Control of Thermally Coupled Distillation Arrangements with Dynamic Estimation of Load Disturbances

Juan Gabriel Segovia-Hernández,[†,‡] Salvador Hernández,[‡] Ricardo Femat,[§] and Arturo Jiménez*,[†]

Departamento de Ingeniería Química, Instituto Tecnológico de Celaya, Av. Tecnológico y García Cubas s/n, Celaya, Gto., 38010, México, Facultad de Química, Universidad de Guanajuato, Noria Alta s/n, Guanajuato, Gto., 36050, México, and Instituto Potosino de Investigación Científica y Tecnológica, Apdo. Postal 3-90, 78231, Tangamanga, San Luis Potosí, SLP, México

Because of their potential energy savings, thermally coupled distillation sequences provide interesting alternatives to the use of sequences based on conventional distillation columns. Three thermally coupled structures have been particularly analyzed for the separation of ternary mixtures: the sequence with a side rectifier, the sequence with a side stripper, and the Petlyuk column. Design methods have been developed for such sequences, but their dynamic and operational characteristics still require a wider understanding to promote their practical implementation. Previous works have shown that thermally coupled systems can provide suitable control properties; most of the studies on closed-loop control analysis of thermally coupled systems have been based on proportional−integral (PI) controllers. In this work, a PI controller with dynamic estimation of uncertainties is implemented for the control of the thermally coupled distillation arrangements. The controller comprises three feedback terms: proportional, integral, and quadratic actions. The last term provides a dynamic estimation of unknown load disturbances to improve the closed-loop performance. Comparison with the classical PI control law was carried out to analyze the performance of the proposed controller in facing unknown load disturbances in feed composition and set point changes. The results show that the implementation of the controller with dynamic estimation of uncertainties improved noticeably the closed-loop responses provided by the PI controller.

1. Introduction

Distillation is a direct separation method that provides an effective way to separate many fluid mixtures and is the preferred separation process in the chemical industry. When one evaluates the yearly cost of distillation columns, it is generally found that the cost of energy is significantly higher than the cost of capital investment for equipment. This economic behavior has provided an incentive toward the search for more energy-efficient distillation structures. Several alternatives have been proposed to lower the energy consumption levels of distillation systems. One may, for instance, consider the integration of distillation columns within overall processes.[1,2] If such integration is limited or not possible, energy integrated solutions either between conventional columns or giving rise to nonconventional arrangements should be considered, for example, heat integration, heat pumping, and thermal coupling.[3−5] In the last couple of decades, attention has been focused on the potential of distillation columns with thermal coupling. Through the implementation of interconnecting streams between two columns (one interconnection stream in the liquid phase with a recycle stream in the vapor phase, or viceversa), thermally coupled distillation arrangements can be obtained. If properly designed, thermally coupled distillation systems (TCDS) provide a more energy-efficient operation than sequences based on conventional columns. When conventional sequences are used for the separation of ternary mixtures, a remixing of the intermediate component occurs, thus affecting the total energy required for the separation. TCDS, on the other hand, can be designed in such a way as to reduce or even eliminate such a remixing effect, which is then translated into lower energy consumptions.[6,7]

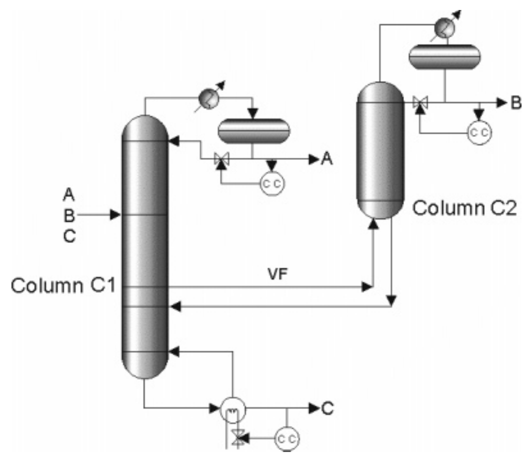

Figure 1. Thermally coupled distillation sequence with side rectifier (TCDS-SR).

Three TCDS arrangements have been particularly studied, the sequence with a side rectifier (TCDS-SR, Figure 1), the sequence with a side stripper (TCDS-SS, Figure 2), and the fully thermally coupled system, or Petlyuk column (Figure 3). Early studies on these systems dealt with their theoretical performances under total reflux conditions.[8−11] Those studies showed that TCDS can provide lower values of the minimum internal vapor flowrates than conventional sequences. More appropriate models for the design of TCDS systems under operating reflux conditions were then developed. Finn[12] and Hernández and Jiménez[13] reported design methods for the systems with side columns. Triantafyllou and Smith[6] and Hernández and Jiménez[14]

* To whom correspondence should be addressed. Tel.: (+52-461) 611-7575 Ext. 130. Fax: (+52-461) 611-7744. E-mail address: arturo@iqcelaya.itc.mx.

[†] Instituto Tecnológico de Celaya.

[‡] Universidad de Guanajuato.

[§] Instituto Potosino de Investigación Científica y Tecnológica.

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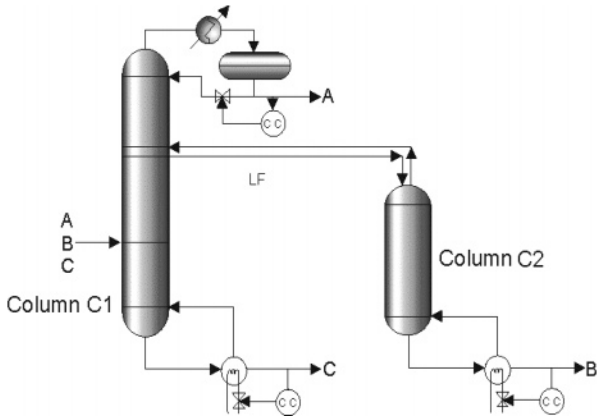

Figure 2. Thermally coupled distillation sequence with side stripper (TCDS-SS).

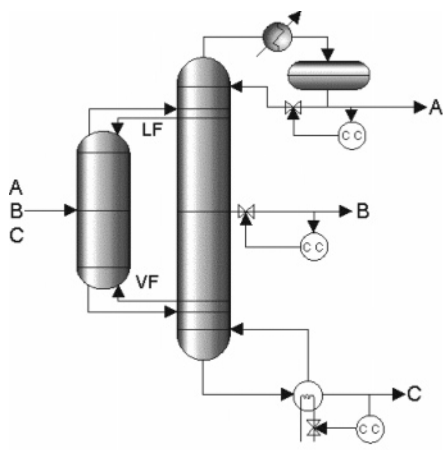

Figure 3. Petlyuk column.

showed how Petlyuk columns can be designed and optimized for energy consumption. In particular, if a search procedure is carried out over the values of the interconnecting streams, the integrated system can be optimized for energy consumption and provide significant energy savings with respect to conventional sequences. These types of studies under operating reflux conditions corroborated the energy-savings potential of TCDS.

The energy savings, however, seem to be in conflict with the controllability properties of TCDS, since their structures are more complex than those of the conventional sequences. Such uncertainties on the control properties of TCDS have affected their industrial implementation. It has not been until recently that Petlyuk columns have been implemented, in the form of divided wall columns.[15]

In an attempt to provide thermally coupled alternatives with better dynamic properties, several simplifications to the systems shown in Figures 1−3 have been recently reported. Agrawal and Fidkowski[16,17] proposed some conceptual variations to the original TCDS arrangements aiming to simplify their structures and therefore provide a better expectation on their controllability properties. Rong and Kraslawski[18] showed how systems with a lower number of interconnections can be developed and optimized. Jiménez et al.[19] showed that some variations to the Petlyuk system could provide similar energy savings. Ramírez and Jiménez[20] analyzed two alternative arrangements to the TCDS with side columns and found that the modified structures that performed the easiest split first provided good alternatives as far as energy consumption is concerned.

