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Dynamic Control of a Petlyuk Column via Proportional-Integral Action with Dynamic Estimation of Uncertainties

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Abstract

A three point control configuration based on a proportional-integral controller with dynamic estimation of unknown disturbances was implemented in a Petlyuk column. The proposed controller comprises three feedback terms: proportional, integral and quadratic actions. The first two terms act in a similar manner as the classical PI control law, while the quadratic term (double integral action) accounts for the dynamic estimation of unknown disturbances. Comparison with the classical PI control law was carried out to analyze the performance of the proposed controller in face to unknown feed disturbances and set point changes. The results show that the closed-loop response of the Petlyuk column is significantly improved with the proposed controller.

1. Introduction

Since the energy consumption of distillation columns can have a significant influence on overall plant profitability, several strategies have been suggested to improve their energy efficiency. One strategy is the use of thermal coupling, in which the transfer of heat is accomplished by direct contact of material flow between two columns. For the separation of ternary mixtures, the Petlyuk column (also known as the fully thermally coupled distillation column) provides a choice of special interest (Figure 1). The Petlyuk column had not gained interest in the process industries until recent times (Hairston, 1999) even though its concept was established some 50 years ago (Brugma, 1937; Wright 1949). Savings in both energy consumption and fixed investment can be accomplished through the implementation of such a separation scheme. Theoretical studies have shown that Petlyuk columns can save up to 30% in energy costs compared to conventional schemes (e.g. Petlyuk et al, 1965; Glinos and Malone, 1988). Such results have promoted the development of more formal design methods (Triantafyllou and Smith, 1992; Hernández and Jiménez, 1999a; Amminudin et al, 2001; Muralikrishna et al, 2002). To promote a stronger potential for industrial implementation, a proper understanding of operation and control aspects are needed to complement the energy savings results. Recent efforts have contributed to the understanding of the dynamic properties of the Petlyuk column (Wolff and Skogestad, 1995; Abdul-Mutalib and Smith, 1998; Hernández and Jiménez, 1999b; Serra et al, 1999; Jiménez et al, 2001).

