A Short Note on Control Structures for Thermally Coupled Distillation Sequences for Four-Component Mixtures

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Thermally coupled distillation represents an alternative to conventional distillation to separate multicomponent mixtures. Industrial implementation of those systems can be achieved by using the divided-wall distillation column. It has been proven that a savings of up to 30% in the total annual costs can be obtained with these complex distillation sequences. In a previous work by Cárdenas et al. (Cárdenas, J. C.; Hernández, S.; Gudiño-Mares, I. R.; Esparza-Hernández, F.; Irianda-Araraujo, C. Y.; Domínguez-Lira, L. M. Analysis of Control Properties of Thermally Coupled Distillation Sequences for Four-Component Mixtures. *Ind. Eng. Chem. Res*. **2005**, *44*, 391−399), it was found that thermally coupled distillation sequences not only can provide savings in the total annual costs but also can present good dynamic responses under closed-loop operation in contrast to distillation sequences based on conventional columns. In the previous study, pairings in the control loops were established according to practical considerations, i.e., distillate composition−reflux rate, bottoms composition−reboiler heat duty, and side-stream purity−flow rate. As a result, in this work some new pairings in the control loops, obtained by using the relative gain array, were tested in order to improve the dynamic responses of the thermally coupled distillation sequences for the separation of quaternary mixtures of hydrocarbons. The results showed that the dynamic responses were improved significantly for the case of changes in the set points. As a result, savings in total annual costs can be achieved without introducing control problems.

Introduction

Conventional distillation trains are characterized by their large demands of energy in the reboilers;[1] as a result, researchers and engineers are interested in developing new distillation arrangements that can reduce energy consumption. One method that has been used for this purpose consists of using thermally coupled distillation schemes, which, in the case of the separation of ternary mixtures, can decrease energy requirements around 30% in contrast to conventional distillation trains.[2−12] Thermal links reduce remixing in conventional distillation sequences, which contributes to the energy savings achieved by thermally coupled distillation sequences (Triantafyllou and Smith[4] and Hernández et al.[13]). Mixtures with more than three components have not been studied to the same degree as ternary mixtures have.[14,15] It is well-known that the separation of a quaternary mixture can be done by using the five conventional distillation trains[16] shown in Figure 1. Parts A and B of Figure 1 show two classical distillation trains: the direct distillation train, in which the components are removed one by one in the overheads, and the indirect distillation train, in which the components are obtained one by one in the bottoms products. These conventional distillation sequences are widely used in the industry. Two thermally coupled distillation schemes can be used in order to improve the separation task. Figure 2 shows a Petlyuk-type column, which is useful because it can be implemented in a single shell, reducing both energy and capital costs. Typical energy and capital savings of 30% are obtained with this column. BASF has implemented this kind of thermally coupled distillation sequence in the industry by using the divided-wall distillation column; recently Kaibel and Schoenmakers[17] have reported that BASF has implemented the biggest thermally coupled distillation column in a Fischer−Tropsch plant.

The thermally coupled distillation sequence with side columns (Figure 3) is important because it offers additional energy savings through the use of both thermal links and heat integration, as indicated in Figure 4. These two thermally coupled distillation sequences can be obtained from the conventional distillation sequence of Figure 1D, as indicated in the work of Blancarte-Palacios et al.[18]

As reported by Rong et al.,[12] there are many thermally coupled distillation sequences for the separation of quaternary mixtures. We have selected two thermally coupled distillation sequences that, in principle, can be more easily implemented: the TCDS-SR/SS (Figure 3) and the Petlyuk-type column (Figure 2). The Petlyuk-type column can be implemented through the divided-wall column proposed by Kaibel and Schoenmakers.[17] Also, for the case of the separation of three or more component mixtures, Halvorsen and Skogestad[19−22] have used diagrams of the minimum vapor generated in the reboiler in order to achieve the separation at minimum reflux conditions and have found that