Some preliminary studies on the control properties of TCDS have already been conducted. One of the first dynamic studies

Table 1. Energy Requirements for Each Separation Sequence (Btu/h)

feed	direct sequence	indirect sequence	TCDS-SR	TCDS-SS	Petlyuk column
			Mixture M1		
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
			Mixture M2		
F1	7 430 812.6	7 277 925.1	7 106 695.5	6 895 831.3	6 300 486.6
F2	7 816 270.4	7 344 143.3	7 073 923.0	6 958 312.5	6 142 722.5
			Mixture M3		
F1	5 887 458.3	5 697 594.6	2 952 695.0	3 045 980.6	2 399 649.4
F2	5 756 130.7	5 300 344.3	3 859 170.5	3 816 550.1	2 600 934.7

Table 2. Parameters of the Controllers Obtained after the Minimization of IAE Values for Mixture M1 for Each Control Loop

	control of A		control of B		control of C	
PI controller	K_C	τ_I	K_C	τ_I	K_C	τ_I
TCDS-SR	130	3	30	400	100	90
TCDS-SS	40	1.5	24	80	70	20
Petlyuk	70	40	90	20	90	30
PII^2 controller	K_C	L	K_C	L	K_C	L
TCDS-SR	30	75	2.5	10	180	0.001
TCDS-SS	115	130	95	15	5500	1000
Petlyuk	105	135	2	200	60	0.0005

Table 3. IAE Results for Feed Disturbance Test, M1 (One Closed Loop)

sequence	components	PII^2	PI
TCDS-SR	A	1.07×10^{-1}	1.62×10^{-1}
	B	1.49×10^{-3}	7.77×10^{-1}
	C	3.52×10^{-2}	5.68×10^{-1}
TCDS-SS	A	1.13×10^{-2}	5.32×10^{-2}
	B	1.26×10^{-2}	9.94×10^{-2}
	C	1.34×10^{-2}	5.03×10^{-2}
Petlyuk	A	1.22×10^{-2}	2.20×10^{-2}
	B	2.82×10^{-1}	8.74×10^{-1}
	C	1.74×10^{-2}	3.11×10^{-2}

Table 4. IAE Results for Set Point Change, M1 (One Closed Loop)

sequence	components	PII^2	PI
TCDS-SR	A	2.72×10^{-2}	5.18×10^{-2}
	B	3.51×10^{-1}	4.01×10^{-1}
	C	3.60×10^{-2}	1.08×10^{-1}
TCDS-SS	A	1.56×10^{-2}	5.67×10^{-2}
	B	1.03×10^{-1}	8.00×10^{-1}
	C	1.55×10^{-2}	9.62×10^{-2}
Petlyuk	A	1.60×10^{-2}	9.61×10^{-2}
	B	2.63×10^{-1}	4.87×10^{-1}
	C	1.54×10^{-2}	2.16×10^{-2}

was reported by Alatiqi and Luyben,[21] who compared the closed-loop performance of a TCDS with a side stripper to that of a conventional indirect separation sequence. They found that the integrated arrangement provided better responses to load disturbances. Wolff and Skogestad[22] carried out a control analysis of the Petlyuk system and found the system to be controllable when a three-point control structure was implemented. Hernández and Jiménez[23] and Jiménez et al.[24] have compared the controllability properties of TCDS with the conventional distillation trains for ternary mixtures and found that in many cases TCDS show better theoretical control properties and closed-loop responses than the conventional sequences. Serra et al.[25] extended the dynamic analysis on TCDS and showed that the dynamic performance of the Petlyuk column can be improved by changing the operating point with respect to the one with minimum energy consumption. The control performance of several alternative structures to the Petlyuk column has been recently reported,[26] and the results showed

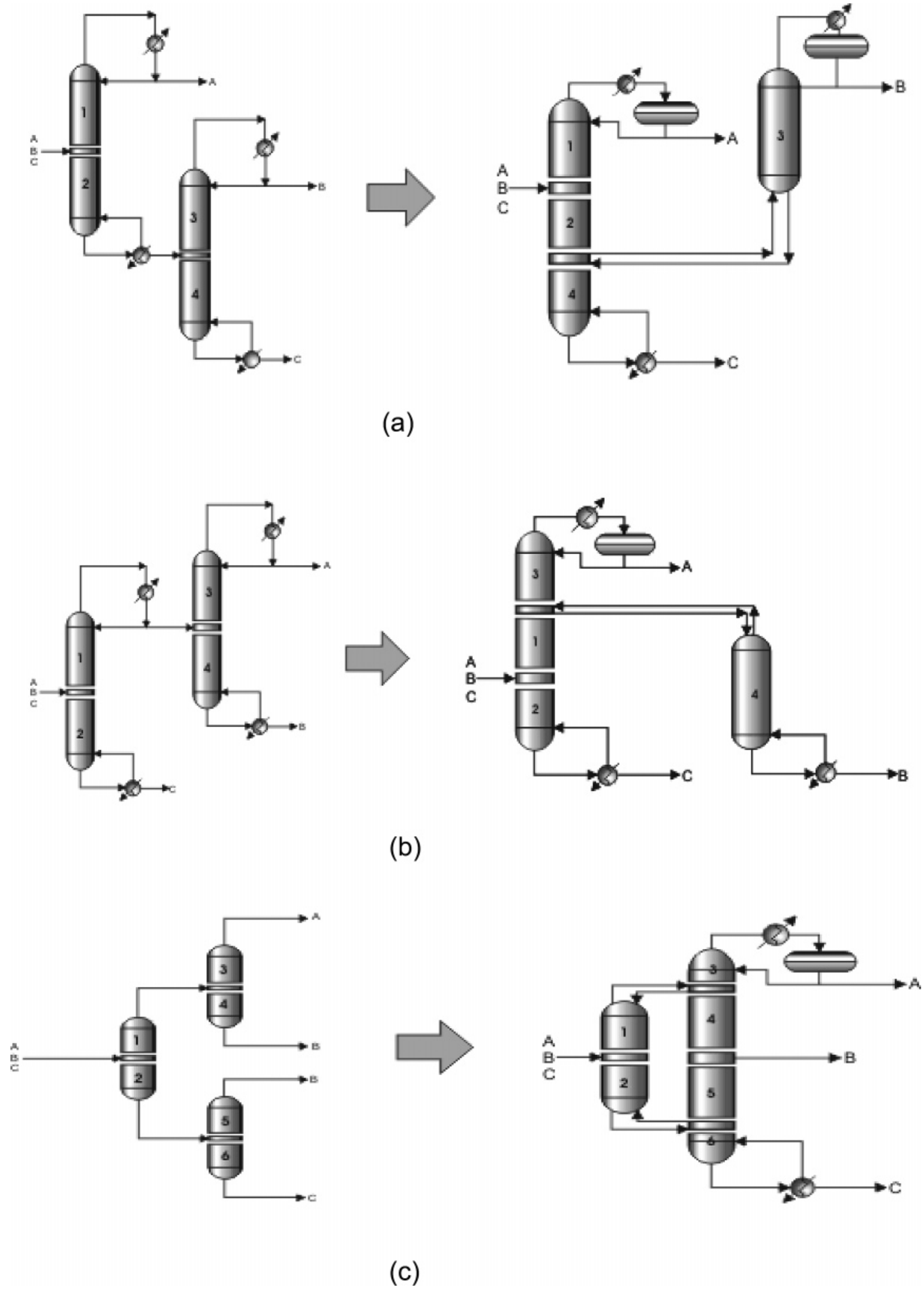

Figure 4. Rearrangement of conventional sequences into TCDS: (a) system with a side rectifier; (b) system with a side stripper; (c) Petlyuk column.

that the control behavior of the Petlyuk system is not necessarily improved by lowering the number of thermal couplings.

We can highlight two aspects from the set of works carried out on the control aspects of TCDS. One, their controllability properties do not seem as troublesome as originally expected, and two, most of the works on the closed loop behavior of TCDS have been conducted assuming the implementation of conventional proportional−integral (PI) controllers. The room is then open for the test of alternative controller schemes. In this work, we analyze the use of a proportional−integral controller with dynamic estimation of unknown disturbances,[27] as an option for the control of the three TCDS structures shown in Figures 1−3. The results from the implementation of such a controller are compared to the dynamic performance of the systems under a standard PI controller.

