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Conventional Proportional−Integral (PI) Control of Dividing Wall Distillation Columns: Systematic Tuning

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ABSTRACT: This work addresses the systematic tuning of proportional−integral (PI) controllers for dividing wall distillation columns. By following an approach of stable pole assignment to a linear dynamics that approximately describes the control system convergence, a technique results that forces the gains of controllers to be dependent on well-known parameters for each control loop: a static gain and a time constant that characterize the open-loop response of the output with respect to the control input, and a damping factor and a response velocity that outline the path of the closed-loop response. Then, it becomes possible to tune all the controllers in a simultaneous way, substantially reducing trial-and-error activities on tuning the entire control system. Via simulation, the control system performance is illustrated for disturbance rejection and set-point tracking in a representative dividing wall distillation column, showing that this tuning technique is an effective choice.

1. INTRODUCTION

Distillation is a separation process that offers an effective way to separate mixtures of liquids; this process is the most used in the chemical industry, but it has the disadvantage of being a large consumer of energy, accounting for up to 50% of operating costs of a plant.[1] For that reason, designs that can provide reductions in energy requirements are being explored in both academia and industry. Options that have been being considered are the thermally coupled distillation sequences, which can reduce the energy consumption, compared to conventional distillation schemes.[2−4] Thermally coupled distillation sequences can result in an energy savings of 30%−50%, depending on the composition of the mixture to be separated, in contrast to the well-known conventional distillation sequences.

Among the thermally coupled distillation sequences, maybe the most important is the fully thermally coupled distillation sequence or Petlyuk distillation column (see Figure 1); this complex distillation sequence involves a prefractionator coupled to a main distillation column, using two recycle streams. One recycle, in the form of liquid, is fed into the top of the prefractionator, and the second one, in the form of vapor, is injected directly into the bottom of the prefractionator. By physical and practical restrictions, the Petlyuk distillation column has been implemented using a single shell divided by a wall, and then called dividing wall distillation column (DWDC), because this is thermodynamically equivalent to the Petlyuk column when no heat transfer occurs through the wall. Indeed, this configuration has been successfully implemented in industry since some decades ago,[5] where the predicted energy savings and reductions in capital costs have been achieved.

Studies regarding short cut and rigorous design methods have driven some industrial applications of DWDCs,[6,7] but the control and operation have not been studied to the same depth. Initially, this class of processes was supposed not easy to control; however, some works have reported performances of DWDC control systems that become even better than corresponding conventional systems.[8,9] Then, the inherent valuable issue after DWDC design is to obtain an appropriate control system. In conventional distillation, configurations from conventional approaches up to advanced ones have been applied to design control systems. Those based on conventional PI controllers have shown an efficient performance,[10] and those based on advanced control have been explored with motivating results.[11,12] For complex distillation systems, a similar procedure is followed,[13−15] and it is noteworthy that PI controllers seem to be sufficiently efficient to operate distillation columns.

Going through control systems of DWDCs and Petluyk columns with conventional PI controllers,[16,17] the demanding tasks of design have relied on defining the control structure. Ling and Luyben[18] have recently reviewed the problem of defining control structures, underlying that different workers recommend different control structures in which three product purities should be controlled, and, in addition, they have proposed a fourth controlled variable that is related to the minimization of the energy consumption. Once the control structure is settled down, and since construction of controllers is straightforward, the next demanding task is the tuning of controllers. In a similar way, different works follow different tuning approaches and techniques; for example, one approach is to tune each controller sequentially by scanning values of gains to minimize an index of convergence,[14] or by applying tuning rules based on a continuous cycling method;[18] in other methods, methods of direct synthesis and internal model control are followed.[19] In addition, although typically the tuning procedure is not described extensively, it can be observed that this task has somewhat of trial and error

