IChemE
www.catchword.com/titles/02638762.htm

0263–8762/02/$23.50+0.00
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Trans IChemE, Vol 80, Part A, October 2002

CONTROL BEHAVIOUR OF THERMALLY COUPLED DISTILLATION SEQUENCES

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The controllability properties of thermally coupled distillation sequences for the separation of ternary mixtures are compared with those of the conventional direct and indirect sequences. Closed loop responses to set point changes were performed, and controllers were tuned to minimize their ISE values. The results indicate that the integrated systems exhibit better control properties than sequences based on conventional distillation columns. This result provides a further incentive for the use of those integrated systems.

Keywords: distillation; thermally coupled distillation; distillation control; energy integration

INTRODUCTION

The design of distillation systems for the separation of three component mixtures has received special attention in recent years. In particular, thermally coupled distillation systems (TCDS), such as columns with side-rectifiers (TCDS-SR, Figure 1), columns with side-strippers (TCDS-SS, Figure 2), and the Petlyuk column (Figure 3), have been subjected to special research efforts aiming to develop proper design methods and to understand their control properties. The incentive is that these integrated systems have been shown to provide energy savings of up to 30% with respect to the conventional direct and indirect sequences[1–3]. Other studies[4,5] have shown that the minimum vapor flowrate (under minimum reflux conditions) can be lowered by 50% for TCDS for feed streams that contain low amounts of the intermediate component of the ternary mixture. Wolff and Skogestad[6] and Hernández and Jiménez[7,8] have reported more formal design procedures that include 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[8].

The understanding of the control properties of TCDS is an issue of extreme importance since often designs with economic incentives conflict with their operational characteristics. Fidkowski and Krolikowski[5], among others, pointed out that, despite their energy savings, TCDS schemes may show controllability problems because of their integrated nature. The expected energy savings and its compromise with control properties have sparked the development of additional schemes to the ones presented in Figures 1–3. For instance, Agrawal and Fidkowski have reported some newer configurations for TCDS that appear to have some operational advantages over the expected dynamic properties of the designs shown in Figures 1–3[9,10]. Also, Agrawal has recently shown how TCDS configurations can be extended to include alternatives with multieffect arrangements[11] and with a reduction in intercolumn vapor transfers[12].

Controllability measures from the design stage of a process can be used to take into account the interaction between design and control[13]. In particular, through the application of singular value decomposition techniques, Hernández and Jiménez[14] compared the controllability properties of the TCDS schemes of Figures 1–3, and found that sequences with side columns offer better properties than the Petlyuk system. When these integrated schemes were compared to four other sequences based on conventional columns, Jiménez *et al.*[15] found the rather unexpected result that the theoretical control properties of the integrated sequences were better than those of the conventional schemes. These properties are independent on the controller type or its tuning parameters.

In this work, we extend the controllability analysis of TCDS and conventional distillation sequences by developing a comparative analysis of dynamic properties under closed loop operation. Rigorous dynamic simulations for set point tracking are presented.

DESIGN OF TCDS

While the direct and indirect separation sequences are based on conventional distillation columns for which design procedures are well known, design methods for integrated systems have not been developed to the same degree. In this work we use the methodology proposed by Hernández and Jiménez[7,8] for the design of TCDS with minimum energy consumption. After design specifications are given, the procedure begins with a preliminary design for the integrated system, which is obtained from the use of shortcut methods for a nonintegrated counterpart based on conventional columns (a direct and an indirect sequence for TCDS with side columns, and a prefractionator with two binary