2. Design of TCDS

Dynamic models for the sequences shown in Figures 1−3 were developed. The models are based on the total mass balance,

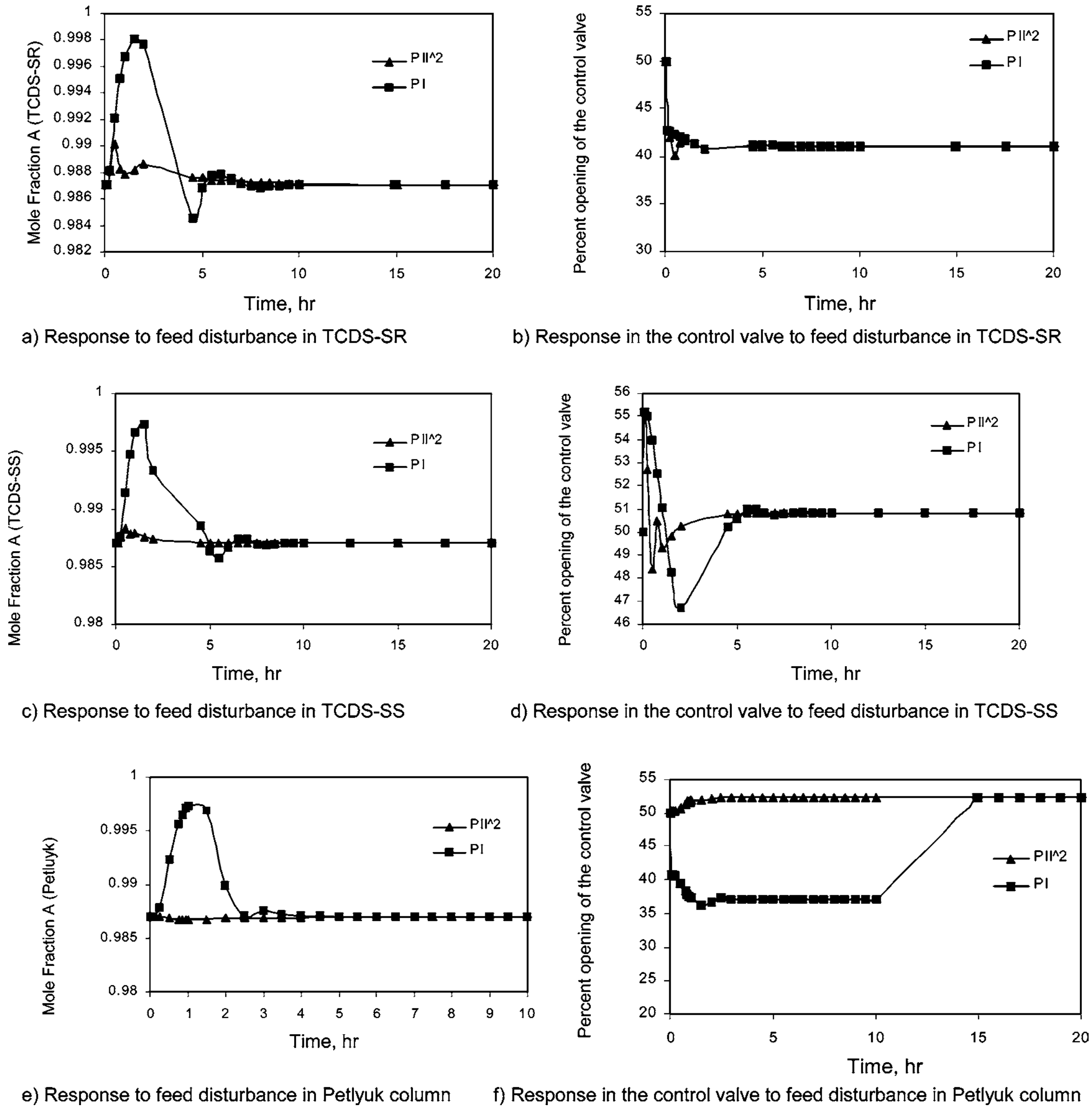

Figure 5. Dynamic responses for feed disturbance elimination in component A, mixture 1, and one closed loop.

component mass balances, equilibrium relationships (assuming ideal vapor liquid equilibrium (VLE)), summation constraints, energy balance, and stage hydraulics (Francis Weir formula). One set of equations are written for each column of the TCDS. Since the equations are coupled because of the recycle streams between the columns, the set of equations are solved simultaneously. The design of the three TCDS was conducted following the method reported by Hernández and Jiménez.[13,14] The method provides a tray structure for the integrated systems by a section analogy procedure with respect to the design of a conventional distillation sequence; the TCDS-SR is obtained from the tray arrangements of a direct sequence (Figure 4a), the TCDS-SS, from an indirect sequence (Figure 4b), and the Petlyuk system, from a sequence of a prefractionator followed by two binary distillation columns (Figure 4c). 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. 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). The dynamic analysis was then conducted using a validated design with minimum energy consumption for each case.

3. PI Control with Dynamic Estimation of Uncertainties

The integral action of a conventional PI controller can be viewed as a controller's capability to estimate load disturbances. An extension of this property has been developed by Alvarez-Ramírez et al.[27] to provide a controller with enhanced capabilities to estimate load disturbances. The main idea behind such an extended controller is to estimate the input $d = d(t)$ from the system output and, if the estimated value is close to the actual one, substitute it with a PI-like control law. The resulting controller is referred to as a PII^2 controller.

The estimated value of the input d is calculated from,

$$\dot{\bar{y}} = -\frac{1}{\tau}y + K_P u + \bar{d} + g_1(y - \bar{y}) \qquad (1)$$

$$\dot{\bar{d}} = g_2(y - \bar{y}) \qquad (2)$$

where $\bar{d}$ and $\bar{y}$ are the estimated values for d and y, with estimation constants g_1 and g_2; such constants must be strictly positive to provide a stable performance.[28]

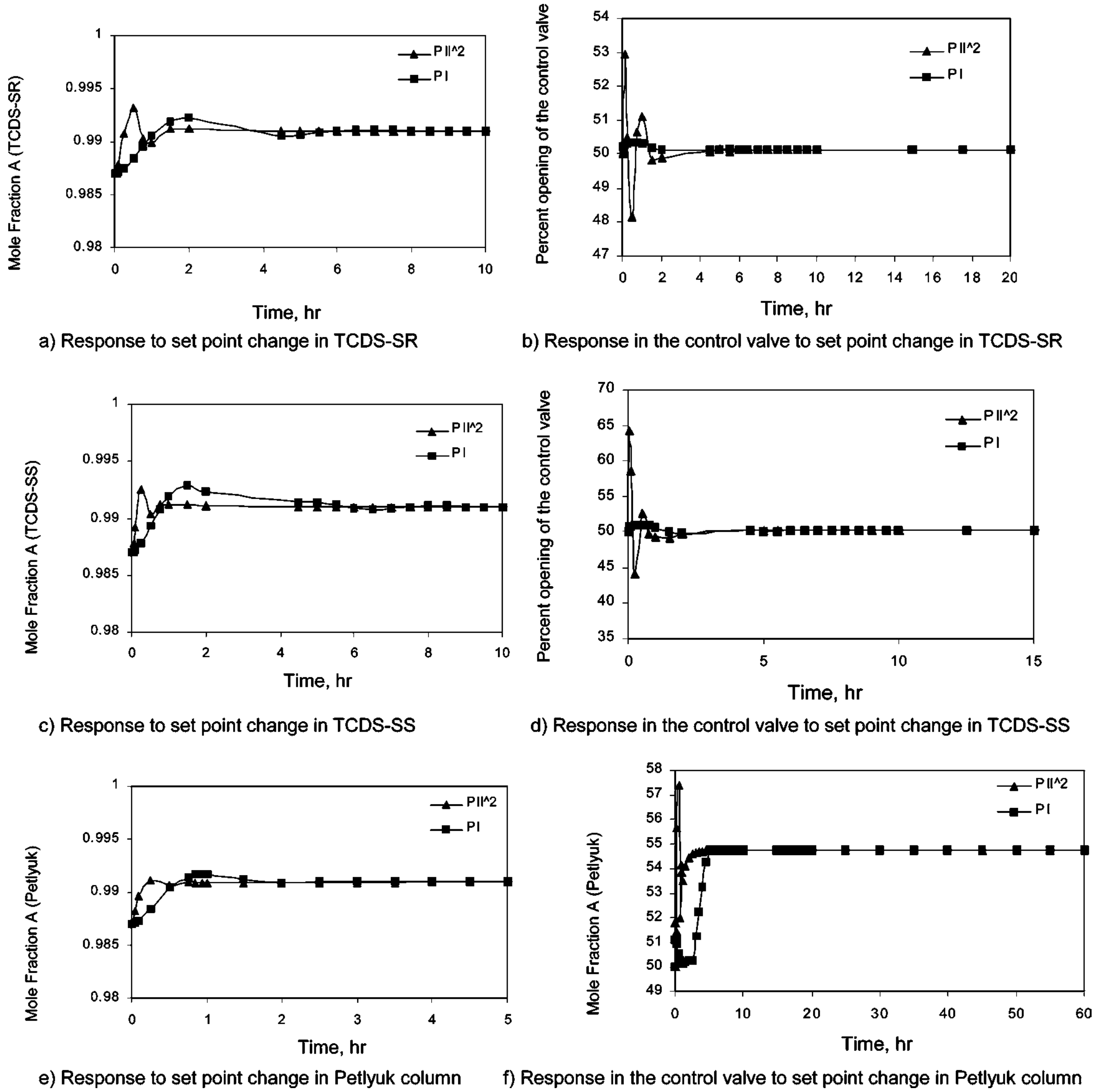

Figure 6. Dynamic responses for set point change in component A, mixture 1, and one closed loop.

