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Dynamic Study of Thermally Coupled Distillation Sequences Using Proportional – Integral Controllers

Juan Gabriel Segovia-Hernández[a], Salvador Hernández[b], Vicente Rico-Ramírez[a] and Arturo Jiménez[a]
[a]Instituto Tecnológico de Celaya, Departamento de Ingeniería Química, Av. Tecnológico y García Cubas s/n, Celaya, Gto., 38010, México.
[b]Universidad de Guanajuato, Facultad de Química, Noria Alta s/n, Guanajuato, Gto., 36050, México, hernasa@quijote.ugto.mx

Abstract

A comparative study of the energy requirements and control properties of three thermally coupled distillation schemes and two conventional distillation sequences for the separation of ternary mixtures is presented. The responses to set point changes under closed loop operation with proportional–integral (PI) controllers were obtained. Three composition control loops were used, and for each separation scheme, the parameters of the PI controllers were optimized using the integral of the absolute error criterion. The effects of feed composition and of the ease of separability index were considered. The results indicate that there exist cases in which integrated systems may exhibit better control properties than sequences based on conventional distillation columns.

1. Introduction

Distillation process, the most widely-used separation method in industry, is characterized by its high energy consumption. Alternate arrangements to the conventional distillation columns (one input, two outputs) have received noticeable attention in recent years. Through the use of recycle streams between two columns, several thermally coupled distillation systems have been proposed. The three thermally coupled systems that have been analyzed to a greater extent are the system with side rectifier (TCDS-SR, Figure 1a), the system with side stripper (TCDS-SS, Figure 1b), and the fully thermally coupled distillation system (or Petlyuk column, Figure 1c). Several studies have shown that those TCDS schemes can save up to 30% on energy consumption with respect to the direct and indirect sequences based on conventional columns (Tedder and Rudd, 1978; Alatiqi and Luyben, 1985; Glinos and Malone, 1988; Fidkowski and Krolikowski, 1991; Finn, 1993; Yeomans and Grossmann, 2000). Most of these results were obtained through energy consumption calculations at minimum reflux conditions, and they spawned the development of more formal design procedures. Hernández and Jiménez (1996, 1999a) have reported the use of optimization strategies for TCDS to detect designs with minimum energy consumption. When comparing the energy savings of the integrated schemes, it has been found that in general the Petlyuk system offers better savings than the systems with side columns. However, the complex column configurations that can potentially produce larger energy savings are not commonly used in industrial practice, largely because of control concerns (Dunnebier and Pantelides, 1999). Recent research efforts have been conducted to understand the operational properties of TCDS. The works of Wolff and Skogestad (1995), Abdul-Mutalib and Smith (1998), Hernández and Jiménez (1999b) and Jiménez et al. (2001) have shown that some of these integrated options are controllable, so that their potential implementation would probably not be at the expense of control problems. In this work, we present an analysis on the closed loop behavior of three TCDS, and compare their responses to those of the conventional direct and indirect distillation sequences. The analysis is based on rigorous dynamic simulations using changes in set points of product compositions.

2. Design procedure

The design of the three TCDS under consideration was carried out following the procedure suggested by Hernández and Jiménez (1996, 1999a). The method provides a tray structure for the integrated systems by a section analogy procedure with respect to the design of a conventional sequence; the TCDS-SR is obtained from the tray arrangements of a direct sequence, the TCDS-SS from an indirect sequence, and the Petlyuk system from a sequence of a prefractionator followed by two binary distillation columns. The degrees of freedom that remain after design specifications (one degree of freedom for the systems with side columns, and two for the Petlyuk system) were used to obtain the operating conditions under which the integrated designs provide minimum energy consumption.