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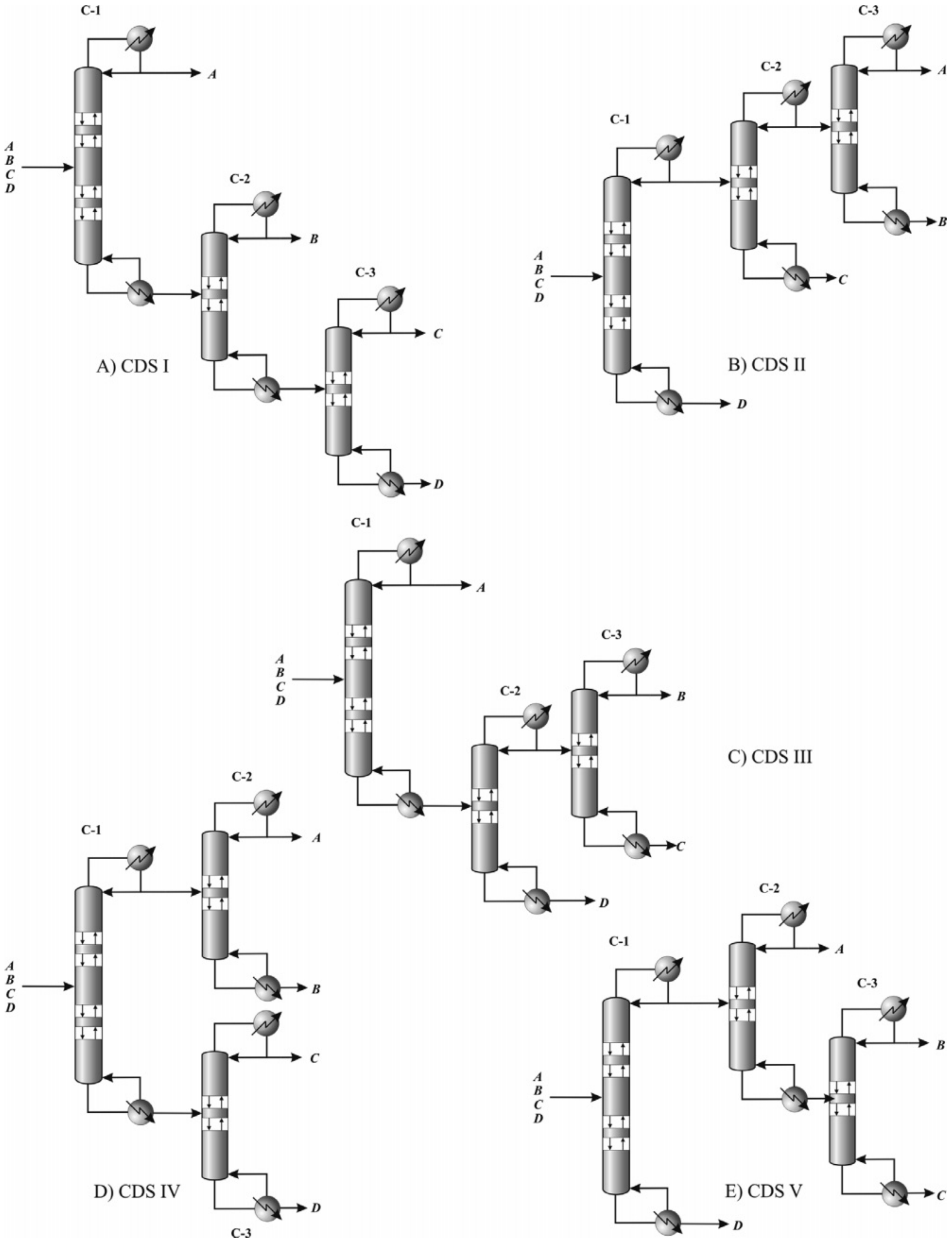

Figure 1. Conventional distillation sequences for the separation of quaternary mixtures.

Petlyuk-type schemes present the largest energy savings (around 40%). The Petlyuk-type option can reduce both energy and capital costs.

In some papers, it has been reported that the thermally coupled distillation schemes can outperform the dynamic responses of the conventional distillation sequences.[6,9] As a result, the dynamic responses of the thermally coupled distillation sequences of Figures 2 and 3 are studied under the action of proportional–integral (PI) controllers for some pairings in the control loops obtained by using the relative gain array (RGA).