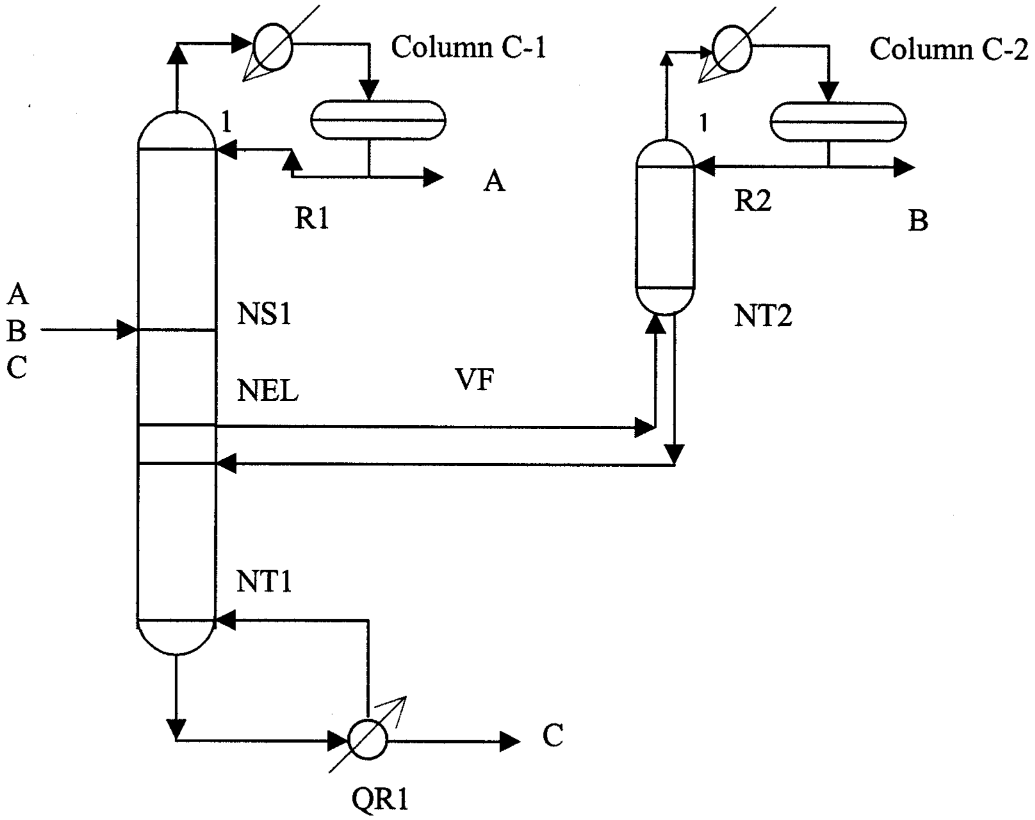


Figure 1. Column with a side rectifier and its relevant design variables (TCDS-SR).

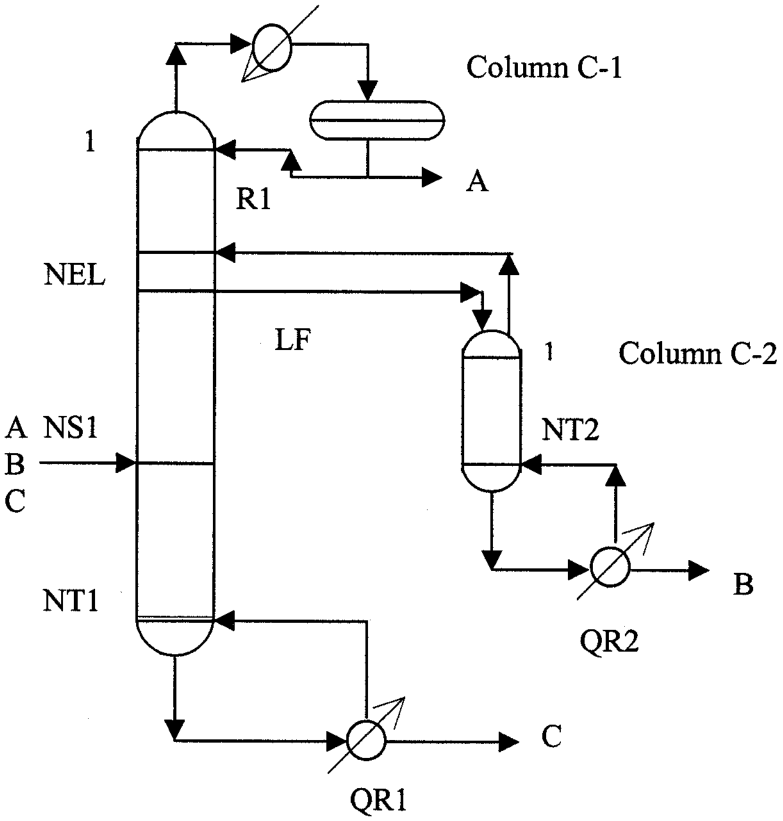


Figure 2. Column with a side stripper and its relevant design variables (TCDS-SS).