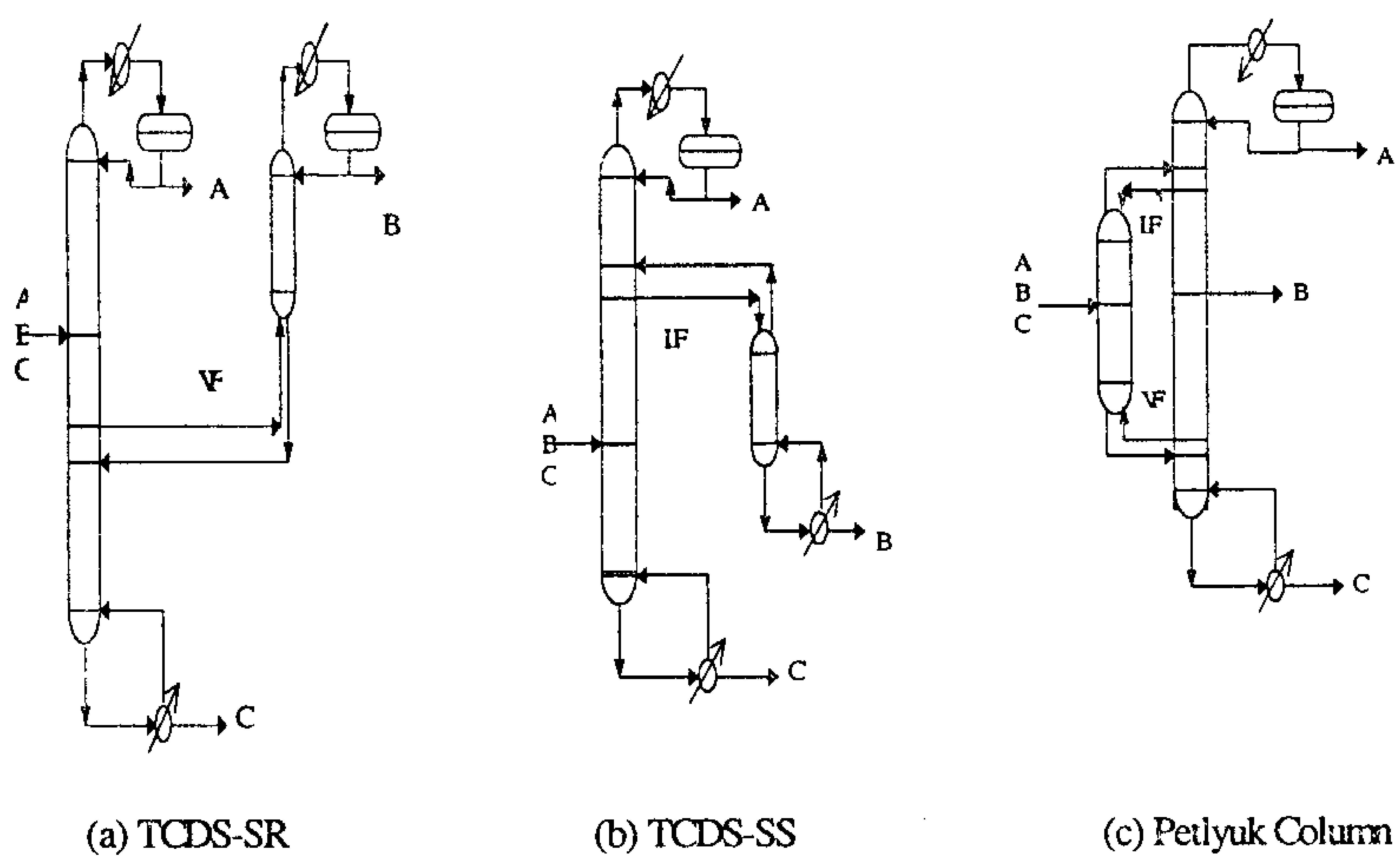


Figure 1. Thermally coupled distillation sequences.

The search procedure provided the optimal values of the interconnecting vapor flowrate (VF) for the TCDS-SR (Figure 1a), the interconnecting liquid flowrate (LF) for the TCDS-SS (Figure 1b), or both streams for the case of the Petlyuk column (Figure 1c). Rigorous simulations, using the dynamic model developed by Hernández and Jiménez (1996), were conducted to test the designs. The model is based on the total mass balance, component mass balances, equilibrium relationships (assuming ideal VLE), summation constraints, energy balance and stage hydraulics (Francis weir formula). Because of the coupling between the columns, the set of equations must be solved simultaneously.