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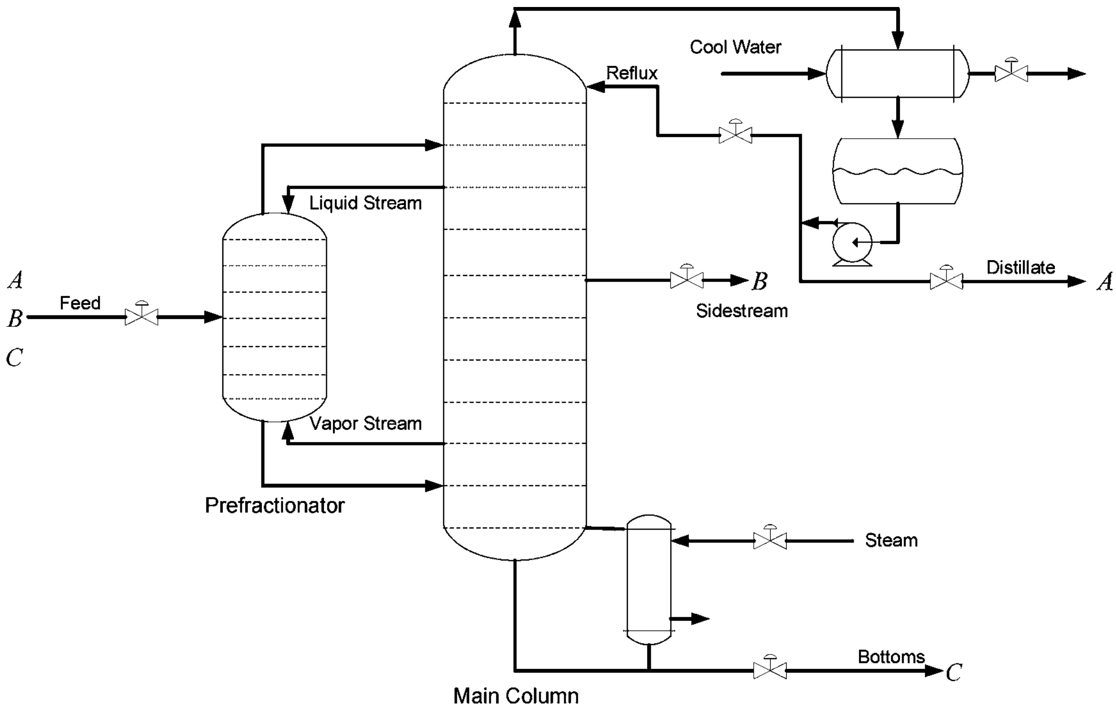

Figure 1. Petlyuk column.

activity. Then, as well as control works for the attempts of DWDCs to obtain a convenient control configuration, a framework for tuning in a systematic way is convenient.

In this work, the tuning of PI controllers for DWDCs is addressed within a pole placement framework to compute values of controller gains, in terms of well-known (and identifiable) parameters for each control-loop (input−output pair), such as static gains and time constants. The goal is to establish a methodology that reduces the number of tuning freedom degrees that inclusively allows a simultaneous tuning of all controllers. As a representative case, the DWDC control system of Ling and Luyben[18] is recalled to characterize and illustrate the functioning and performance provided by the resulting technique. It is important to mention that, in industrial practice, for distillation columns, it is more common to control temperatures instead of compositions, since the last option requires an online gas chromatograph, but the main objective of this work is the comparison of closed-loop dynamic responses for the composition control system reported in Ling and Luyben[18] and the proposed method using pole assignment.

2. THE DWDC CONTROL SYSTEM AND THE TUNING PROBLEM

2.1. Dividing Wall Distillation Column (DWDC). A dividing wall distillation column (DWDC) to separate continuously a ternary mixture is considered (see Figure 2). The column is built of N stages, along with a dividing wall that runs from stage N_{DS} up to stage N_{DI}; the first stage is the condenser and the final one is the reboiler. The DWDC is modeled using the radfrac module contained in Aspen Plus, which includes transient total mass balance, transient component mass balances, liquid−vapor equilibrium, summation constraints, and energy balance in each equilibrium stage.