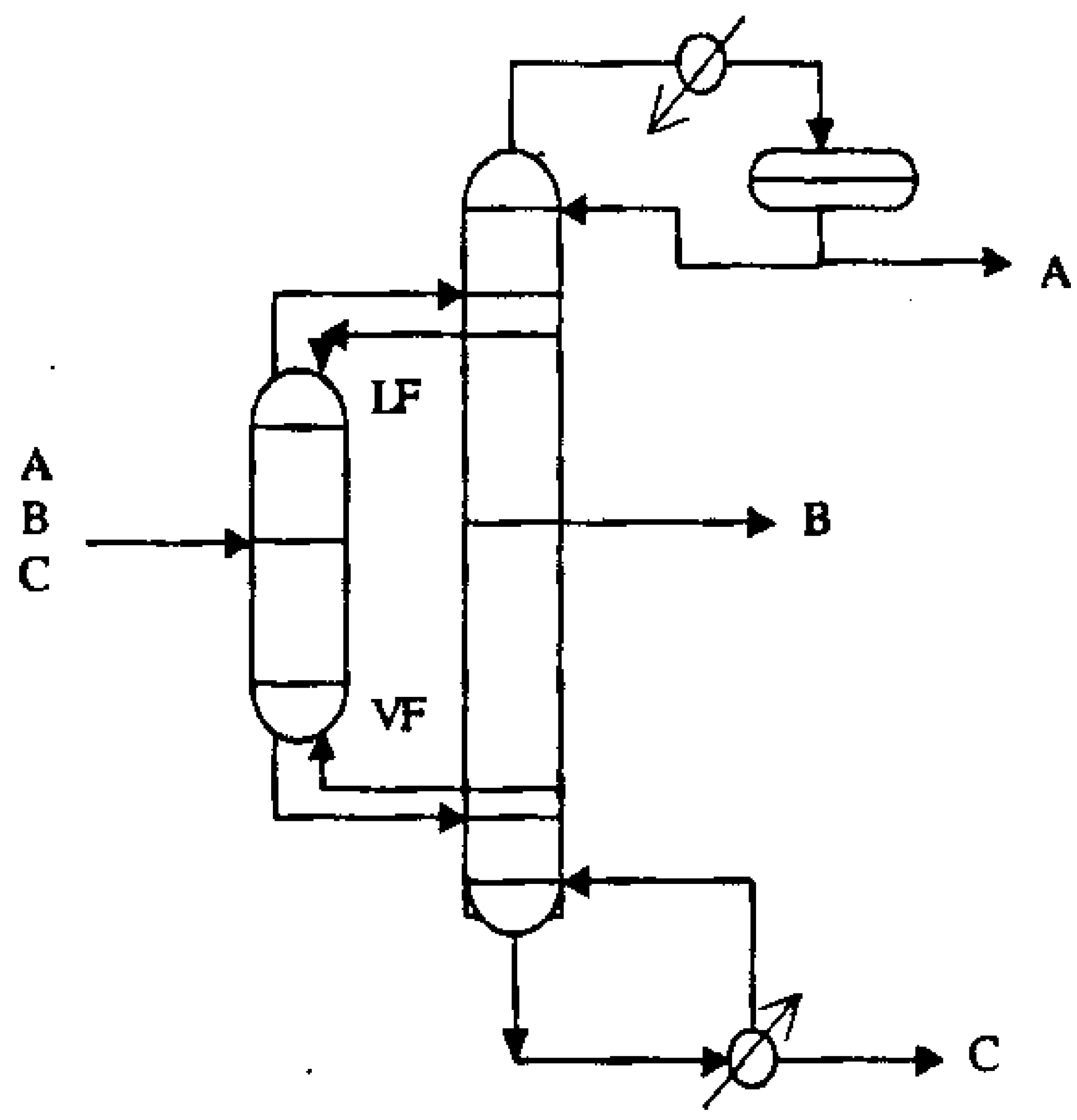


Figure 1. Petlyuk column.

The expectance that the dynamic properties of Petlyuk columns may cause control difficulties, compared to the rather well-known behavior of the conventional direct and indirect sequences for the separation of ternary mixtures, has been one of the factors that has contributed to their lack of industrial implementation. In this work, we analyze the closed-loop behavior of Petlyuk columns when a proportional-integral controller with dynamic estimation of unknown disturbances is implemented (Alvarez-Ramirez et al., 1997). The performance of the integrated column under such a controller is compared to the behavior under a traditional proportional-integral controller. The analysis is based on rigorous dynamic simulations, and two cases are considered: (i) set point tracking and (ii) output regulation under load disturbances in the feed mixture.

2. Design of Petlyuk Columns

A base design for the Petlyuk column was first obtained, followed by an optimization procedure to detect the base operating conditions under which the minimum energy consumption for such a design was achieved. The optimization procedure has been described by Hernández and Jiménez (1999a). An ODE model was formulated with equations for total mass, component mass and energy balances, along with ideal VLE and stage hydraulics relationships. After the model is formulated, the design problem of the Petlyuk column shows five degrees of freedom; three of them are consumed by the implementation of three control loops, and the two additional degrees of freedom are used as search variables to detect the operation with minimum energy consumption. The search variables we used were the flowrates of the liquid and the vapor interconnecting streams (LF and VF, Figure 1).

3. The PI Control with Dynamic Estimation of Uncertainties

The implementation of the output feedback control for distillation column can be configured such that only the liquid composition of the output flowrate is regulated (i.e., uncoupled one-point configuration control; see second example by Alvarez-Ramirez et al., 1998). In such a configuration, the liquid compositions for the main product streams A, B and C (see Figure 1) were taken as the controlled variables whereas, respectively, the reflux flowrate, the side stream flowrate and the reboiler heat duty were chosen as the manipulated variables. The ideas behind the simulations are (i) to show that Petlyuk column 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 (also called PII^2). The main idea behind the proposed 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 PI control law can be written as the following dynamic system (Luyben, 1990)

$$\begin{aligned} u &= K_C(y-r) - z \\ \dot{z} &= K_I(y-r) \end{aligned} \tag{1}$$

where r stands for the input reference, y denotes the system output and z is the integral of the control error. The constants K_C and $K_I = K_C/\tau_i$ (where τ_i denotes the reset time) stand for the proportional and integral gains, respectively. The estimated value of the input d is computed via the following equations:

$$\dot{\bar{y}} = -\frac{1}{\tau}y + K_P u + \bar{d} + g_1(y - \bar{y}) \tag{2}$$