3. Dynamic Simulations and Case Studies

Although more formal techniques to define the control loops for the integrated columns may be used (for instance the relative gain array method), we based our selection on practical considerations. Thus, the control of the lightest component was manipulated with the reflux flowrate, the heaviest component with the reboiler heat duty, and the control of the intermediate component was a function of the integrated structure; for the TCDS-SR it was tied to the reflux flowrate of the side rectifier, for the TCDS-SS to the heat duty of the side stripper, and for the Petlyuk column to the product stream flowrate. The closed loop analysis was based on proportional-integral controllers. The parameters of the controllers, proportional gains (K_C) and the reset times (τ_i), were optimized for each conventional and integrated scheme following the integral of the absolute error (IAE) criterion. The case studies were selected to reflect different separation difficulties and different contents of the intermediate component of the ternary mixtures. Three mixtures with different values of the ease of separability index (ESI, the ratio of relative volatilities of the split AB to the split BC, as defined by Tedder and Rudd, 1978) were considered. The selected mixtures were n-pentane, n-hexane and n-heptane (M1, ESI = 1.04), n-butane, isopentane and n-pentane (M2, ESI = 1.86), and isobutane, n-butane and n-hexane (M3, ESI = 0.18). To examine the effect of the content of the intermediate component, two types of feed compositions were assumed. One feed with a low content of the intermediate component (where mole fractions of A, B, C, were equal to 0.40, 0.20, 0.40, feed F1) and another one with a high content of the intermediate component (A, B, C equal to 0.15, 0.70, 0.15, feed F2), were used. The total feed flowrate for all cases was 45.5 kmol/h. Specified product purities of 98.7, 98 and 98.6 percent for A, B and C respectively were assumed.

4. Energy Requirements

The results on energy requirements reflect the optimization procedure carried out on the recycle streams for the three integrated sequences.

4.1. Mixture M1

Table 1 shows the energy requirements for each integrated scheme and conventional sequences when mixture M1 was considered. The Petlyuk system shows the best potential, offering savings in energy consumption of up to 50% with respect to the conventional distillation sequences. The TCDS-SR and TCDS-SS require between 14 and 20% less energy consumption than the conventional sequences.

4.2. Mixtures M2 and M3

The superior behavior on energy efficiency of the Petlyuk column was also observed for mixtures M2 and M3 (Segovia-Hernández, 2001). In the case of mixture M2 the Petlyuk column can offer savings in energy consumption of up to 15% with respect to the conventional sequences, while the savings achieved by the TCDS-SR and TCDS-SS schemes are in the order of 10%. In the case of mixture M3 the Petlyuk column requires between 40 and 50% less energy consumption, whereas the TCDS-SR and the TCDS-SS options offer energy savings of up to 30% with respect to the conventional sequences.

Table 1. Energy requirements (Btu/h) for separating mixture M1.

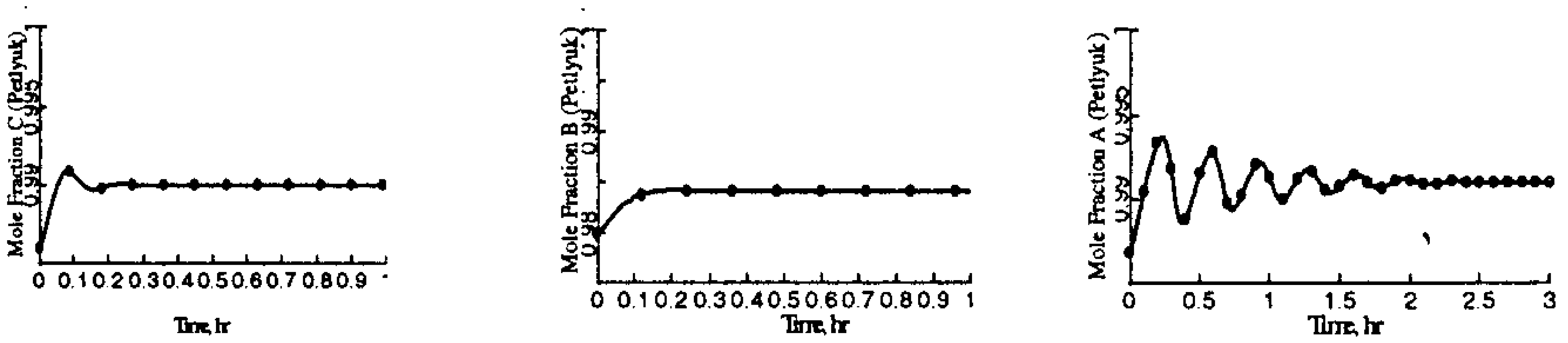
Feed	Direct Sequence	Indirect Sequence	TCDS-SR	TCDS-SS	Petlyuk column
F1	3,263,772.2	3,547,190.0	2,521,007.0	2,730,465.2	1,709,474.1
F2	4,127,083.9	4,356,343.8	3,167,085	3,511,610.3	2,142,722.5