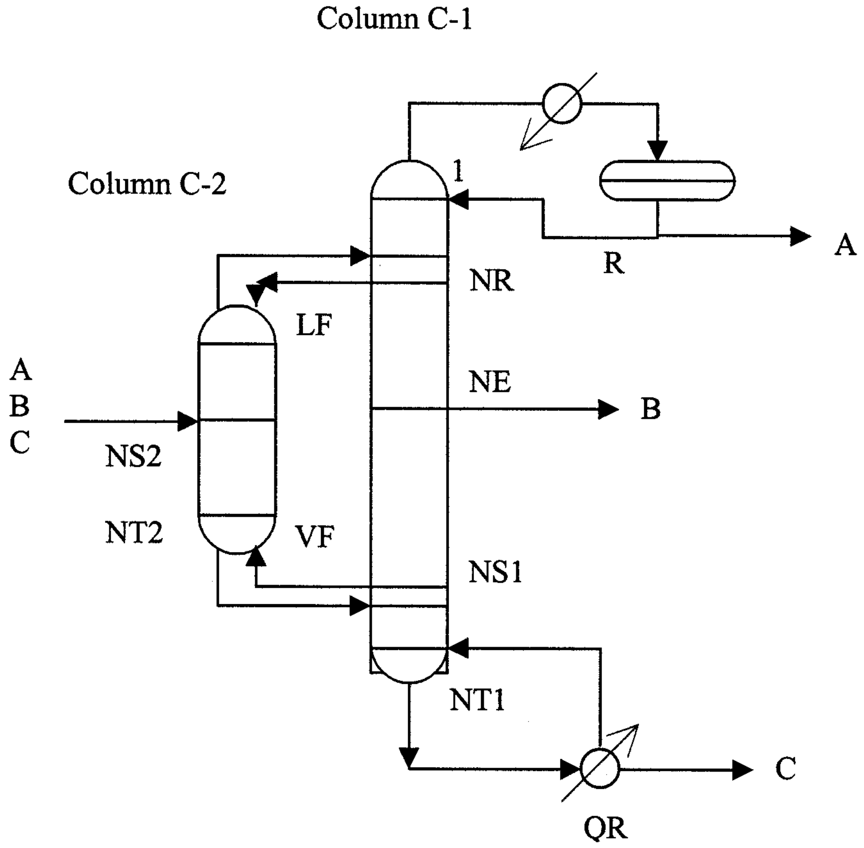


Figure 3. The Petlyuk column and its relevant design variables.

separation columns for the Petlyuk system.) Steady-state rigorous simulations using Aspen Plus 10.1 are then conducted to test the preliminary design. If the design specifications are met, the preliminary design was successful; otherwise, proper arrangements in the design are implemented until the specified product compositions are obtained. After the specification of tray arrangements (including feed and side-stream trays locations), one degree of freedom remains for the systems with side columns, and two for the Petlyuk system. The degrees of freedom for each integrated system were used within a search procedure to detect the conditions under which minimum energy consumption in the reboilers is obtained. The search procedure provided the optimal values of the interconnecting vapor flowrate (VF) for the TCDS-SR (Figure 1), the interconnecting liquid flowrate (LF) for the TCDS-SS (Figure 2), or both streams for the case of the Petlyuk column (Figure 3).

CASE STUDY

A ternary mixture of n-pentane, n-hexane and n-heptane was considered. The feed flowrate was taken as 45.5 kmol/h, with a molar composition (A, B, C) equal to 0.40, 0.20 and 0.40, respectively. Specified product recoveries of 98.7, 98 and 98.6% for A, B and C respectively were assumed.