At stage N_F, the mixture of composition $z_1/z_2/z_3$ (given in mol %, in order of volatility) is fed at a rate F_F, temperature T_F, and pressure P_F. The wall cannot be located at the middle of the cross-sectional area of the column; thus, the vapor split ratio is S_V, and the liquid split ratio is S_L, according to the fraction of the fluid that passes by the prefractionator side (or feeding side). The column is operated under a reflux ratio R and a reboiler heat input Q, with a sidestream flow F_S, at the intermediate stage N_M on the opposite side of the feeding; this way, one obtains a distillate stream rich in the more-volatile component, a sidestream rich in the intermediate volatile component, and the less-volatile component is obtained from the bottom. Equivalently, following the conventional distillation control wisdom,[18] which suggests that one focus on impurities in the output streams because these are more sensitive to process conditions than purities, one obtains the distillate stream (with a composition x_D of the intermediate volatile component), the sidestream (with a composition x_S of the less-volatile component), and the bottom stream (with a composition x_B of the intermediate volatile component).

The operative goal is to obtain every output stream within a low level of impurity that will maintain a certain purity level, which can be achieved by manipulating R, Q, F_S, and even S_L. For the sake of simplicity, it is assumed the DWDC is equipped with devices that regulate liquid levels in the reboiler and the condenser, as well as guarantee a base pressure P_B and temperature T_B. In addition, Ling and Luyben[18] advise another operative goal: to maintain minimum energy consumption, which is driven through the composition x_{NS-1} of the less-volatile component at stage N_{S-1}, which is affected by S_L. Indeed, Wolf and Skogestad[8] prompted that the manipulation of the liquid split is important, since energy consumption is strongly dependent on it.

2.2. Control System. The DWDC is a system of a set y of four outputs ($y = (x_D, y_{P10}, x_S, x_B)$), which can be controlled through a set u of four control inputs ($u = (R, S_L, F_S, Q)$), facing potential changes in nonmanipulated and/or nonknown

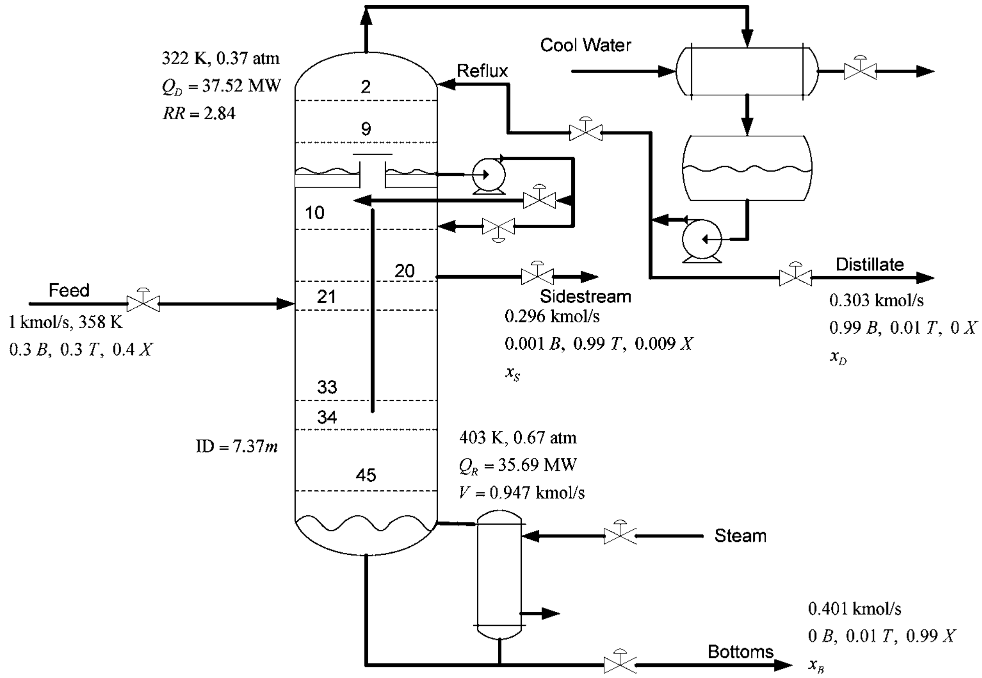

Figure 2. Dividing wall distillation column (DWDC) flow sheet.