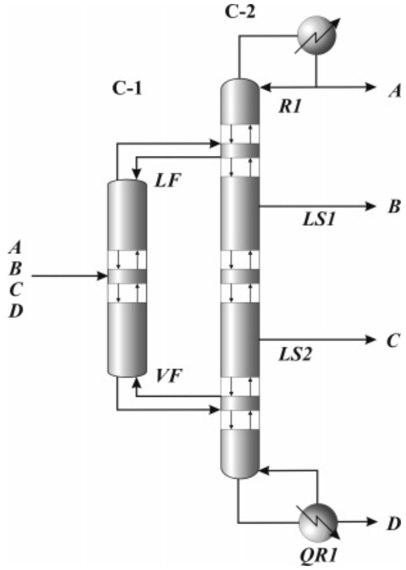

Figure 2. Thermally coupled distillation sequence (Petlyuk-type column, TCDS-PR).

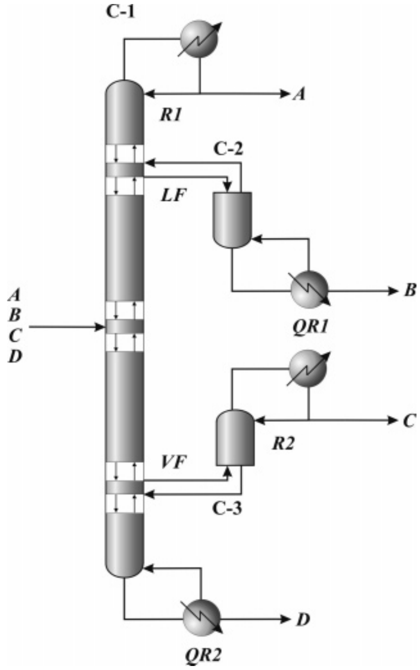

Figure 3. Thermally coupled distillation sequence with side columns (TCDS-SR/SS).

Design of Thermally Coupled Distillation Sequences

To study the control strategies in the TCDS options, energy-efficient designs were obtained by using the method described in the work of Blancarte-Palacios et al.[18] The design strategy of the TCDS schemes requires two stages.

In the first part, the number of stages, feed stage, and reflux ratio are obtained for each column by using the shortcut distillation method of Fenske–Underwood–Gilliland implemented in the process simulator Aspen Plus 11.1. In this part, distillation columns are designed considering reflux ratios equal to 1.33 times the minimum reflux ratios.

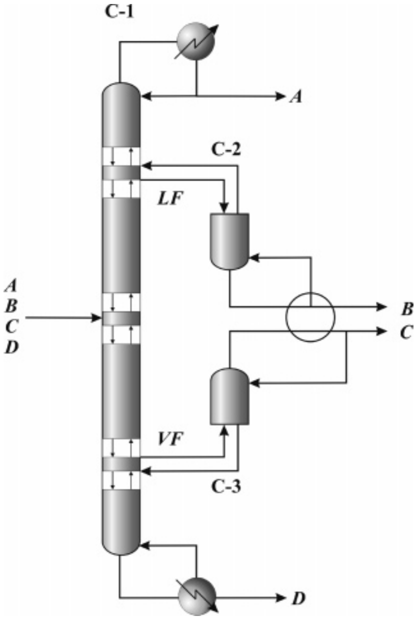

Figure 4. Thermally coupled distillation sequences with side columns and heat integration.

In the second stage, the tray sections of the TCDS schemes are obtained directly from the conventional distillation sequence (Figure 5). As can be seen in Figure 5, two recycle streams are introduced in the TCDS options, which are set to guarantee the minimum energy consumption in the reboilers. When the recycle streams are varied in order to obtain the minimum energy consumption, four design specifications are established to adjust the product compositions to the desired values.

Dynamic Simulations

After the energy-efficient designs were obtained, open-loop dynamic simulations were carried out in Aspen Dynamics 11.1 in order to obtain the transfer function matrix. The transfer functions were generated by implementing very small step changes (0.5%) in each of the manipulated variables (reflux rate, reboiler heat duty, and side-stream flow rate) and recording the dynamic behavior of the four product compositions (A–D). The dynamic responses were adjusted to first, first plus dead time, second, or parallel processes by using standard methods reported by Stephanopoulos.[23] The complete transfer function matrices are reported in the work by Cárdenas et al.[24] Four feedback control loops to control the product compositions were implemented. PI controllers were considered and tuned to minimize the Integral of the Absolute Error (IAE) of the product compositions for a positive set-point change. As reported in the work of Cárdenas et al.,[24] a perfect control level was assumed and PI controllers for the pressure were considered. The four control loops were tuned one by one.