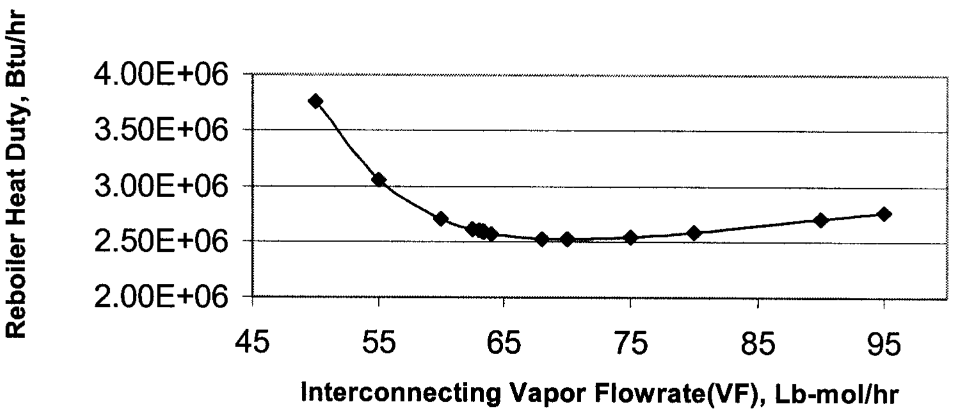


Figure 4. Search results for the column with side rectifier.

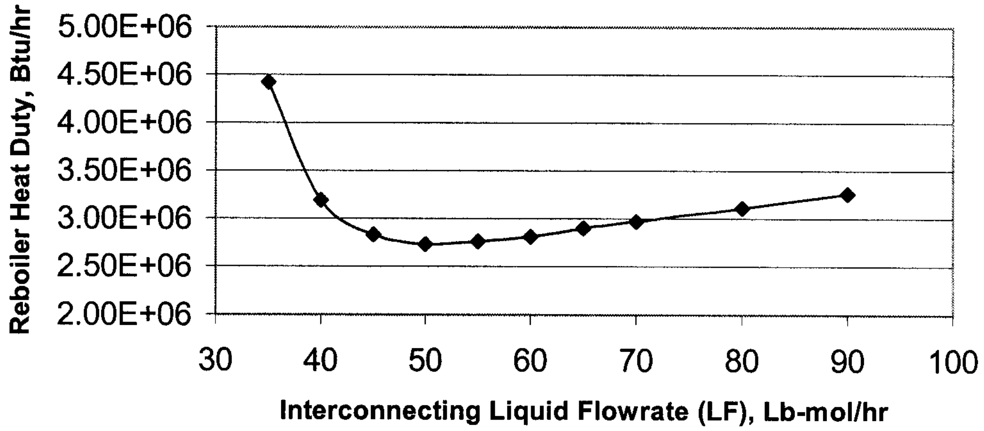


Figure 5. Search results for the columns with side stripper.

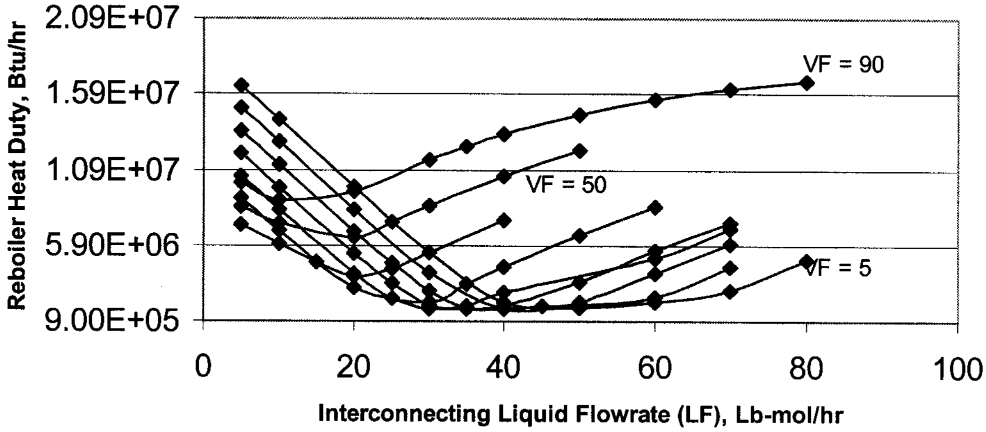


Figure 6. Search results for the Petlyuk column.