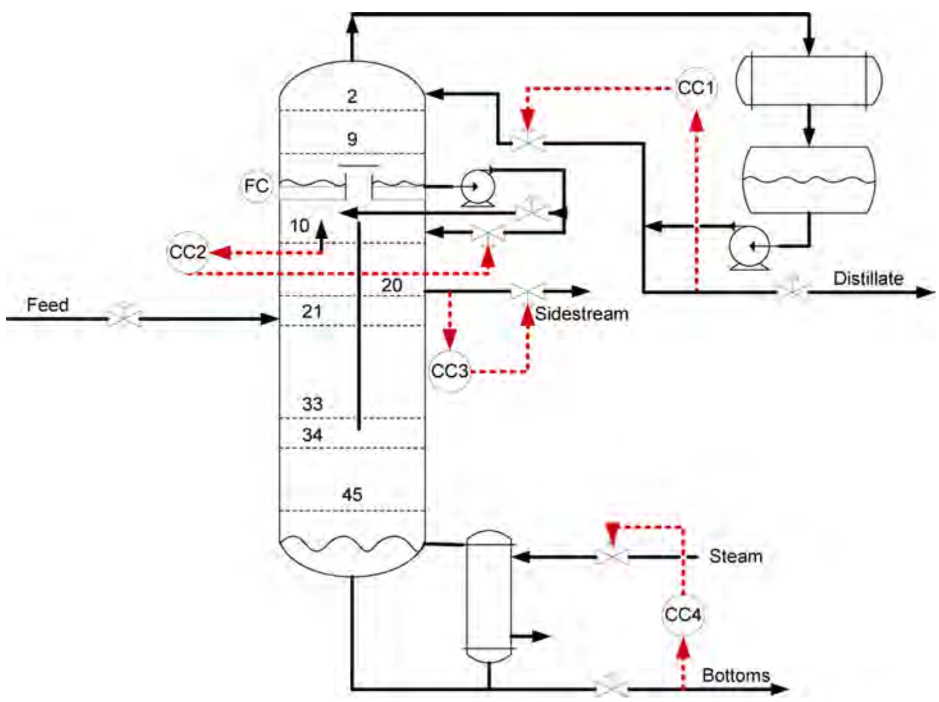

Figure 3. DWDC control system.

disturbances, such as $z_1/z_2/z_3$ and F_F. Toward the construction of an automatic control system based on PI controllers, the multiple inputs and multiple outputs set out the problem of defining a control configuration, where different control configurations result. Following Ling and Luyben,[18] an effective control system (Figure 3) is conformed by the following control loops:

$$L_j: (u_j, y_j): \quad L_1: (R, x_D), \quad L_2: (S_L, y_{P10}),$$
$$L_3: (F_S, x_S), \quad L_4: (Q, x_B) \tag{1}$$

For each control loop, the PI controller is

$$u_j = \bar{u}_j + K_C^j\left(\tilde{y}_j + \frac{1}{\tau_I^j}\int_0^t \tilde{y}_j(s)\,ds\right)$$
$$\tilde{y}_j = \bar{y}_j - y_j \quad (j = 1, 2, 3, 4) \tag{2}$$

$\bar{y}$ and $\tilde{y}$ are the nominal and deviation values of the variable y, respectively. K_C^j and τ_I^j are the proportional gain and the integral time, respectively, of the controller for the control loop L_j (eq 1).

2.3. Tuning Problem. At this point, the designing of a control system for DWDCs has just recalled previous works; the tuning of controllers continues to be a problem. Whatever the control configuration is settled down, there are two gains to be determined for each control loop; in the above case, a total of eight gains result. Such a number of parameters set out the problem of developing a systematic tuning technique, which, in this work, is considered to mean a technique with a reduced number of tuning buttons (that drive all the controllers), that uses the simplest information that can be obtained from a process: response time and sensitivity of the process, with respect to certain inputs.

Thus, resorting to a pole-placement approach, and based on the type of first-order dynamics that is identified for each control loop, the tuning problem consists of obtaining tuning relationships in terms of time constants and static gains, as well as tuning parameters that drive the convergence behavior of all of the controllers.

3. DEVELOPMENT OF THE TUNING TECHNIQUE

In this section, the tuning technique is developed by assigning stable poles to the dynamics that approximately describes the convergence of certain output when the corresponding PI controller is implemented.