Case Study

We have considered the case of study of the separation of an equimolar four-component mixture of *n*-pentane, *n*-hexane, *n*-heptane, and *n*-octane, with a feed flow rate of 45.5 kmol/h as a saturated liquid at 23.6 psia. There was a fixed design pressure of 21.1 psia in all columns in order to use cooling water in the condensers. The complete design and optimization variables (number of stages, interconnection stages, reflux ratios, heat duties, and residence times) are reported in the work of Cárdenas et al.[24]

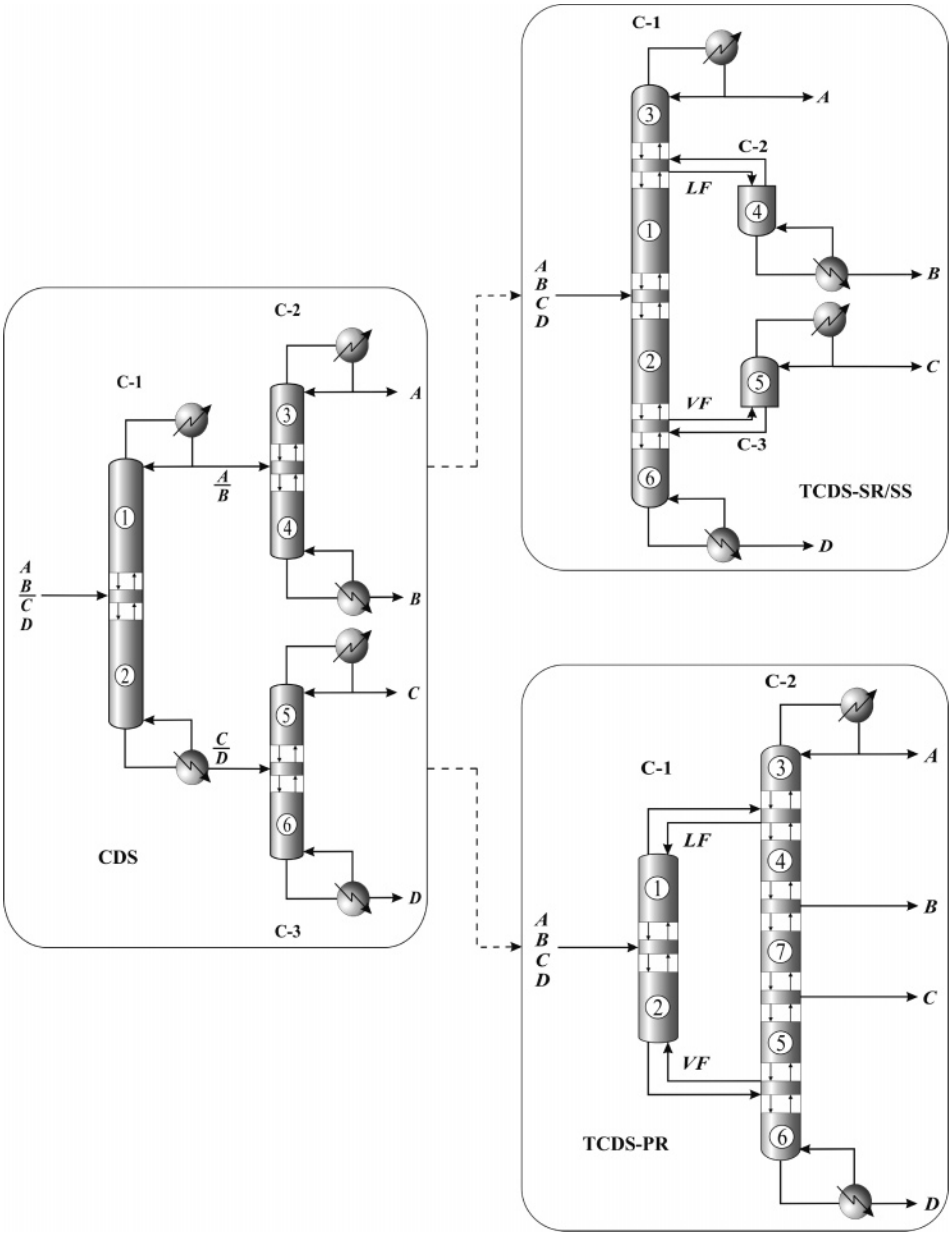

Figure 5. Design of the thermally coupled distilllation sequences.