$$\dot{\bar{d}} = g_2(y - \bar{y}) \tag{3}$$

where $\bar{d}$ and $\bar{y}$ are, respectively, the estimated values for d and y whereas g_1 and g_2 are estimation constants, which must be strictly positive to guarantee convergence of the estimation errors $e_1 = (y - \bar{y})$ and $e_2 = (d - \bar{d})$ to the origin, i.e., if $g_1,g_2 > 0$ then $(e_1,e_2) \to (0,0)$ for all time $t > t_0 > 0$ and any initial condition $e_{1,0} = e_1(0)$, $e_{2,0} = e_1(0) \Rightarrow y \to \bar{y}$ and $d \to \bar{d}$ for all $t > t_0 > 0$ and any initial condition at the physically realizable operation of the column (Femat et al., 1999). Note that equations (1) - (3) are linear; therefore, one can readily obtain a transfer function for the system. Indeed, the transfer function takes the form: $C(s) = u(s)/e_C(s) = K_C + K_I/s + K_E/s(\tau_{II}s + 1)$, where $s = \omega j$, $j = (-1)^{1/2}$ and $e_C(s) = (y(s) - r(s))$; $K_E = K_E(g_1,g_2)$ and $\tau_{II} = \tau_{II}(g_1,g_2)$ stand for the gain and characteristic time of the dynamic estimation term (namely $K_E/s(\tau_{II}s + 1)$). Note that such a term is quadratic and provides a dynamic estimation of the input d, which can represent load disturbances (regulation problem) or step changes in references (servo-control problem). For further details on tuning and closed-loop stability analysis of the PII^2 controller, see Alvarez-Ramirez et al. (1997) and Femat et al. (1999), respectively.
The performance of the PII^2 controller was compared with the performance of the classical PI control action, which is a widely-used type of controller in the chemical industry. Both controllers were tuned following the criterion of the integral of the absolute error (IAE), such that the values of the control gains (K_C, K_I and τ_i in the case of PI controllers, or K_C, g_1 and g_2 in the case of the PII^2) that provided a minimum value of IAE for a set point change for each separation scheme were detected.

4. Separation Objective and Control Goals

The analysis presented in this work is based on the separation problem of three different ternary mixtures with molar compositions (A, B, C) equal to (0.40, 0.20, 0.40) and product purities of 98.7, 98 and 98.6 percent, respectively. The three mixtures considered were n-pentane, n-hexane and n-heptane (mixture 1), n-butane, isopentane and n-pentane (mixture 2), and isobutane, n-butane and n-hexane (mixture 3). Two set of simulations were carried out. (i) *Servo-control*: Step was induced as set point changes for each product composition under SISO feedback control at each output flowrate (see Figure 1) and (ii) *Regulation under load disturbances*: the effect of feed composition disturbances was induced to test and compare the performance of the proposed controller (a 5% change in the composition of one component with the same total feed flowrate).

5. Dynamic Simulations and Results

The dynamic results are presented on a comparative basis to allow for a better assessment of the controllers performance. For mixture 1, the results of the IAE values for the case of responses in the face to feed disturbances show that the PII^2 controller provides a better behavior than the PI controller. Table 1 shows how the IAE values for the PII^2 controller are smaller than those for the PI controller. The highest values for IAE, which reflect the most difficult control task, are obtained for the stabilization of the intermediate component. This is probably because the dynamic behavior of the composition of the intermediate component under open loop operation shows an inverse response. However, it should be noted that the most significant improvement of the PII^2 controller over the PI controller was obtained for the control of the intermediate component (in contrast to the control problem of the lightest and heaviest components).