The linear equations that provide the basis for the PII^2 controller allow the determination of the following transfer function,

$$C(s) = \frac{U(s)}{Y(s)} = K_C\left[1 + \frac{1}{\tau_I s} + \frac{K_e}{s(s + g_1)}\right] \qquad (3)$$

where

$$K_C = \frac{(1/\tau - 1/\tau_C)}{K_P}$$

$$\tau_I^{-1} = -\frac{g_2}{(1/\tau - 1/\tau_C)}$$

$$K_e = \frac{-g_2(g_1 - 1/\tau_C)}{(1/\tau - 1/\tau_C)}$$

One may notice that, in addition to the standard PI actions, a quadratic term appears which can be viewed as a second order integral action. The quadratic term provides a dynamic estimation of the input d, which can represent load disturbances (regulation problem) or step changes in references (servo-control problem).

To tune up the controller, it is convenient to use the following parametrization of the estimator gains g_1 and g_2; $g_1 = 2L$ and $g_2 = L^2$, where $L > 0$. Therefore, the controller parameters are L and either τ_c or K_C. The parameter L is interpreted as the rate of the estimated value convergence. One may notice that the PII^2 controller reduces to a PI controller if $L = {}^1/_2\tau_c$. Alvarez-Ramirez et al.[27] and Femat et al.[28] report additional details on tuning and closed-loop stability analysis of the PII^2 controller.

4. Dynamic Simulations and Case Studies

In the first set of dynamic tests, the implementation of the output feedback control for the distillation systems are configured such that only the liquid composition of the output flowrate is regulated (i.e., uncoupled one-point configuration control), as in Jiménez et al.[24] and Segovia-Hernández et al.[29] In such a configuration, the liquid compositions for the main product streams (A, B, and C) are taken as the controlled variables. Several control structures can be implemented for distillation columns, and the selection can affect their closed-loop performance (see, for instance, the work of Hurowitz et al.[30]). In this work, the control loops for the thermally coupled columns were chosen from an extension of the energy balance configuration for conventional distillation columns. Thus, the manipulated variables were the reflux flowrate for the control of A (always

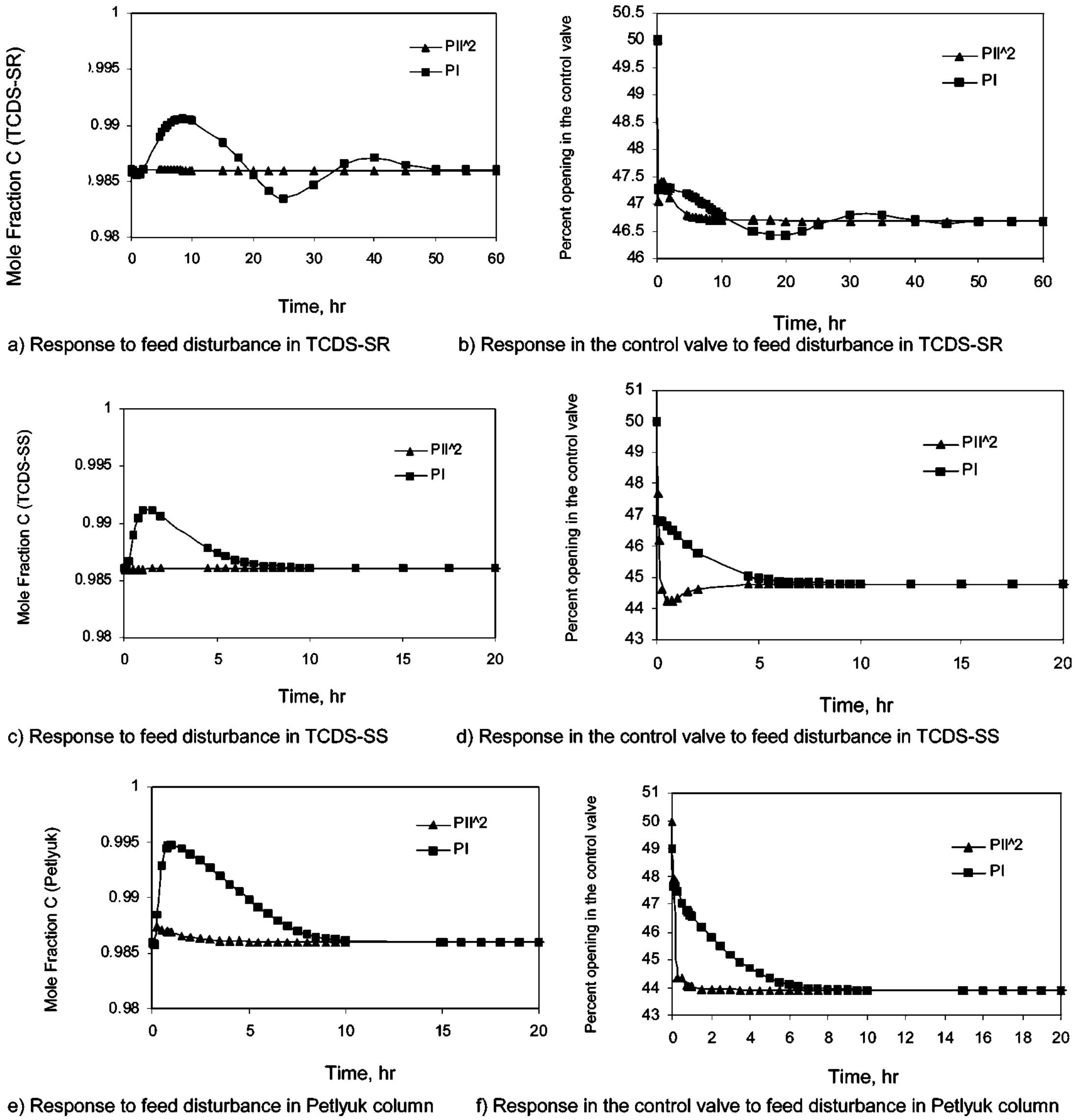

Figure 7. Dynamic responses for feed disturbance elimination in component C, mixture 1, and one closed loop.

a distillate stream) and B (when such a product stream was a distillate stream) and the reboiler heat duty for the control of B (when produced as a bottoms product) and C (always a bottoms stream). The control of B for the Petlyuk configuration was regulated with the side product flowrate. Figures 1−3 show the control loops.

The goals of the dynamic analysis are (i) to show that the TCDS arrangements can be controlled by exploiting a simple control configuration and (ii) to improve the closed-loop performance by implementing a proportional−integral feedback with dynamic estimation of unknown disturbances. To establish some kind of reference, the performance of the PII^2 controller was compared with that of the classical PI control action. From several of the techniques available for tuning up the controller parameters, the integral of the absolute error (IAE) criterion was used. To accomplish this task, a set point change in each product composition 0.5% higher than their nominal values was implemented (i.e., for product A from 0.987 to 0.991, for product B from 0.98 to 0.984, and for product C from 0.986 to 0.99). Therefore, the values of K_C and τ_I for the PI controllers, or K_C and L in the case of the PII^2, that provided a minimum value of the IAE for a set point change for each separation scheme were detected and used for the closed-loop dynamic analysis for each separation sequence. This type of tuning method provided a common basis for the comparison of the controller's actions.

For the dynamic analysis, we are assuming an instantaneous measurement of the output variables to be controlled, in this case product compositions. In practice, such a measurement, if done directly, involves delay times associated with the measuring devices. We are implicitly assuming that a suitable observer is available for such estimation. In particular, for distillation columns, the task can be effectively performed with temperature measurements, as shown for instance in the experimental work by Abdul-Mutalib et al.[31] in which a temperature control system was carried out for a Petlyuk system (implemented in the form of a divided-wall column). We are also assuming perfect level control on the condenser accumulator and the reboiler.