Table 1. Control Strategies for the TCDS Sequences

	manipulated variable		
	TCDS-SR/SS		TCDS-PR
controlled variable	RGA_1	RGA_2	RGA_1
A	R2	QR2	LS1
B	QR1	QR1	LS2
C	QR2	R2	R1
D	R1	R1	QR1

Discussion of Results

In the case of TCDS-SR/SS, three control schemes were analyzed. The first one uses the reflux rate to control the composition of the distillate and the heat duty supplied to the reboiler to control the bottoms composition. The last two control structures, reported in Table 1, are obtained through the use of the results of the RGA presented in the work of Cárdenas et al.[24] When the RGA was applied to the TCDS-PR scheme, only one possibility was obtained, which is indicated in Table 1.

In the case of TCDS-SR/SS, Figure 6 shows the dynamic responses for a positive set-point change of magnitude of 0.005 in component A. As we can see, the dynamic responses of the conventional coupling and the RGA_1 are very similar because they reach the new steady state approximately at the same time and both present oscillations. In contrast, the dynamic response obtained with the control structure RGA_2 is better than the previous two responses because no oscillations are presented and the time to adjust the composition is very short. When the analysis was extended for changes in the set points in components B−D (Figures 7−9), the dynamic responses are similar to those obtained in component A. The dynamic responses for the control structure RGA_2 (Table 1) are significantly better than the others. This result is important because previously it has been reported that the thermally coupled distillation sequences can have theoretical control properties similar to those of conventional distillation sequences.[24] Moreover, in some cases the dynamic responses of the TCDS options outperformed those of the conventional

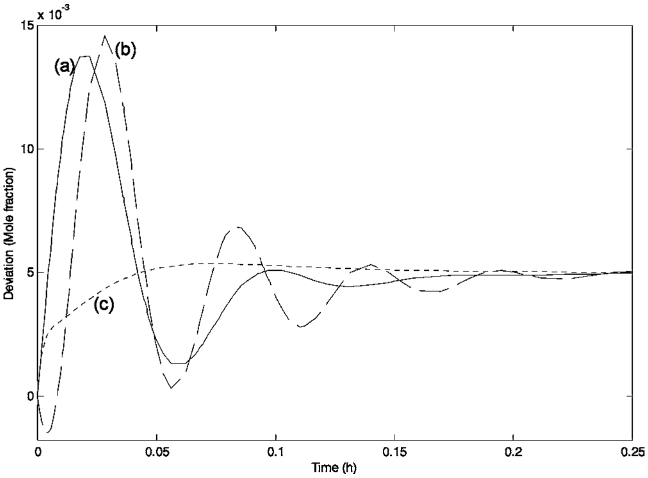

Figure 6. Dynamic responses in component A for a positive set-point change: (a) conventional; (b) RGA_1; (c) RGA_2. TCDS-SR/SS option.

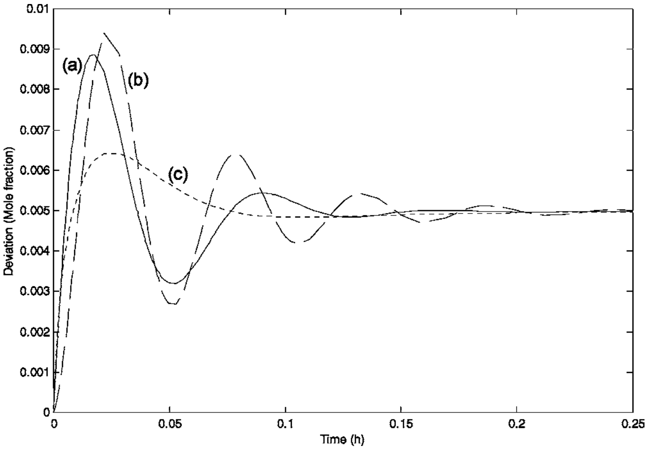

Figure 7. Dynamic responses in component B for a positive set-point change: (a) conventional; (b) RGA_1; (c) RGA_2. TCDS-SR/SS option.