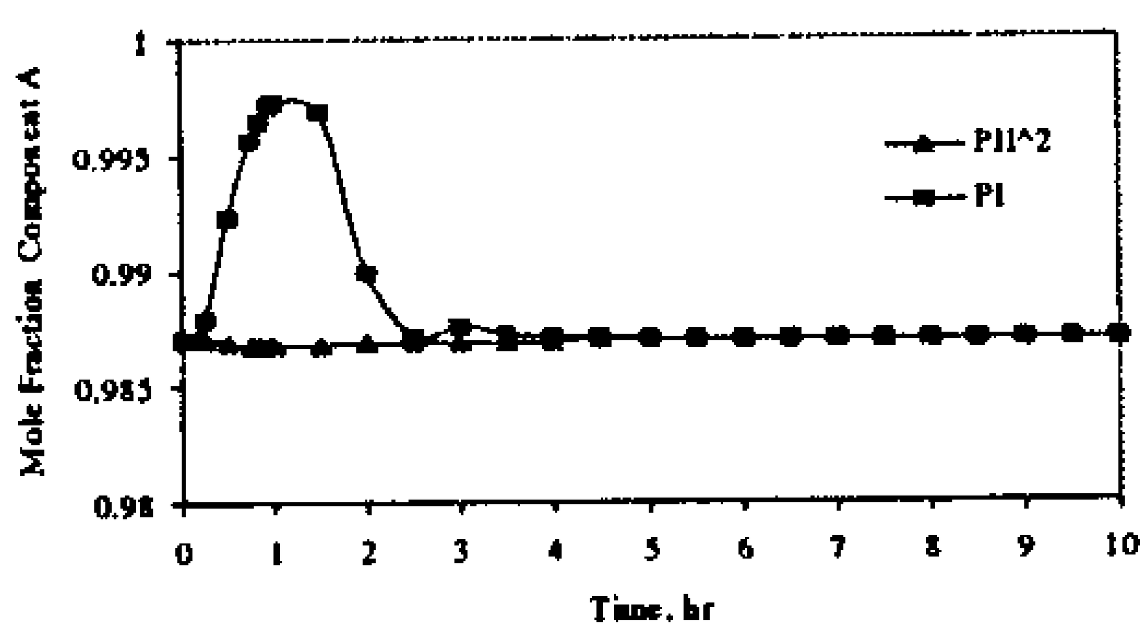
Table 1. IAE results for the mixture 1 under load disturbances at feed compositions.

Component	PII^2	PI
A	1.2296×10^{-2}	2.2082×10^{-2}
B	2.8259×10^{-1}	8.7463×10^{-1}
C	1.745939×10^{-2}	3.1119×10^{-2}

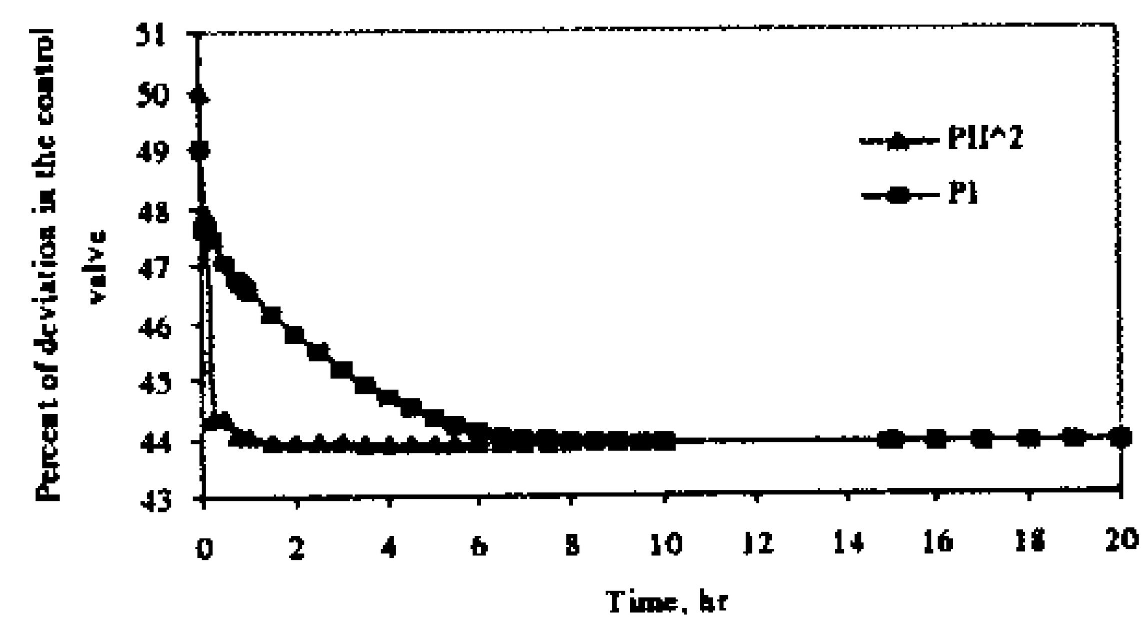
A more detailed analysis of the dynamic performance obtained for the lightest (A) component and the heaviest (C) component follows. Figure 2 displays the simulation results obtained for the control analysis of component A. When load disturbances were induced, the PII^2 controller adjusts the composition of product A smoothly, while the PI action shows a significant time period of product quality deterioration (Figure 2a). The control effort, measured through the changes in the control valves positions (Figure 2b), reflects the superior performance of the PII^2 controller accordingly. When a set point change in the composition of component A was imposed, the controllers showed a fairly similar behavior, as observed in Figures 2c and 2d.