To classify the mixtures for the case studies, the ease of separability index (ESI $= \alpha_{AB}/\alpha_{BC}$) as defined by Tedder and Rudd[32] was used. The 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). The feed flowrate was taken as 45.4 kmol/h as saturated liquid, and the specified purities for the product streams were assumed as 98.7, 98, and 98.6% for A, B, and C, respectively. A feed composition with a low

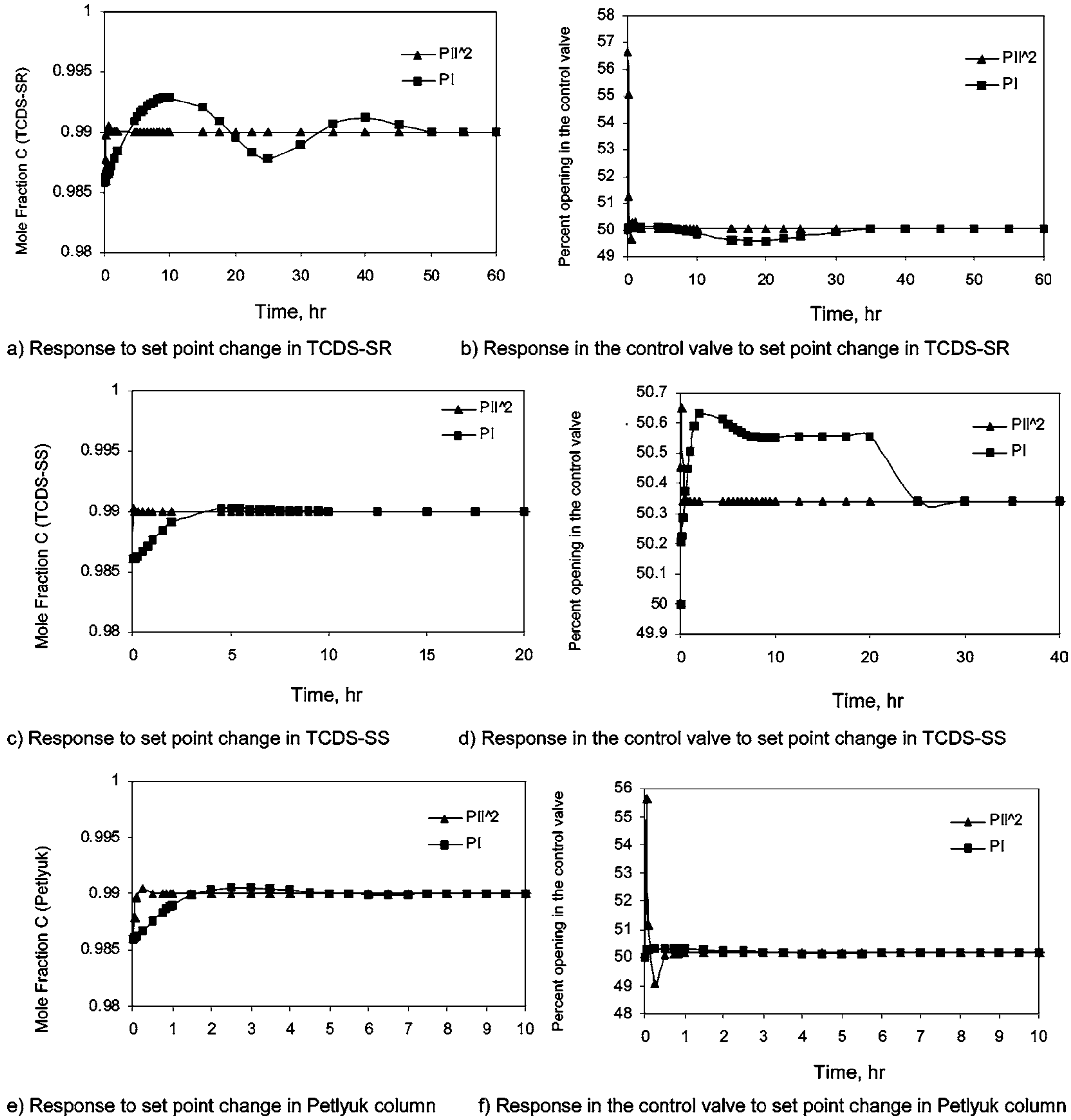

Figure 8. Dynamic responses for set point change in component C, mixture 1, and one closed loop.

amount of the intermediate component (A, B, and C equal to 0.4, 0.2, and 0.4) was considered. This type of composition has been shown to provide significant energy savings of the thermally coupled configurations with respect to the conventional direct or indirect sequences. Isobaric conditions were assumed, and the design pressure for each sequence was chosen such that all condensers could be operated with cooling water.

5. Results

Base designs were first obtained and optimized for energy consumption. Table 1 shows the minimum energy consumption required by each arrangement. The energy required by the conventional direct and indirect distillation sequences is also given as a reference for each separation problem. It can be observed that the thermally coupled systems provide energy savings with respect to the operation of conventional distillation sequences and that those savings depend on the type of mixture (i.e., their ESI values). If one compares the energy savings provided by the systems with side columns to the corresponding conventional structure (direct or indirect sequence), it can be seen that as the value of ESI decreases the savings become more significant. When ESI $>$ 1 (mixture M2), savings of around 5% with respect to the corresponding conventional sequence are observed. When ESI $=$ 1 (mixture M1), the savings are equivalent to 23%. Finally, the most significant savings are obtained for the mixture with ESI $<$ 1 (mixture M3), ranging from 28 to 50%. As for the Petlyuk system, this structure provides higher energy savings than the systems with side columns. When the ESI is lower than or equal to 1, energy savings of about 50% with respect to the conventional columns are obtained. The lowest energy savings are again observed for the mixture with ESI $>$ 1, of about 15%.

Once the base designs were obtained, the control tests were carried out. Tests for servo control and for regulation under load disturbances were implemented. For the former, a step change was induced in the set point for each product composition under single-input single-output (SISO) feedback control at each output flowrate, and for the latter, a 5% change in the composition of one component (with a proportional adjustment in the composition of the other components to keep the same total feed flowrate) was implemented. The simulations were carried out assuming first SISO operation for the control of each individual component (i.e., the products not being analyzed were assumed to be under open-loop operation).

5.1. Mixture M1. For mixture M1, the values of the parameters that were obtained for each type of controller after

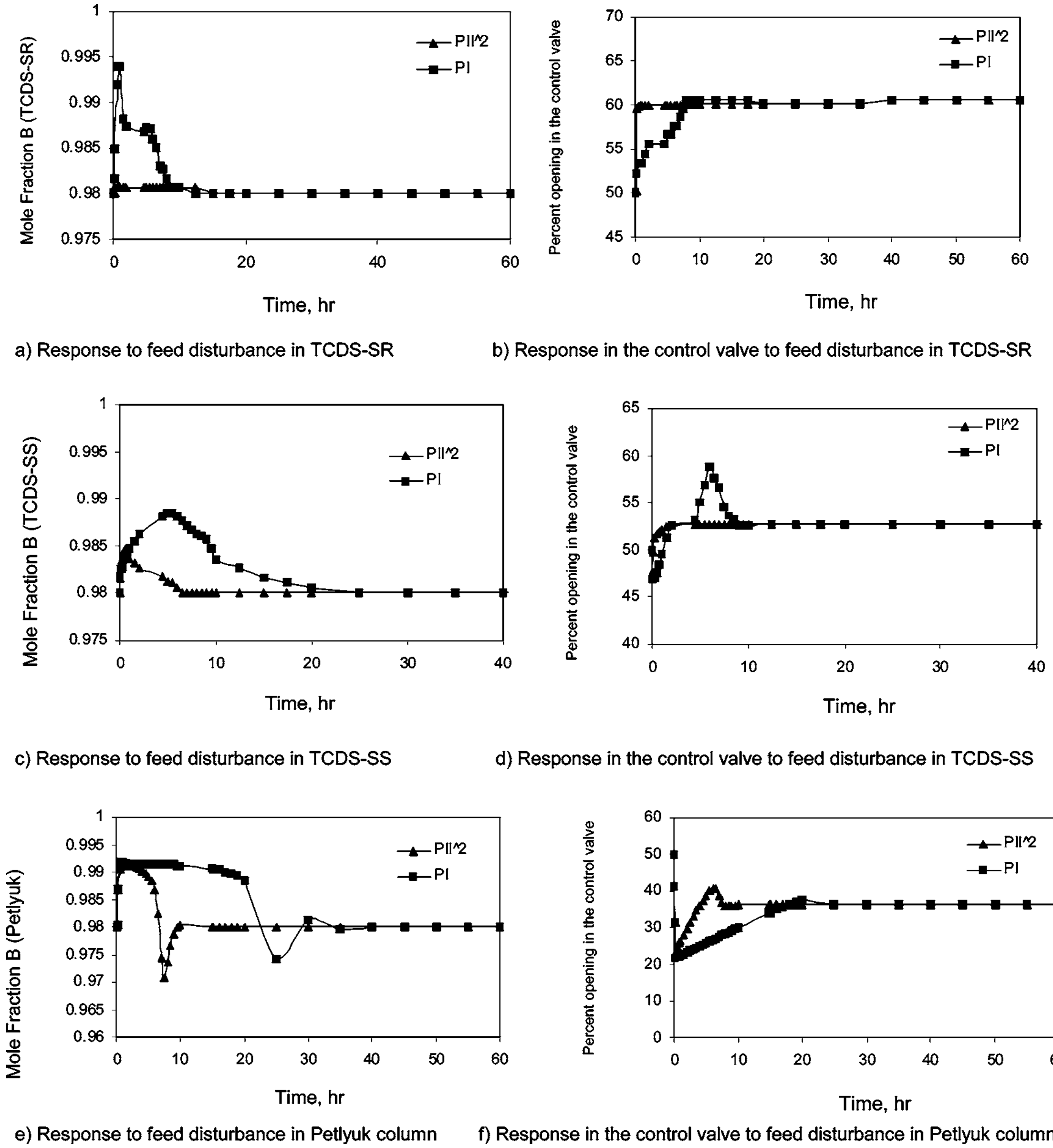

Figure 9. Dynamic responses for feed disturbance elimination in component B, mixture 1, and one closed loop.

the minimization procedure of the IAE for each control loop are shown in Table 2.