Thermodynamic properties were predicted with the Chao–Seader correlation.

The first aspect for the analysis is to detect a basic design for each system under steady-state conditions. Designs for the direct and indirect sequences were obtained through standard methods, but search procedures were conducted for the integrated systems, as described above. Figures 4–6 show the results of the search for the optimum values of recycle streams that provide minimum energy consumption for each TCDS. Figures 4 and 5 show how the interconnecting liquid flowrate and the interconnecting vapor flowrate affect the energy consumption of each system with side columns, while Figure 6 displays the combined effect of both interconnecting streams for the Petlyuk system. Note that the energy consumption of the Petlyuk system provides a better incentive than those achieved by the systems with side columns. The details of the tray arrangements for each integrated system are shown in Table 1, where the operating conditions (such as reflux ratios and reboiler heat duties) associated with the optimum design for energy consumption are also reported. These designs provided the starting basis for the dynamic analysis.

Table 1. Tray arrangements and operating conditions for minimum energy consumption of the thermally coupled distillation sequences.

TCDS-SR	TCDS-SS	Petlyuk column
NT1 = 25	NT1 = 32	NS2 = 9
NS1 = 9	NS1 = 25	NT2 = 17
NEL = 17	NEL = 16	NR = 10
NT2 = 10	NT2 = 9	NE = 17
R1 = 8.37	R1 = 4.75	NS1 = 27
R2 = 0.43	LF (kmol h^{-1}) = 22.75	NT1 = 36
VF (kmol h^{-1}) = 31.85	QR1 (kW) = 692.6	R = 2.53
QR1 (kW) = 738.1	QR2 (kW) = 106.7	LF (kmol h^{-1}) = 15.9
		VF (kmol h^{-1}) = 36.4
		QR (kW) = 500.5

DYNAMIC SIMULATIONS

After the base designs were obtained, a dynamic analysis using Aspen Dynamics 10.1 was conducted. Product compositions were taken as the controlled variables. The control schemes follow from practical considerations and from previous analysis we have conducted on integrated distillation systems. The manipulated variables for the TCDS-SR and the TCDS-SS were the corresponding reflux flowrates and the reboiler heat duties, while for the Petlyuk column the manipulated variables were the reflux flowrate, the side stream flowrate and the reboiler heat duty.

PI controllers were used for each loop. The controllers were tuned following an optimization procedure using the

Table 2. Optimal controller parameters for the heavy component.

Sequence	K_c	τ_i
Direct	40	25
Indirect	40	30
TCDS-SR	100	90
TCDS-SS	70	20
Petlyuk	90	30

Table 3. Optimal controller parameters for the light component.

Sequence	K_c	τ_i
Direct	70	90
Indirect	120	80
TCDS-SR	130	3
TCDS-SS	40	1.5
Petlyuk	70	40

Table 4. Optimal controller parameters for the intermediate component.

Sequence	K_c	τ_i
Direct	60	1
Indirect	90	10
TCDS-SR	30	400
TCDS-SS	24	80
Petlyuk	90	20