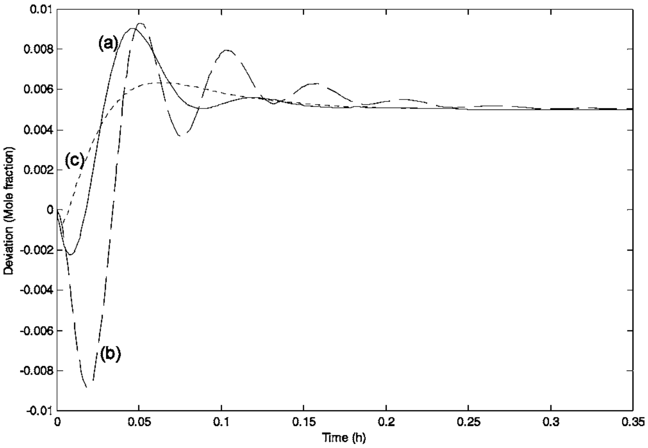

Figure 8. Dynamic responses in component C for a positive set-point change: (a) conventional; (b) RGA_1; (c) RGA_2. TCDS-SR/SS option.

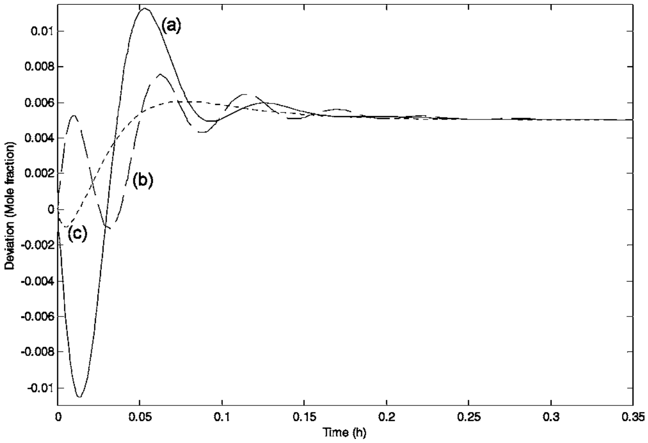

Figure 9. Dynamic responses in component D for a positive set-point change: (a) conventional; (b) RGA_1; (c) RGA_2. TCDS-SR/SS option.

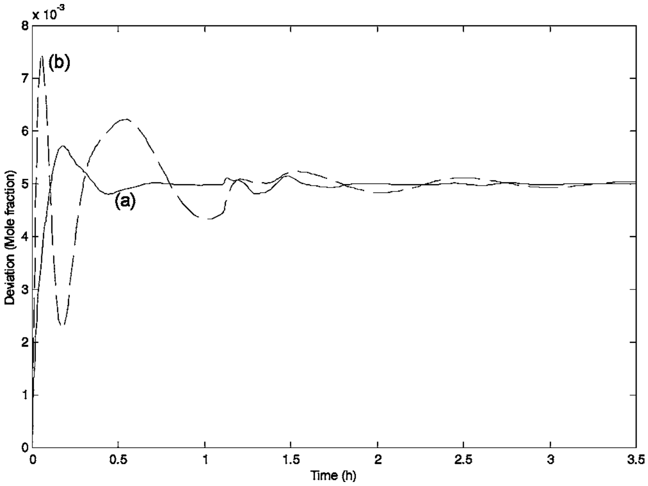

Figure 10. Dynamic responses in component A for a positive set-point change: (a) conventional; (b) RGA_1. TCDS-PR option.

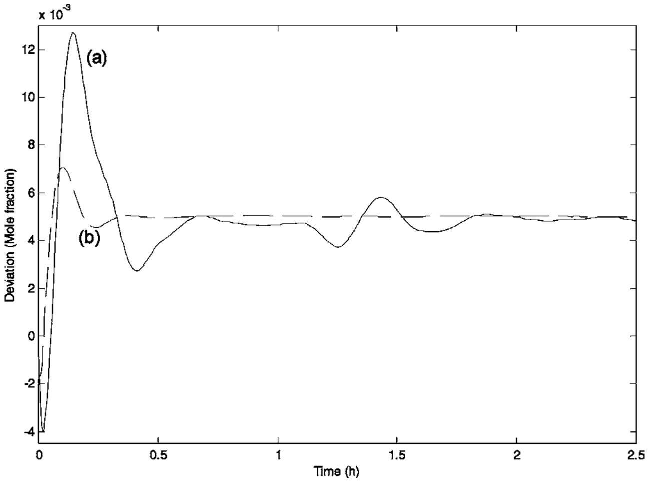

Figure 11. Dynamic responses in component B for a positive set-point change: (a) conventional; (b) RGA_1. TCDS-PR option.

distillation sequences when they were studied under the action of PI controllers in the feedback fashion. As a result, we can improve the dynamic responses of the TCDS options by selecting the proper pairings in the control loops.