The dynamic responses for product stream A under each type of controller are shown in Figure 5. When a feed disturbance was implemented, both the PI and the PII^2 controllers successfully rejected the disturbance to bring the product composition back to its design value. However, the responses of the TCDS were remarkably improved through the use of the PII^2 controller. While the action of the PII^2 controller provided rather smooth dynamic responses, the implementation of the PI controller gave high initial deviations, along with high settling times (2−5 h). For the set of dynamic simulations, the control valves were assumed at a 50% opening for the nominal steady state. Figure 5 also shows the change in the control valve position required by the dynamic responses. In agreement to the smooth disturbance rejection of the PII^2 controller, the control valve showed a quick adjustment toward the new steady state of the manipulated variable, which may also be interpreted as a lower control effort. Therefore, the PII^2 controller proved to be remarkably effective for disturbance control rejection.

When a set point change in the required composition of product A (from 0.987 to 0.991) was implemented, the PII^2 controller reached the new steady state faster than the conventional PI controller (see Figure 6). The corresponding action of the control valve can be also observed, with the PII^2 controller showing again a lower control effort. In general, the PII^2 controller performs better than the PI mode under load upsets because its transfer function (eq 3) accounts for the low-frequency components of the closed-loop response. That is, the PII^2 includes an additional term with respect to the traditional PI feedback controller, which arises from a quadratic integration that accounts for disturbances[28] that introduces a second-order integration component (given by eqs 1 and 2) into the closed loop. The new transfer function of the controller provides an improved sensitivity to the control action at low frequencies. Thus, while the integral action introduces a phase lag at all frequencies to the response interval of the thermally coupled distillation sequence, the quadratic term increases the response at low frequencies. This can be seen through a frequency response analysis on the controller. It can be shown that when the frequency goes to zero, the magnitude ratio for PII^2 is larger than that for PI, which means that the PII^2 controller responds with a larger magnitude at low frequencies than the PI controller. On the other hand, as the frequency increases, the responses of

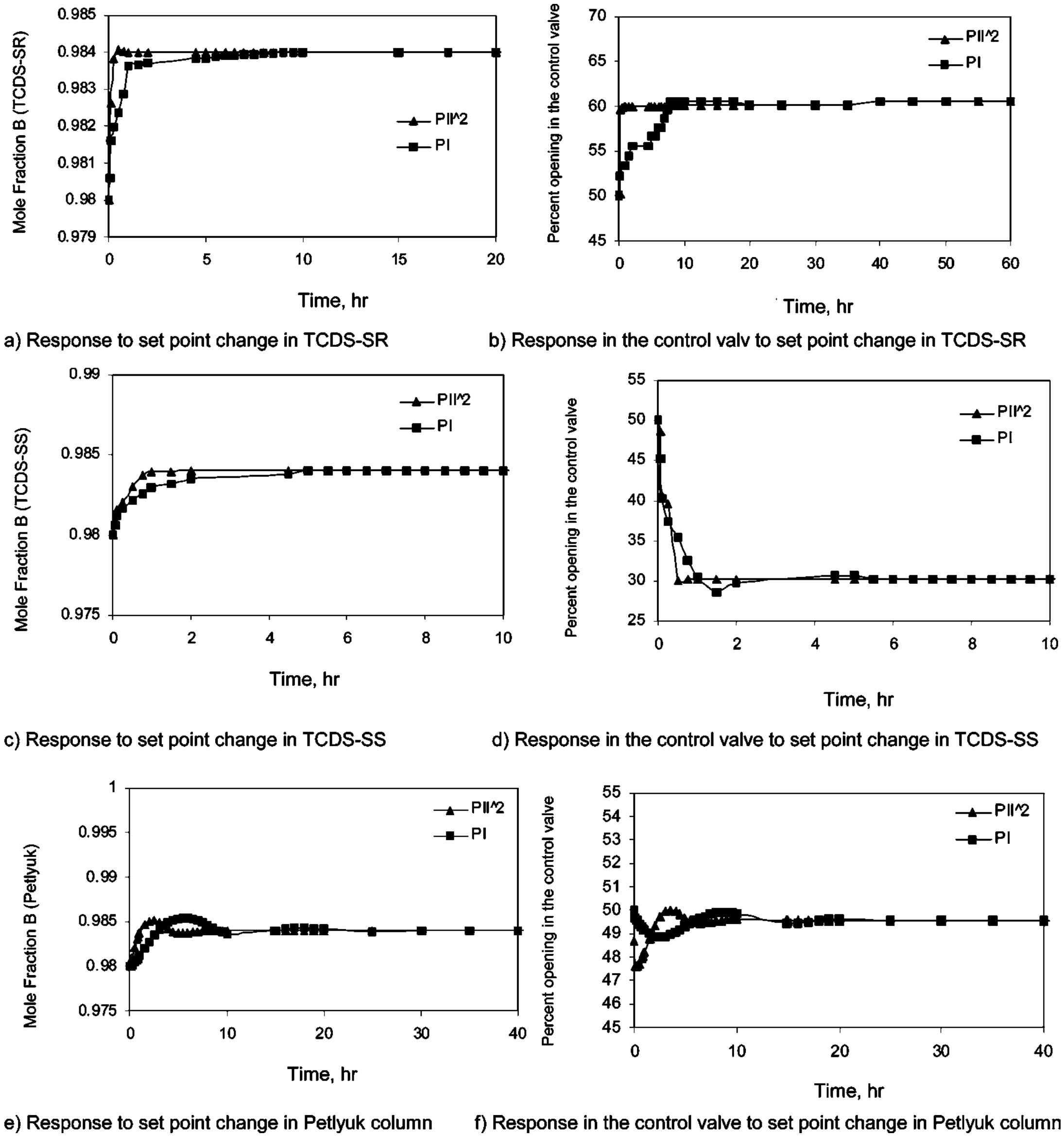

Figure 10. Dynamic responses for set point change in component B, mixture 1, and one closed loop.

both the PI and PII^2 controllers become similar. The interested reader can plot a Bode diagram to compare both the PI and PII^2 responses.

When a 5% change in the feed composition of component C was implemented, the responses shown in Figure 7 were obtained. The PII^2 controller provided a smooth and fast attenuation of the load disturbance, while the PI controller showed a rather poor behavior with large settling times. The control valve motion for each test is displayed in Figure 7; one may notice the higher control effort required by the PI controller. The control actions required by the PII^2 controller, on the other hand, were rather smooth.

For the servo problem of the heavy component, a set point change for component C from 0.986 to 0.99 was induced. Figure 8 shows the closed loop response of the heavy component; it can be observed how the PII^2 controller provides a smaller settling time.

For the intermediate component, the results of the load disturbance and servo tests for mixture 1 are displayed in Figures 9 and 10. The PII^2 controller provided a significant improvement for the load rejection test with respect to the action of the PI controller (see Figure 9). For the servo problem (with a set point change from 0.98 to 0.984), Figure 10 shows that the integrated sequences reach the new steady state faster under the action of the PII^2 controller; the valve responses reflect the lower control effort required by the PII^2 controller.

To provide a more quantitative analysis for the comparison of the controller's actions, the IAE value for each response was calculated. The numerical values of the IAE for the disturbance rejection cases and set point changes are given in Tables 3 and 4. The superior behavior of the PII^2 controller for mixture 1 is reflected in the corresponding IAE values. In particular, such values reflect a remarkable improvement of the action of the PII^2 controller for the disturbance rejection cases.

5.2. Mixtures M2 and M3. When mixtures M2 and M3 were considered, the results were quite consistent with those observed for mixture M1. The TCDS structures were controlled significantly better under the action of the PII^2 controller. A summary of the IAE values for each test and for each type of controller is reported in Tables 5−8. This behavior of the PII^2 controller is induced by the disturbance estimator, which resembles the structure of linear state observers. It should be mentioned that when mixtures M2 and M3 were analyzed for feed disturbance rejection, the control valves became at times saturated or completely closed under the action of the PI controller.