First, we consider a first-order dynamics that approximately describes the response of each output, with respect to its paired control input:

$$\dot{\tilde{y}}_j = -\left(\frac{1}{\tau_P^j}\right)\tilde{y}_j + \left(\frac{K_P^j}{\tau_P^j}\right)\tilde{u}_j$$

$$\tilde{y}_j = \bar{y}_j - y_j, \quad \tilde{u}_j = \bar{u}_j - u_j \quad (j = 1, 2, 3, 4) \tag{3}$$

Conventionally, the time constant (τ_P^j) and the static gain (K_P^j) for each input−output pair j are identified based on the y_j responses of the current process, generated by applying step changes in its corresponding control input (u_j).[20] Although a time-delayed dynamics can arise, for tuning purposes, the time delay is not taken in account.

Implementing controller (eq 2) in the approximate process dynamics (eq 3), the following second-order linear dynamics result:

$$\left(\frac{\tau_P^j}{K_P^j}\right)\left(\frac{\tau_I^j}{K_C^j}\right)\ddot{\tilde{y}}_j + \left(\frac{K_P^jK_C^j + 1}{K_P^jK_C^j}\right)\tau_I^j\dot{\tilde{y}}_j + \tilde{y}_j = 0 \tag{4}$$

This dynamics is supposed to describe approximately the behavior of each closed loop L_j. As it can be noticed, its peculiarity is that the poles can be assigned through the values of the gains (K_C^j, τ_I^j).

Toward the determination of gain values, consider the following second-order dynamics of reference:

$$(\tau_R^j)^2\ddot{y}_R^j + 2\xi_R^j\tau_R^j\dot{y}_R^j + y_R^j = 0 \qquad \xi_R^j, \tau_R^j > 0 \tag{5}$$

This dynamics has stable poles whose convergent behavior is drawn through its well-known parameters:[21] ξ_R^j is the damping factor, and τ_R^j is the natural time. Next, establishing the settling time of this reference dynamics (t_R^j), as a fraction of the settling time of the output response dynamics (eq 3) (t_P^j),

$$t_R^j = \left(\frac{1}{n}\right)t_P^j$$

where

$$t_R^j = \frac{4\tau_R^j}{\xi_R^j}, \quad t_P^j = 4\tau_P^j$$

the natural time of reference τ_R^j is written in terms of the time constant of process τ_P^j, as follows:

$$\tau_R^j = \left(\frac{1}{n}\right)\xi_R^j\tau_P^j \tag{6}$$

Thus, n can be considered as the number of times that the reference dynamics (eq 5) is faster than the natural dynamics of the process (eq 3).

To make the closed-loop dynamics (eq 4) behave as the convergent reference dynamics (eq 5), poles of eq 4 must be equal to those of eq 5, or, in other words, the poles of eq 5 must be assigned to eq 4. This is easily done by matching the coefficients of eq 4 with the corresponding coefficients of eq 5, and with the previous insertion of eq 6 in eq 5, the controller gains results in the following form:

$$K_C^j = \frac{2n - 1}{K_P^j}, \qquad \tau_I^j = \tau_P^j(\xi_R^j)^2\left(\frac{2n - 1}{n^2}\right) \tag{7}$$

Then, tuning expressions (eq 7) are obtained to give values to the gains in terms of the natural behavior of the process (through τ_P^j and K_P^j), and certain new parameters: ξ_R^j and n. In addition, note that the proportional gain K_C^j is dependent on static gain K_P^j, but not on the constant time τ_P^j, and in a similar sense, integral time τ_I^j depends on the constant time τ_P^j, but not on the static gain K_P^j. Furthermore, if a same value ξ is considered for every ξ_R^j, then the number of tunning buttons for the entire control system is reduced to two: ξ and n.