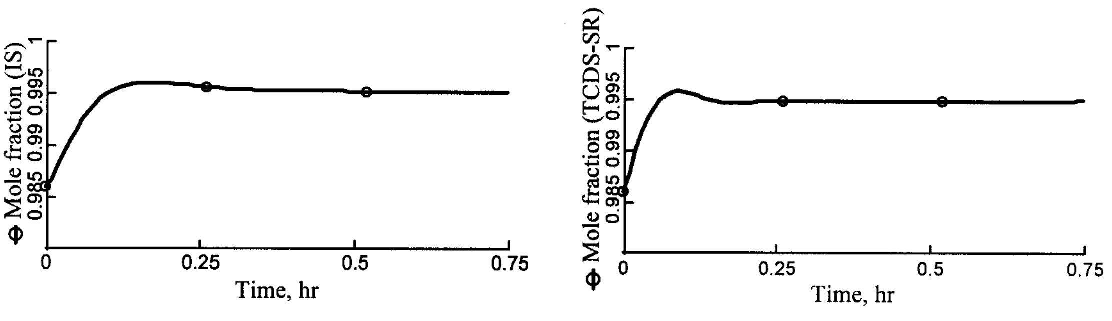
integral of the square error (ISE) criterion[16]. Through the use of Aspen Dynamics 10.1, the values of the controller gains (K_c) and the reset times (τ_i) that provided a minimum value of ISE for a set point change for each separation scheme were detected. The search procedure was conducted in the following way. An initial value for K_c was assumed and different values for τ_i, were tested until a local minimum of the integral square error was detected. Other values for K_c were similarly considered, so that the locus of local optimum points was obtained. From here, the global minimum for the ISE value was obtained, thus providing the optimum controller parameters. Tables 2–4 show the best values of the tuning parameters that were obtained for each integrated sequence.

RESULTS

The results presented here correspond to the dynamic response of each product composition under set point changes for a single closed loop. For each case, the products not being analyzed were assumed to be under open loop operation.

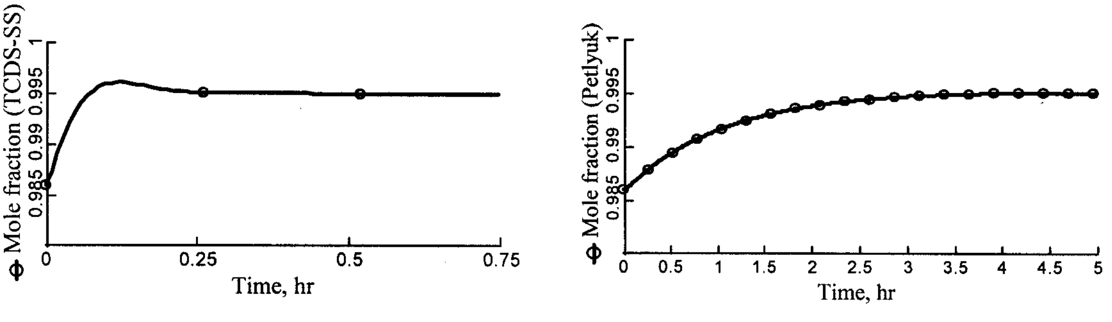
Dynamic Behavior of the Heavy Component

A set point change from 0.986 to 0.995 for the heavy component (C) was implemented. When the conventional, nonintegrated sequences were analyzed, it was found that the indirect sequence (ISE = 2.41153×10^{-6}, Figure 7a) showed a better dynamic behavior than the direct sequence (ISE = 3.62845×10^{-6}). When the indirect sequence was compared with the integrated schemes, the results shown in Figure 7(b)–(d) were obtained. The TCDS-SR option shows a better stabilization time (less than 0.25 h) than the TCDS-SS scheme. This is reflected in their ISE values: 1.30897×10^{-6} for the TCDS-SR against 1.6665×10^{-6} for the TCDS-SS. Although the stabilization time for each of these three sequences may seem acceptable, the dynamic behavior of the TCDS-SR shows the best ISE values overall. In contrast, the response of the Petlyuk column shows the worst dynamic