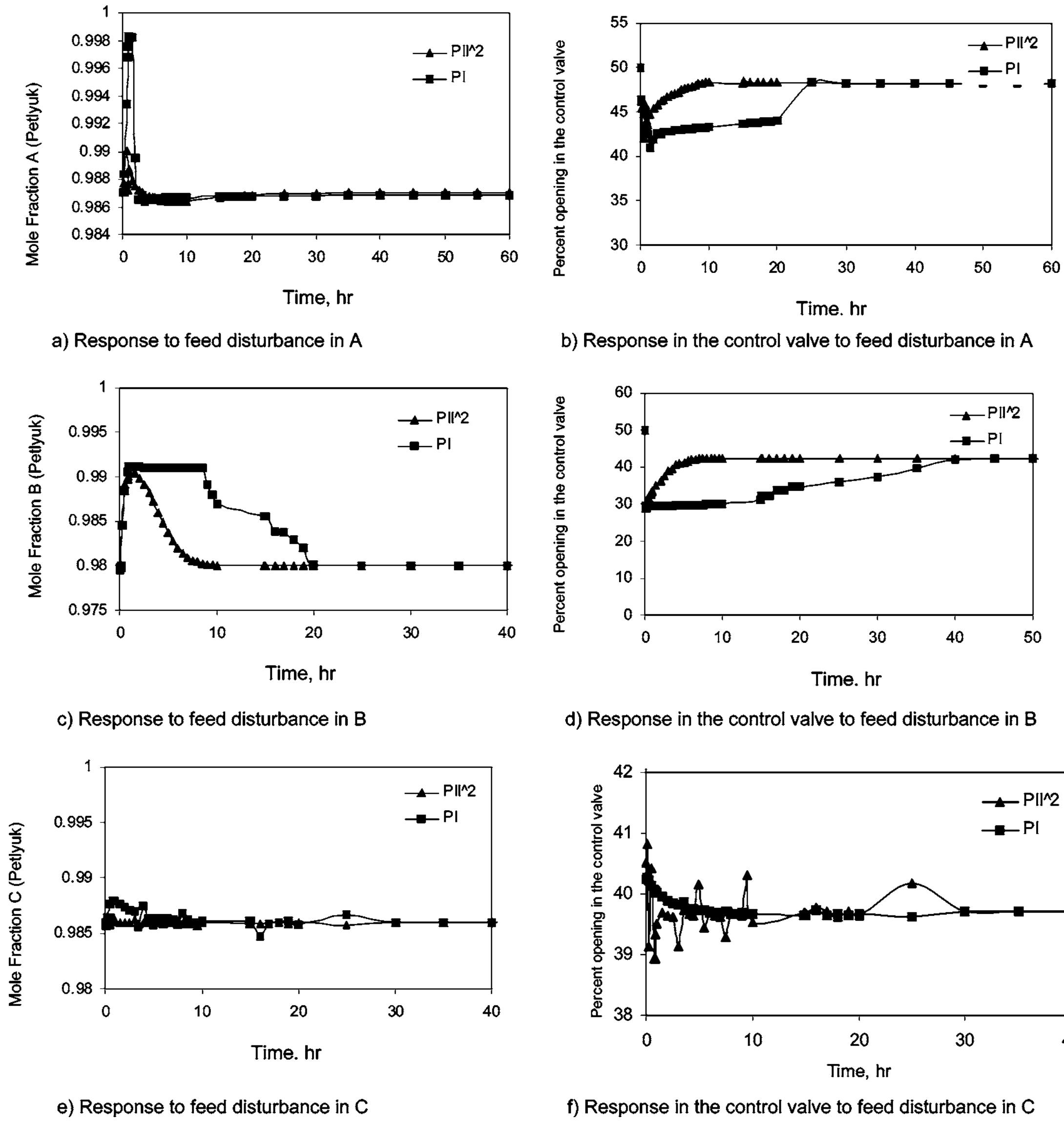

Figure 11. Dynamic responses for feed disturbance elimination of the Petlyuk column, mixture 1, and three closed loops.

Table 5. IAE Results for Feed Disturbance Test, M2 (One Closed Loop)

sequence	components	PII^2	PI
TCDS-SR	A	4.82×10^{-2}	2.97×10^{-1}
	B	2.78×10^{-2}	5.76×10^{-1}
	C	2.02×10^{-2}	4.92×10^{-1}
TCDS-SS	A	1.38×10^{-1}	2.92×10^{-1}
	B	2.00×10^{-1}	8.48×10^{-1}
	C	9.99×10^{-2}	6.02×10^{-1}
Petlyuk	A	7.57×10^{-2}	7.73×10^{-2}
	B	6.47×10^{-2}	9.01×10^{-2}
	C	5.31×10^{-2}	6.90×10^{-2}

Table 6. IAE Results for Set Point Change, M2 (One Closed Loop).

sequence	components	PII^2	PI
TCDS-SR	A	4.26×10^{-2}	2.46×10^{-1}
	B	1.00×10^{-2}	4.75×10^{-1}
	C	1.51×10^{-2}	4.48×10^{-1}
TCDS-SS	A	1.38×10^{-1}	2.96×10^{-1}
	B	4.27×10^{-2}	8.99×10^{-1}
	C	1.73×10^{-2}	5.18×10^{-1}
Petlyuk	A	7.37×10^{-2}	8.71×10^{-2}
	B	5.49×10^{-2}	8.47×10^{-2}
	C	5.16×10^{-2}	6.71×10^{-2}

5.3. Dynamic Responses with Three Closed Loops. A series of dynamic responses for the multivariable control of the TCDS arrangements, with the three control loops closed, were also obtained, both for set point tracking and feed disturbance rejection analysis. For the load disturbance tests, three types of changes in feed composition were assumed: in each of them, a 5% change in one of the components was made (as with the one-point control cases), but with the three control loops closed. For the servo problem, a simultaneous set point change in the three control points was implemented.

When the responses of the distillation sequences under feed disturbances were analyzed, the PII^2 controller provided a remarkable improvement over the use of the PI controller. Figures 11 and 12 show some of the responses obtained for one of the TCDS arrangements (Petlyuk column, for mixture M1). One can observe in Figure 11 how the implementation of the PII^2 controller outperforms the dynamic responses provided by the PI controller for the load disturbance tests. The disturbance rejection under a change in the feed composition of the A component takes similar settling times with both controllers (Figure 11a), but the PI controller shows a higher overshoot. When the feed disturbance on the intermediate component was analyzed (Figure 11c), the settling time required by the PI controller (about 20 h) was more than twice that required by the PII^2 controller. For the disturbance rejection on