Figure 3 shows some results obtained for the control of the heaviest component. A superior behavior of the PII^2 option is again evident. Although for the set point tracking case (Figure 3c), the use of the PII^2 controller shows only a slightly better performance than the PI controller, a remarkable improvement of the use of the PII^2 controller is obtained when responses against feed disturbances were considered (Figure 3a).

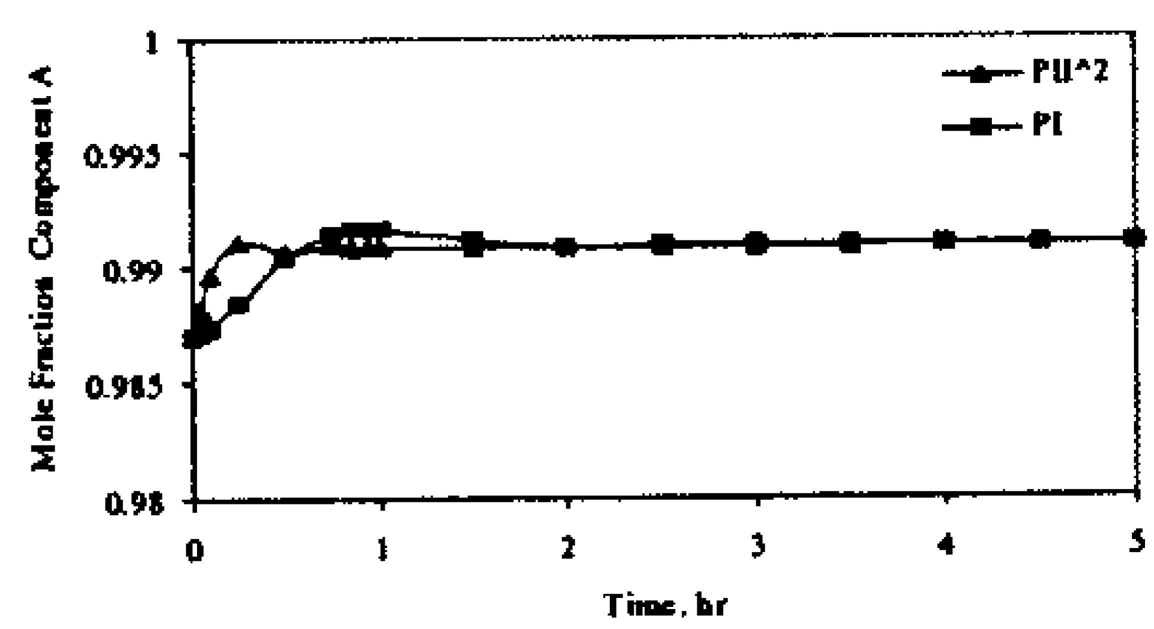
For the case of set point tracking, the responses of the system under the action of either the PII^2 controller or the traditional PI controller were not significantly different, although the use of the PII^2 controller provided generally a faster adjustment with fewer oscillations. When the response of the column to feed disturbances was analyzed, the PII^2 controller provided a remarkable improvement over the use of the PI controller; while in several cases the implementation of the PI controller yielded extremely high settling times, the PII^2 controller showed an excellent capability to eliminate the feed disturbance fast and without overshoot problems. As far as control efforts are concerned, the implementation of the PII^2 controller provided smoother control actions; the variations in control valves positions were minor, in contrast with the results for the PI-classical control mode, in which the valves even became saturated (or completely closed) in several of the tests conducted.