a) Indirect Sequence

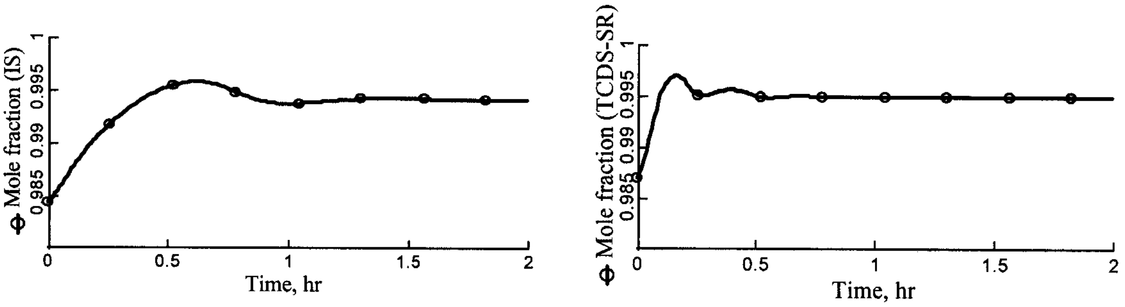
b) TCDS - SR



c) TCDS - SS

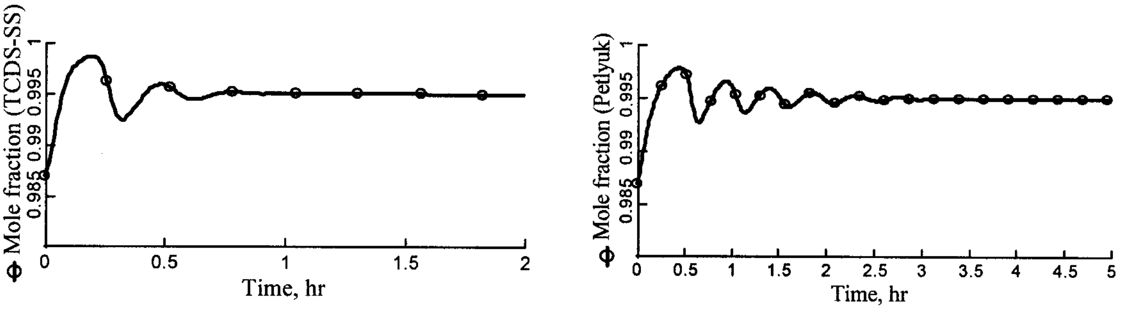
d) Petlyuk Column

Figure 7. Dynamic responses for a setpoint change in the composition of the heavy component.



a) Indirect Sequence

b) TCDS - SR



c) TCDS - SS

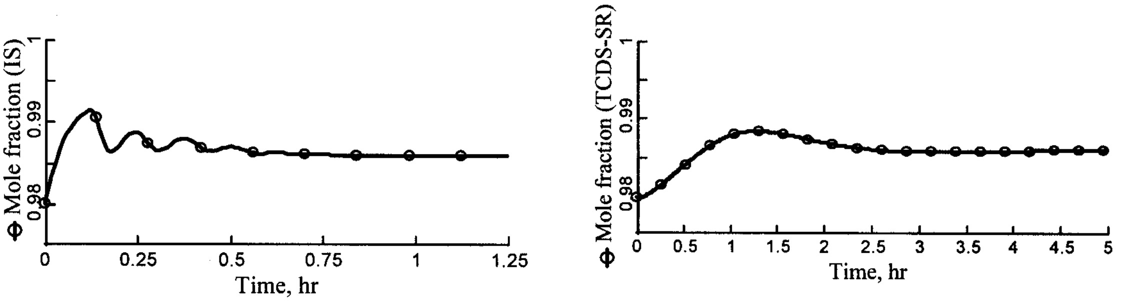
d) Petlyuk Column

Figure 8. Dynamic responses for a setpoint change in the composition of the light component.

behavior, with a stabilization time of nearly 5 h and an ISE value of 4.02773×10^{-5}. The superior performance on energy consumption by the Petlyuk column is obtained at the expense of an undesirable control behavior as compared to the other separation sequences when the primary objective is the control of the heavy component.