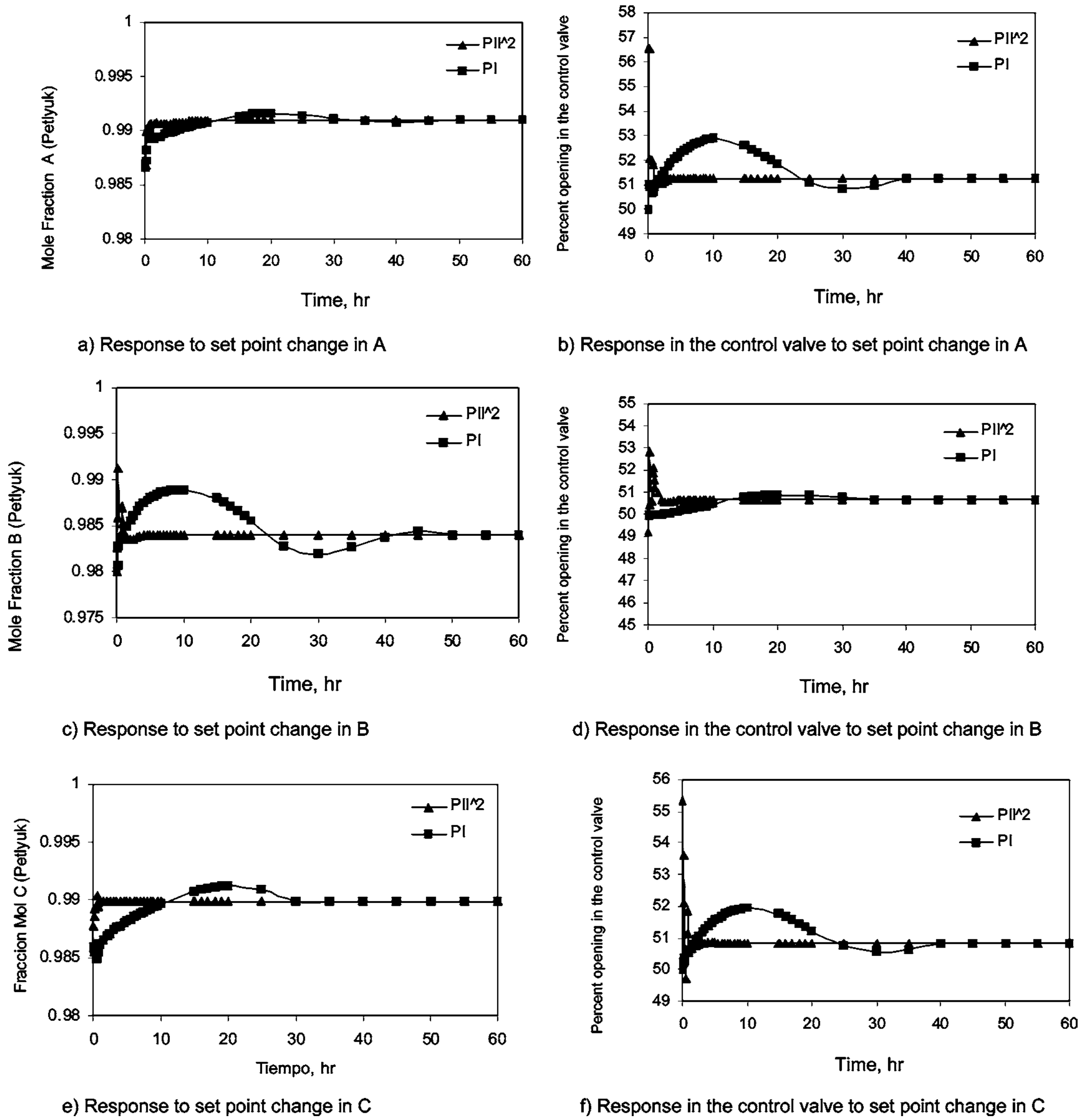

Figure 12. Dynamic responses for set point change of the Petlyuk column, mixture 1, and three closed loops.

Table 7. IAE Results for Feed Disturbance Test, M3 (One Closed Loop)

sequence	components	PII^2	PI
TCDS-SR	A	6.16×10^{-2}	4.05×10^{-1}
	B	6.47×10^{-2}	1.49×10^{-1}
	C	7.95×10^{-2}	1.02×10^{-1}
TCDS-SS	A	1.55×10^{-2}	8.14×10^{-1}
	B	2.75×10^{-2}	1.48×10^{-1}
	C	4.42×10^{-3}	8.55×10^{-2}
Petlyuk	A	5.04×10^{-2}	0.1290
	B	1.48×10^{-2}	8.47×10^{-2}
	C	0.1280	0.1767

Table 8. IAE Results for Set Point Change, M3 (One Closed Loop)

sequence	components	PII^2	PI
TCDS-SR	A	6.13×10^{-2}	4.66×10^{-1}
	B	4.78×10^{-2}	6.78×10^{-1}
	C	8.09×10^{-2}	7.19×10^{-1}
TCDS-SS	A	1.05×10^{-2}	8.79×10^{-2}
	B	4.78×10^{-2}	9.89×10^{-2}
	C	4.62×10^{-3}	6.58×10^{-2}
Petlyuk	A	5.21×10^{-2}	1.38×10^{-1}
	B	4.99×10^{-2}	7.48×10^{-1}
	C	0.1247	0.1759

the feed mole fraction of the heavy component (Figure 11e), the PII^2 controller yielded a quick readjustment of the product composition, while the PI implementation took about 4 h to stabilize. One can also observe in Figure 11 how the implementation of the PII^2 controller provided smother control actions by the control valves.

Figure 12 shows the responses of the Petlyuk arrangement when a simultaneous change in set points was implemented for the three product compositions. The PII^2 controllers provided smooth responses in the three control loops, while the action of the PI controllers yielded high settling times, particularly for the control loops of the B and C product streams. Control efforts provided by the PII^2 controllers were noticeably smoother.

When mixtures 2 and 3 were subjected to the same tests, similar trends on the dynamic responses of TCDS were obtained. It should be noted again that, in several of the tests conducted, the control valves became saturated (or completely closed) under the action of PI controllers. Overall, the PII^2 controller provided a remarkable performance, particularly when load changes in the feed composition were considered.

Tables 9 and 10 report the IAE values for the closed-loop responses for the three-point control tests for the three mixtures of the case studies. One can notice the improved dynamic behavior of the PII^2 control mode with respect to the imple-

Table 9. IAE Results for Feed Disturbance Test, Petlyuk Column (Three Closed Loops)

mixture	components	PII^2	PI
M1	A	6.09×10^{-2}	8.12×10^{-2}
	B	4.52×10^{-1}	7.99×10^{-1}
	C	1.69×10^{-1}	4.34×10^{-1}
M2	A	9.47×10^{-2}	8.41×10^{-1}
	B	1.00×10^{-2}	6.66×10^{-2}
	C	4.78×10^{-2}	6.78×10^{-2}
M3	A	5.94×10^{-2}	1.23×10^{-1}
	B	7.55×10^{-2}	1.84×10^{-1}
	C	6.29×10^{-2}	8.78×10^{-1}

Table 10. IAE Results for Set Point Change, Petlyuk Column (Three Closed Loop)

mixture	components	PII^2	PI
M1	A	2.33×10^{-2}	1.07×10^{-1}
	B	3.19×10^{-1}	9.87×10^{-1}
	C	2.66×10^{-2}	1.54×10^{-1}
M2	A	8.74×10^{-2}	7.00×10^{-2}
	B	1.99×10^{-1}	6.18×10^{-1}
	C	6.54×10^{-2}	3.05×10^{-1}
M3	A	5.15×10^{-2}	9.56×10^{-2}
	B	6.40×10^{-2}	8.01×10^{-2}
	C	7.39×10^{-2}	1.01×10^{-1}

Table 11. Sequences with the Best Dynamic Responses for Each Control Loop

	set point change		feed disturbance	
mixture (ESI)	control of A and C	control of B	control of A and C	control of B
M1 (1.04)	Petlyuk	Petlyuk	Petlyuk	TCDS-SS
M2 (1.86)	TCDS-SR	Petlyuk	TCDS-SR	TCDS-SR
M3 (0.18)	TCDS-SS	Petlyuk	TCDS-SS	Petlyuk

mentation of PI controllers. It should be noticed that the mixtures analyzed in this study do not pose particular difficulties for their separations. It might be of interest to explore further applications of the PII^2 controller on more difficult separation problems, including azeotropic mixtures.

5.4. Comparison of the Dynamic Performances of TCDS. An attempt was made to characterize the TCDS structures in terms of their best dynamic responses for all case studies. The trends of the results are summarized in Table 11. On the basis of the dynamic responses obtained, a distinction can be made between the best TCDS structure for the control of the extreme components of the ternary mixture (A and C) and the best scheme for the control of the intermediate component (B). This observation is consistent with previous results on the dynamic behavior of TCDS.[33] Seemingly, the most volatile and the heaviest components of the ternary mixture show similar dynamic and closed loop performances, but the behavior of the intermediate component poses a different control problem. The reason for this might be that the intermediate component sometimes shows inverse responses under open-loop operation. One can also see that the value of the ESI affects the dynamic performance of the TCDS options. For instance, for the control of the extreme components, either the servo or load disturbance case, the Petlyuk structure shows the best dynamic responses when ESI = 1, the TCDS with a side rectifier, when ESI > 1, and the TCDS with a side stripper, when ESI < 1. The only case in which there was a dominant thermally coupled arrangement for all values of ESI was for the servo problem of the intermediate component, and probably unexpectedly, the Petlyuk column provided the best dynamic responses for all mixtures.

6. Conclusions

The control of three thermally coupled distillation sequences with a proportional−integral controller with dynamic estimation of uncertainties was studied. The dynamic behavior of such a control mode was compared to the TCDS performances under a proportional−integral controller. Set point tracking and responses to feed load disturbances in composition were carried out. The results show that, for the three case studies and after tuning up the controller parameters of each control policy via the minimization of the IAE values, the closed-loop behavior under the PII^2 controller was significantly better than the responses obtained with a PI controller. The superiority of the PII^2 control option was particularly noticeable when the column was subjected to load disturbances. The reasons behind such an improved behavior have to do with the theoretical properties of the PII^2 controller that allow proper compensation of low-frequency disturbances; a proper corrective action can then be implemented to prevent significant deviations of the controlled output from the desired operating point. In general, the PII^2 controller has been found to have an excellent potential for the control of TCDS arrangements.

Nomenclature

A,B,C = ordered ternary mixture, with A being the most volatile component
$C(s)$ = controller transfer function
d = load disturbance
g_1,g_2 = uncertainty estimator gains
K_C = PI controller gain
K_e = PII^2 controller gain
K_P = process gain
s = Laplace domain variable
t = time
u = manipulated input
y = controlled output

Greek Letters

α = relative volatility
τ = process characteristic time
τ_C = nominal closed-loop characteristic time
τ_I = PI integral reset time

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