3.1. Systematic Procedure of Tuning. Based on the tuning expressions (eq 7), the following procedure for tuning all controllers is outlined:

(1) For every input−output pair, identify the corresponding first-order dynamics parameters: τ_P^j and K_P^j.
(2) Set a damping factor (ξ). It is worth mentioning that setting a value for ξ may result from different criteria. In example, the value of ξ that results of minimizing the ITSE of a second-order dynamics, with a natural time equal to 1, is 0.7865; if the criterion is to choose a ξ in such a way the overshoot of a second-order dynamics does not exceed 2%, the resulting value is 0.8412; and, a typical value of damping factors is 0.7071.
(3) Set a value of n. In example, in a first trial, set $n = 1$.
(4) Apply the tuning relations 7 to calculate all controller gains: K_C^j and τ_I^j.
(5) Test the performance of controllers.
(6) If greater convergence rate is desired, and/or feasible according practical constraints, repeat from step 3 with a greater value of n.

As a remark: once the dynamics parameters for every input−output pair are identified, and a damping factor is settled down, all the controllers are adjusted by only one tuning button (n).

4. CONTROL SYSTEM PERFORMANCE

To test the performance that provides the tuning technique, the DWDC control system of Ling and Luyben[18] was recalled, indeed described above, and implemented in Aspen Plus. For this, the DWDC was simulated in Aspen Plus using a stripping column with only one reboiler, two absorber columns in parallel