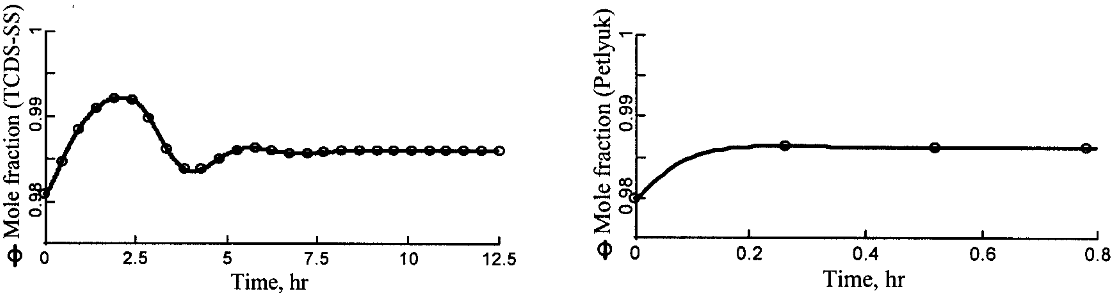
Dynamic Behavior of the Light Component

The results of the dynamic analysis for a positive change in the set point of the light component (A) are shown in Figure 8. For a change in the set point from 0.987 to 0.995, the indirect sequence shows an ISE value of 7.33013×10^{-6}, which again



a) Indirect Sequence

b) TCDS - SR



c) TCDS - SS

d) Petlyuk Column

Figure 9. Dynamic responses for a setpoint change in the composition of the intermediate component.

provides a better behavior than the direct sequence as far as comparing the performance of the conventional sequences.

The new steady state takes longer to reach in this case than in the previous analysis for a composition change of the heavy component. In the case of TCDS schemes, the composition of the light component is stabilized more quickly for the TCDS-SR. The dynamic response of the TCDS-SS shows oscillations before reaching the new steady state. The ISE value for the TCDS-SR is 2.74297×10^{-6}, while that for the TCDS-SS is 3.98807×10^{-6}. For the case of the Petlyuk column, the top composition reaches the steady state after about 3 h (as compared to less than 1.5 h for the other options), with an ISE value of 6.91578×10^{-6}.

Dynamic Behavior of the Intermediate Component

For the case of the dynamic analysis of the intermediate component, the results are displayed in Figure 9. In this case, the change implemented in the set point was from 0.98 to 0.986. The indirect sequence shows an oscillatory behavior before reaching stabilization, with an ISE value of 7.2098×10^{-5}. When TCDS options are considered, the Petlyuk column shows surprisingly the best dynamic behavior; its ISE value is 1.2664×10^{-6}. For the sequences with side columns, the TCDS-SR shows better dynamic properties than the TCDS-SS, which presents a very oscillatory response. This is reflected in their ISE values: 1.58429×10^{-5} for the TCDS-SR, and 6.84045×10^{-5} for the TCDS-SS. The stabilization times vary from 0.3 h for the Petlyuk column to 7 h for the TCDS-SS.

A final remark on the dynamic responses can be made. Although they depend on the controller parameters, some apparent trends are observed. It appears that the loop pairing of the distillate composition for the light component with the reflux flowrate tends to provide oscillatory responses, while the control of the heavy component with the reboiler heat duty results in overdamped responses. The intermediate component, on the other hand, does not appear to follow a consistent trend, probably because of its inverse response behavior under open loop operation. It should be emphasized that these trends were obtained after the optimization of the controllers with the ISE criterion was carried out.

CONCLUSIONS

Through dynamic responses to set point step changes, the controllability properties of distillation sequences that include integrated schemes have been assessed. The controllers that minimize ISE values were detected, and the results show that the TCDS-SR provides the best behavior for the control of the light or the heavy components. When the control of the intermediate component is of primary interest, the Petlyuk column showed the best dynamic performance. An interesting observation is that in the cases analyzed, the dynamic behavior of these integrated schemes outperforms the responses of the sequences based on conventional distillation columns. The results presented here were based on the minimization of the ISE criterion. When the integral of the absolute error (IAE) was used, similar trends were observed. Alternative sets of control loop pairings as suggested by RGA and SVD techniques were also considered, but the dynamic responses were worse than the ones obtained with the loop pairings we used from practical considerations. Overall, the results are consistent with the controllability predictions obtained earlier through a singular value decomposition analysis and they indicate that, in addition to the reported energy savings, the implementation of integrated distillation sequences may provide operational advantages that seemed originally unexpected.

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ACKNOWLEDGEMENT

Financial support from Conacyt and from Concyteg, Mexico, is gratefully acknowledged.

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The manuscript was received 8 March 2001 and was accepted for publication after revision 5 July 2002.