5. Dynamic Results

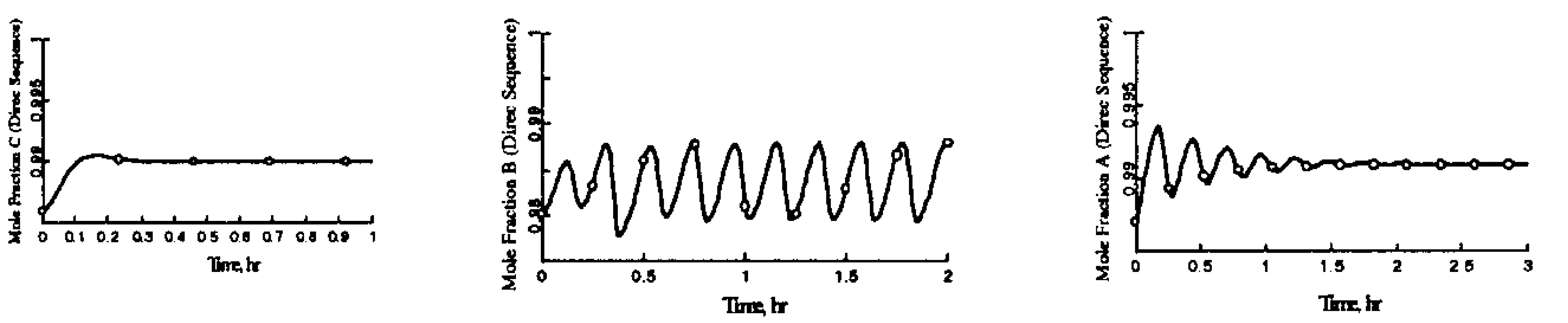
The dynamic analysis was based on individual set point changes for product composition on each of the three product streams. The three control loops for each conventional and integrated sequence were assumed to operate under closed loop fashion.

5.1. Mixture M1, composition F1

Table 2 shows the IAE values obtained for each composition control loop of the distillation sequences under analysis. It is observed that the Petlyuk column offers the best dynamic behavior, which is reflected in the lowest values of IAE, for the control of the three product streams. The dynamic response of each control loop when the Petlyuk column was considered is displayed in Figure 2, where a comparison can be made to the response obtained with the widely-used direct sequence. One may notice in particular how the direct sequence is unable to control the composition of the intermediate component, while the Petlyuk column provides a smooth response, with a relatively short settling time. It is interesting to notice that for this mixture with an ESI = 1, and a low content of the intermediate component in the feed, the Petlyuk column offers the highest energy savings and also shows the best dynamic performance from the five distillation sequences under consideration.



a) Component C (Petlyuk) b) Component B (Petlyuk) c) Component A (Petlyuk)



d) Component C (Direct sequence) e) Component B (Direct sequence) f) Component A (Direct sequence)

Figure 2. Dynamic responses of the Petlyuk column and the direct sequence.

5.2. Mixture M1, composition F2

When the content of the intermediate component in the feed was raised from 20 to 70 percent, significant changes in the dynamic responses of the distillation systems were observed. The first remark is that the Petlyuk column does not provide the best choice from an operational point of view. A second observation is that the best choice depends on the control loop of primary interest. When the control of the light (A) or the heavy (C) component of the ternary mixture is of primary concern, then the TCDS-SS scheme provides the best option since it offers the lowest IAE values for these control loops.

