally integrated distillation column is obtained as the work needed for heat pumps to take the various heats from temperature T_0 to the actual temperature:

$$W_s = \sum Q_{R,i}\left(1 - \frac{T_0}{T_{R,i}}\right) + \sum Q_{C,i}\left(1 - \frac{T_0}{T_{C,i}}\right) \tag{2}$$

where $T_{R,i}$ is the temperature of reboiler i and $T_{C,i}$ is the temperature level in condenser i. The thermodynamic efficiency, η_{eff}, is then found from:

$$\eta_{eff} = \frac{W_s^{id}}{W_s} \tag{3}$$

The thermodynamic efficiency calculated for the three cases are shown in Table 6. Note that we are here considering the columns alone, with the assumption of ideal integration using heat pumps. As expected, due to the larger temperature span in the PF case this arrangement has the lowest efficiency. The base case has the highest efficiency while the ISF case lies between the two.

Table 6
Thermodynamic efficiencies using ideal utility temperature levels

	Base case	ISF	PF
Actual number of stages (%)	21.2	15.5	8.4
Infinite number of stages (%)	22.9	16.5	14.0

So, does this mean that the PF arrangement is not a good option? No, because the exergy analysis assume "ideal integration" with the background process. In an actual setting, for example the actual plant used in this case study, a comparison based on *energy* is much more relevant. This follows because the utility levels are such that the same hot and cold utility will be used in all cases.

7. Discussion of some practical issues

As indicated by the results in Section 4 using the existing number of stages for the PF system is not sufficient for it to be close to the V_{min} target. By increasing the number of stages the energy consumption can be reduced so that it is closer to the minimum. There are limitations on increasing the number of stages, however, in terms of height of the column. If a prefractionator arrangement requires a large number of stages this may mean that the column(s) would have to be divided in two. Alternatively, it may be possible to use high efficiency packing. Both of these options would result in higher capital costs.

The issue of capital cost has not been discussed here. Instead the focus is on the minimum vapour flowrate requirement as a target (indirectly a measure of operating costs). This target is independent of variations of energy prices and other cost factors. However, when looking at a practical design it is necessary to look at *both* the capital and operating costs. This important issue of *total annual cost* has been discussed for multi-effect arrangements by Emtir et al. [12], where the savings in total annual costs are compared for high and low energy prices. They found that for the three feed cases analysed the integrated prefractionator columns (PF/PB) gave high savings. For the case of high amount of middle component B in the feed the PF/PB structures gave the highest savings.

Another issue that has not been discussed, except for the exergy in Table 6, is the integration of the columns with the rest of the process. Using pinch methods the overall process, including the distillation columns can be integrated to give the lowest overall energy consumption. However, in practice this integration with distillation columns may be difficult as integrating a column with the rest of the plant may lead to problems in terms of operation and control. To look at the distillation columns as a separate entity may be easier in practice than integrating with the rest of the plant in a heat exchanger network.

Other issues that have to be considered when integrating the columns in a multi-effect fashion are the controllability and operability. Integrating two or more columns will lead to a loss in the number of degrees of freedom for control. The control and dynamic issued should therefore be carefully investigated. Integration may also lead to a loss of flexibility, e.g. in distillation of different products using the same columns.

8. Conclusion

Four industrial distillation columns in sequence have been studied to see if any two were suitable for integration using a multi-effect prefractionator. The methods presented in Engelien and Skogestad [4] were used to screen three integrated cases to find the case most suitable for integration, in terms of energy consumption. $V_{\min}$-diagrams were presented for all three cases. From the shortcut comparisons it was found that the multi-effect prefractionator arrangement would have the highest energy savings for all cases.

Based on the shortcut analysis the best case was selected for further analysis using a commercial rigorous simulation program (HYSYS). The rigorous simulations were carried out for the original base case, a multi-effect indirect split arrangement (ISF) and a multi-effect prefractionator arrangement. Using the number of stages in the existing columns it was found that the ISF arrangement had the highest energy savings (43%). It was concluded that the PF arrangement required more stages in order to get closer to the minimum vapour flow target ($V_{\min}$). An important point however, is that the assumption of $V_{\min}$ at infinite number of stages is not an unrealistic target since the actual value of V is close to $V_{\min}$ if we are allowed to add stages. At infinite number of stages the results from the rigorous simulations showed that the PF arrangement was the best with savings of 57% compared with the IS arrangement.

A comparison of the base case, ISF and PF arrangement was also made in terms of thermodynamic efficiency. In the ideal case, where the temperature levels of the reboilers and condensers were used in the analysis it was found, as expected, that the efficiency of the integrated prefractionator arrangement is lower than the non-integrated case. For an ideal integration it is therefore not good to consider the integrated prefractionator arrangements. However, when looking at the practical case where the hot utility is supplied at a set temperature level then the energy consumption is the governing factor. The integrated prefractionator arrangements are then high energy saving solutions that should be considered.

The main conclusion from this study is that a multi-effect arrangement can be a good option for an actual industrial distillation, especially in terms of energy consumption. The study showed that in practice, due to the limitations of an already existing plant (i.e. number of stages), if a retrofit were to be carried out then the forward-integrated indirect split arrangement (ISF) would be a good option. If however, a new plant were to be built then the integrated prefractionator arrangement (PF) should be considered as an option as it has the highest potential for energy savings. Rigorous simulations studying the control and dynamic properties would naturally have to be considered in detail.

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