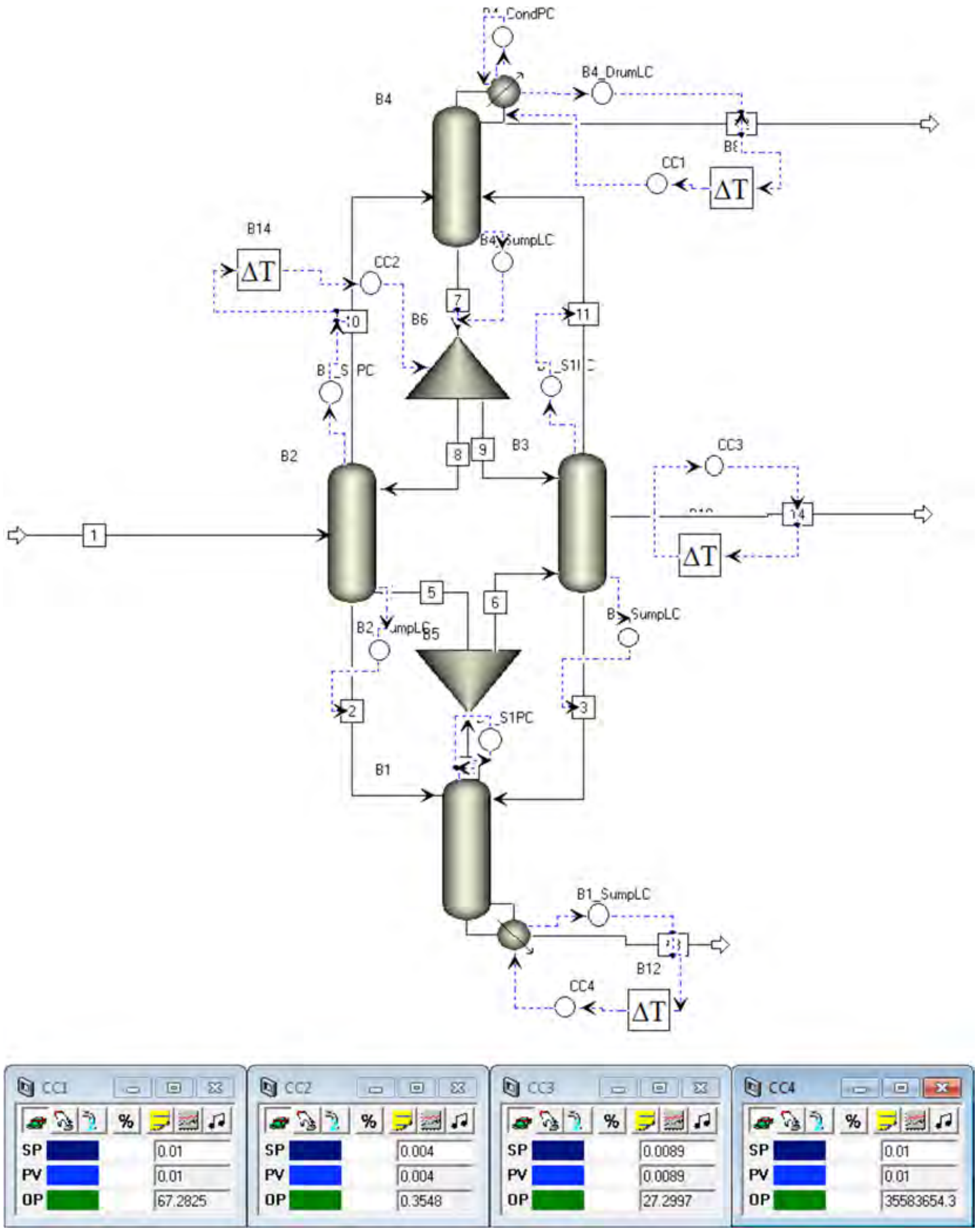

Figure 4. DWDC implementation in Aspen Dynamics.

Table 1. Composition of the Components in the Column's Streams

component	feed composition (mol/mol)	distillate composition (mol/mol)	sidestream composition (mol/mol)	bottoms composition (mol/mol)	composition of the stage 1 prefractionator (mol/mol)
benzene	0.3	0.99	0.001	0	0.543
toluene	0.3	0.01	0.99	0.01	0.453
o-xylene	0.4	0	0.009	0.99	0.004

without any reboiler or condenser, and a rectifying column with only one condenser. Chao−Seader was used to calculate the physical properties of the components. Once the steady-state simulation was settled down, the DWDC was exported to Aspen Dynamics, where the control loops were implemented (see Figure 4). For this DWDC: $N = 46$, $N_{DS} = 10$, $N_{DI} = 33$, $N_F = 21$, $N_M = 20$, $F_F = 1$ kmol/s at $T_F = 358$ K (saturated liquid mixture of benzene−toluene−xylene); $R = 2.84$, $F_S = 0.296$ kmol/s, $S_L = 0.353$, and $Q = 35.69$ MW. Table 1 shows the components and composition of the ternary mixture fed to the DWDC, and compositions of output streams. The above values, also recalled from Ling and Luyben,[18] were assumed to be the nominal ones. To complete the steady-state design, a pressure drop of 0.0068 atm for each valve tray was assumed, and rigorous hydraulics was