Two possible configurations were detected for the TCDS-PR option, the conventional option, and the RGA_1 option included in Table 1. The results displayed in Figures 10−13 are very similar to those obtained in TCDS-SR/SS. The RGA_1 option presents dynamic responses that reach the new steady state faster and with less oscillations than those obtained with conventional loop pairings.

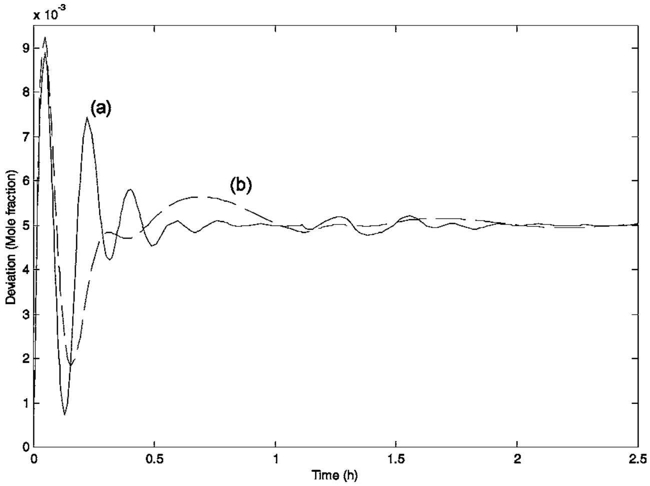

Figure 12. Dynamic responses in component C for a positive set point change: a) Conventional, (b) RGA$_1$. TCDS-PR option.

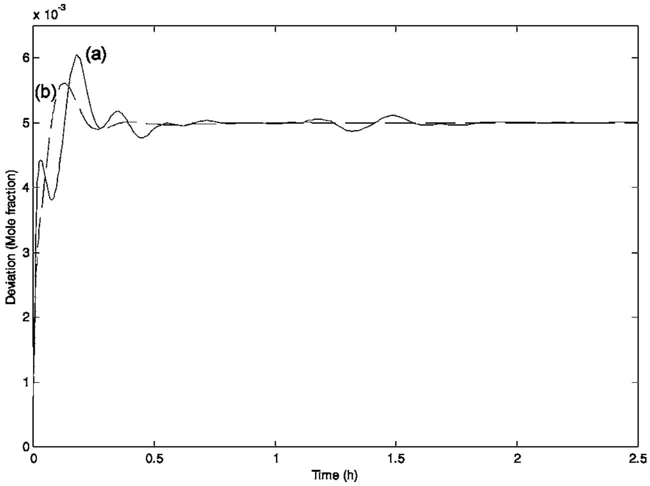

Figure 13. Dynamic responses in component D for a positive set-point change: (a) conventional; (b) RGA$_1$. TCDS-PR option.

Conclusions

We have compared dynamic responses under a closed loop in thermally coupled distillation sequences with side columns or prefractionators; we have tested conventional loop pairings in the distillation field against some couplings obtained through the use of RGA. In general, we found that the dynamic responses are better for the loop pairings predicted by using RGA. More important, however, is the fact that dynamic responses in the TCDS schemes can be improved by exploring alternative control loop pairings. Such a result motivates the practical implementation of TCDS systems and reinforces previous reports about their controllability properties because they have been shown to outperform conventional systems even with conventional loop pairings.

We have also found, for the cases of ternary[9,25] and quaternary separations,[26] that the introduction of thermal links in the distillation sequences can improve the dynamic responses; this result may be unexpected, but it has been corroborated through the use of the theoretical control properties obtained by the use of the singular value decomposition technique in the frequency domain and rigorous dynamic simulations under the action of PI controllers. This result is an incentive to promote the use of thermally coupled distillation sequences in the chemical industry.

Acknowledgment

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