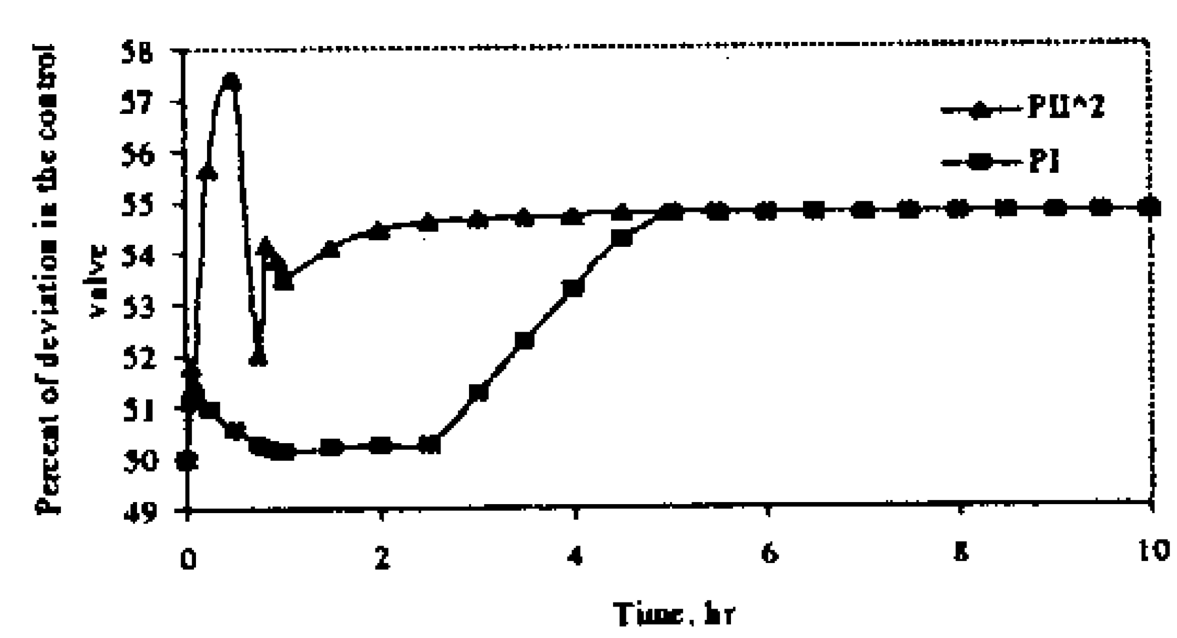
a) Response to feed disturbance in composition A