However, if the control policy calls for the composition of the intermediate (B) component, the indirect sequence shows the best behavior, with the lowest value of IAE. Overall, it may be stated that for this type of mixture, the TCDS-SS may offer a good compromise, providing energy savings with respect to conventional sequences and good dynamic properties.

Table 2. IAE results for mixture M1, composition F1.

Sequence	Component A	Component B	Component C
Direct	7.92441×10^{-3}	5.28568×10^{-2}	2.95796×10^{-3}
Indirect	4.0076×10^{-3}	3.4576×10^{-3}	2.64873×10^{-3}
TCDS-SR	3.55963×10^{-3}	2.78147×10^{-3}	7.99529×10^{-4}
TCDS-SS	7.69839×10^{-4}	8.9876×10^{-3}	3.80888×10^{-4}
Petlyuk	1.74924×10^{-4}	3.42972×10^{-4}	2.10607×10^{-4}

5.3. Other mixtures

The analysis was completed with the consideration of the other four case studies. Some trends were observed. For one thing, the best option depends on the amount of intermediate component. Also, it was found that the best sequence, based on the IAE criterion, for the control of the light component was also the best choice for the control of the heavy component, but a different separation scheme provided the best option for the control of the intermediate component. If the feed contains low amounts of the intermediate component, the Petlyuk column shows the best dynamic behavior for the control of the light and heavy components, while the indirect sequence provides the best responses for the control of the intermediate component. For feed mixtures with high content of the intermediate component, sequences with side columns showed the best responses for the control of light and heavy components, and conventional sequences were better for the control of the intermediate component. The ease of separability index also shows some effect on the topology of the preferred separation scheme when the feed contains a high amount of the intermediate component. For mixtures with ESI higher than one, the systems with two bottom streams (integrated or conventional) show the best dynamic properties, while for mixtures with ESI lower than one, the separation systems with two top distillate streams (TCDS-SR or the direct sequence) provide the best dynamic responses.

Table 3 summarizes the optimal options detected from the dynamic analysis for all case studies. The only case in which there was a dominant structure for all control loops was when the feed contained low amounts of the intermediate component and an ESI value of 1, and the Petlyuk column provided the optimal choice in such a case.

Table 3. Sequences with best dynamic responses for each control loop.

	Feed with low content of intermediate component		Feed with high content of intermediate component	
Mixture	Control of A and C	Control of B	Control of A and C	Control of B
M1	Petlyuk	Petlyuk	TCDS-SS	Indirect
M2	Petlyuk	Indirect	TCDS-SS	Indirect
M3	Petlyuk	Indirect	TCDS-SR	Direct

6. Conclusions

We have conducted a comparison on energy requirements and on the dynamic behavior of five distillation sequences for the separation of ternary mixtures. Three of the sequences considered make use of thermal coupling, and their energy and control properties have been compared to those of the conventional direct and indirect sequences. From energy considerations the Petlyuk column shows generally the highest savings. The dynamic analysis was based on optimal PI controllers for all sequences, according to the IAE criterion. The results from the dynamic analysis do not show a dominant option, but interesting trends were observed. Two factors seem to affect the optimal choice from dynamic considerations. One is the amount of intermediate component, and the other one is the preferred control policy, i.e. which component of the ternary mixture is the most important from operational or marketing purposes. When the control of the lightest or heaviest component is of primary interest, integrated sequences provide interestingly the best options. When the amount of intermediate component is low, the Petlyuk column provided the best dynamic performance; when the amount of intermediate component is high, the integrated sequences with side columns showed the best dynamic results. On the other hand, when the control of the intermediate component is the desired strategy, the energy savings provided by the integrated sequences conflict with their control properties, since the conventional sequences offered generally the best dynamic responses (also interestingly, the indirect sequence was the best option most of the times.) In summary, although the best operational option is not unique, the results show that there are cases in which integrated sequences do not only provide significant energy savings with respect to the conventional sequences, but also may offer some dynamic advantages.

7. References

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8. Acknowledgements

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