b) Response in the control valve to feed disturbance in component A

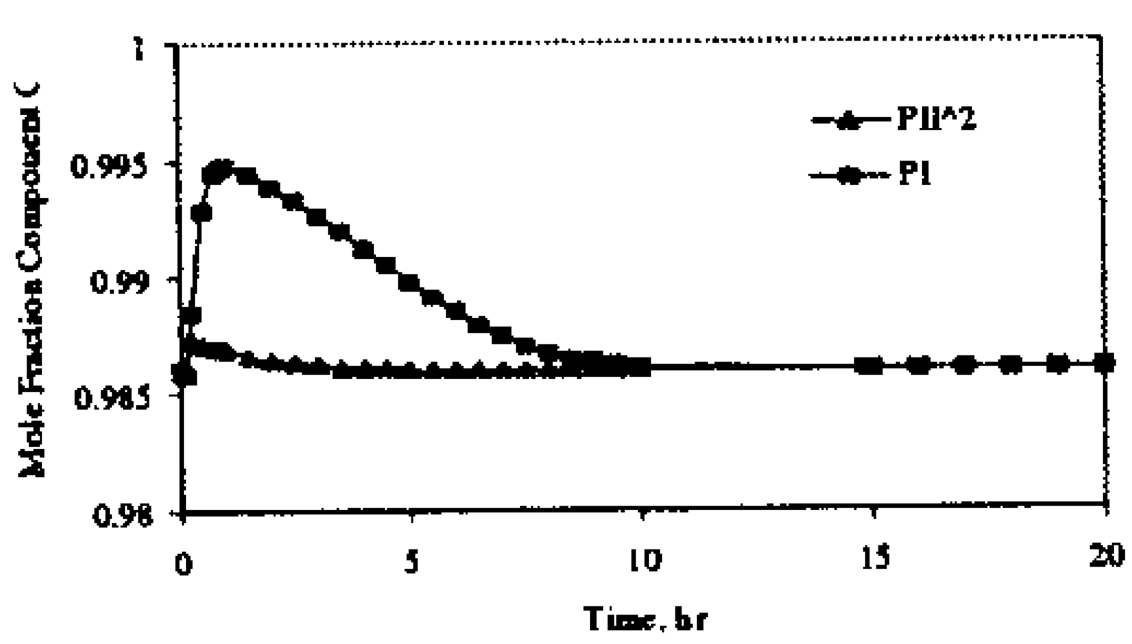


c) Response to set point change in composition A

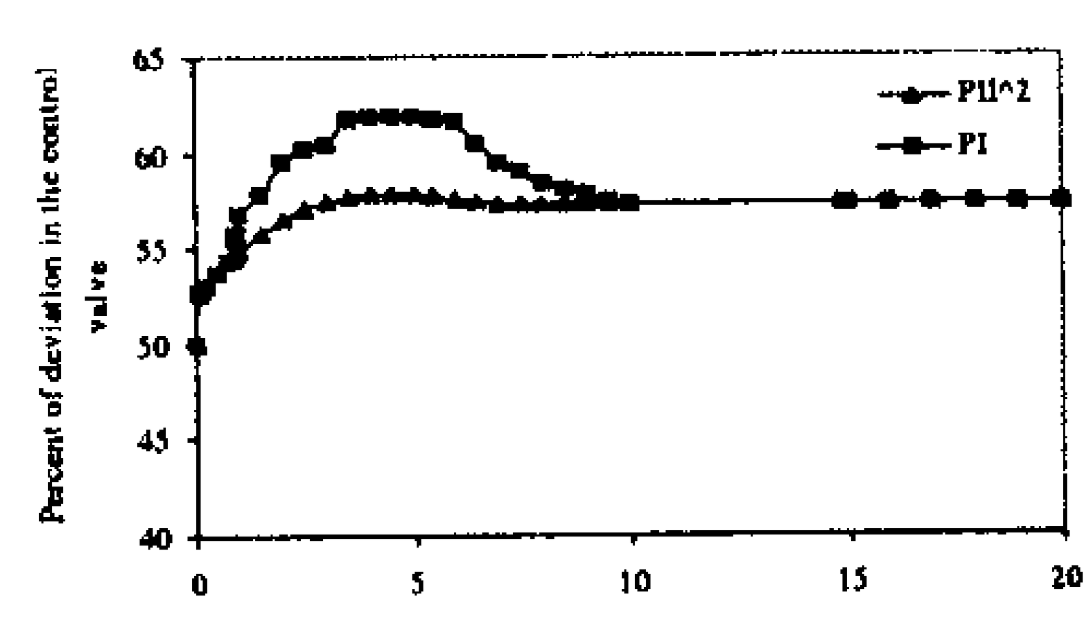


d) Response in the control valve to set point change in component A

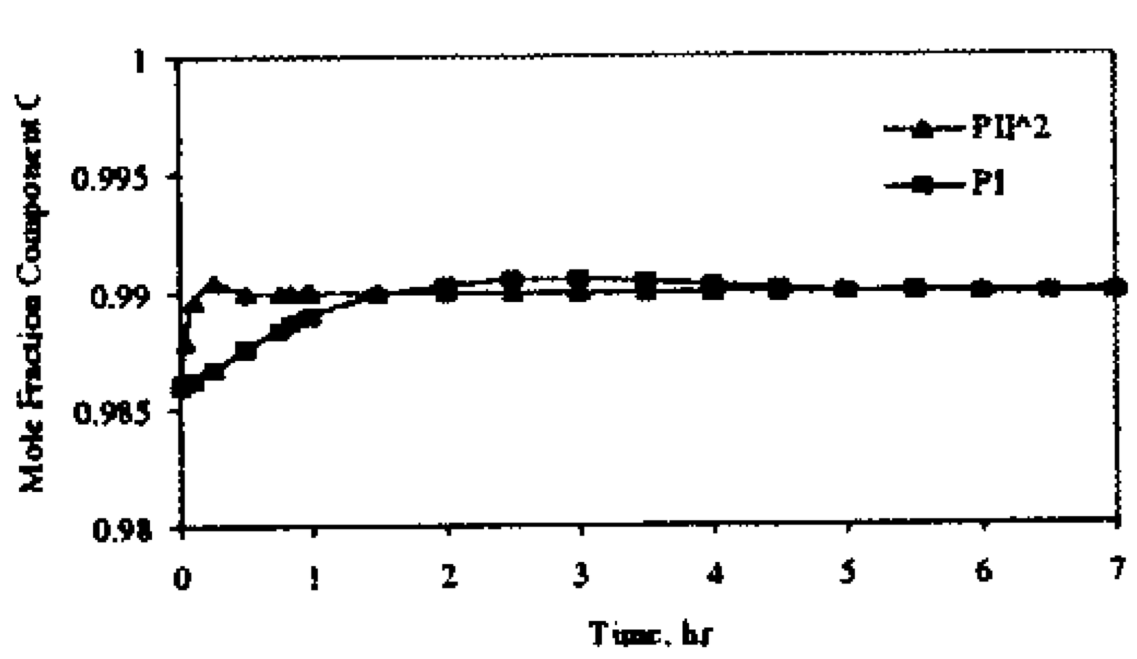
Figure 2. Some representative dynamic responses (component A) for the separation of mixture 1.



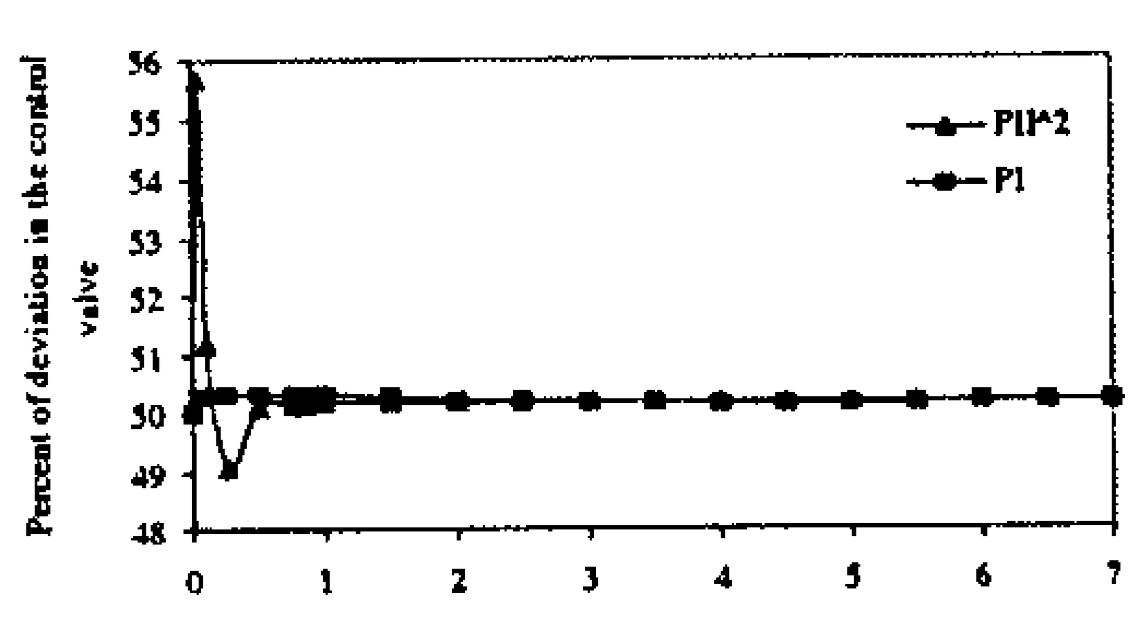
a) Response to feed disturbance in composition C



b) Response in the control valve to feed disturbance in component C



c) Response to set point change in composition C



d) Response in the control valve to set point change in component C

Figure 3. Some representative dynamic responses (component C) for the separation of mixture 1.

When mixtures 2 and 3 were subjected to the same tests, similar trends on the dynamic responses of the Petlyuk column were obtained. Particularly, the PII^2 controller provided a remarkable performance when load changes in the feed composition were considered. The smooth performance of the PII^2 controller is induced by its disturbance estimator, which resembles the structure of linear state observers.

6. Conclusions

The control of a Petlyuk column with a proportional-integral controller with dynamic estimation of uncertainties was analyzed. The dynamic behavior of this action was compared to the Petlyuk column performance under a proportional-integral controller. Set point tracking and responses to feed composition disturbances were analyzed. The results obtained for three case studies show that, after optimizing the controller parameters of each control policy, the closed loop behavior under the PII^2 control mode 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 feed disturbances. The properties of the PII^2 controller allow a proper detection of disturbances and a proper corrective action to prevent the controlled output from significant deviations from the desired operation point. In general, the PII^2 controller has been found to have an excellent potential for the control of the Petlyuk column.

7. References

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8. Acknowledgements

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