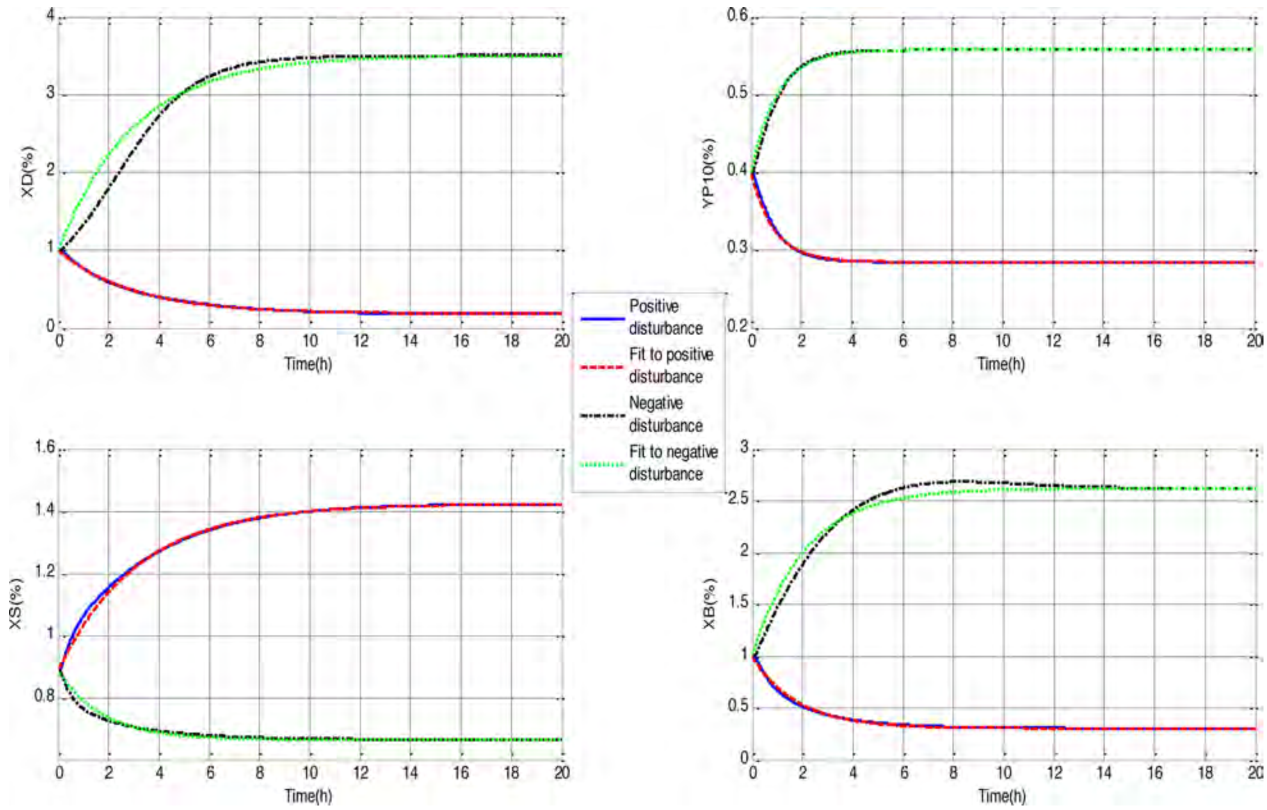

Figure 5. DWDC dynamics fit to a linear dynamics.

considered (Figure 2). Thus, the test was based on maintaining compositions of output streams, particularly the corresponding impurity (x_D, y_{P10}, x_S, x_B), in their nominal values by rejecting changes on the flow or/and composition of the input stream. For disturbance cases, as in the work of Lin and Luyben,[18] a dead time of 5 min was implemented in every composition control loop; and positive and negative changes, 5% in magnitude, in the flow and composition of the feed were implemented after 2 h of operation under nominal conditions.

In order to identify parameters of the process dynamics (τ_P^j, K_P^j), open-loop responses for each input−output pair were generated by applying positive step changes, in 1% of magnitude, sequentially in each control input.[22] Figure 5 illustrates some representative open-loop responses for impurity composition in the distillate, the sidestream, the top of the prefractionator and the bottom. All of the responses were adequately fit with first-order dynamics. Following step 2 of the tuning procedure, the damping factor for all of the controllers was set to 0.8412. By applying tuning relationships (eq 7), several values of n were tested, beginning with $n = 1$; Table 2 shows the resulting values of controller gains for n = 4. Note that the gains of all of the controllers were simultaneously tuned since the same value of n was used for all of the controllers.

Table 2. Parameters for Controller Tuning Relationships and Resulting Gains

controlled variable	manipulated variable	static gain, K_P^j (%/%)	time constant, τ_P^j (h)	controller gain, K_C^j (%/%)	controller integral time, τ_I^j (h)
$x_{D(T)}$	R	90.7	2.9873	0.0771	0.9248
$y_{P10(X)}$	S_L	34.5	0.9803	0.2029	0.3035
$x_{S(X)}$	F_S	42	2.4703	0.1667	0.7647
$x_{B(T)}$	Q	85	1.9536	0.08235	0.6048

To show the effect of parameter n on the convergence rate, Figure 6 depicts the trajectory of the x_D controller for the different values of n (n = 1, 2, and 4), when a change in the flow of input stream arises; it can be observed that disturbance rejection is reached since n = 1, and that the greater the value of n, the faster the convergence rate, but the greater the effort in the control input. The same effect is observed with the other trajectories of controllers. Figures 7−10 illustrate the responses of DWDC outputs, with rejection of mentioned disturbances. The figures depict controlled variables in the left column and control inputs in the right column; in the bottom of the figure shows the disturbance. In the case of disturbance in the benzene composition of the input stream, Figure 7 depicts how the controllers reject it: the impurity compositions go back to their nominal values within a short period, which is less than the settling time of DWDC in open-loop operation (Figure 5); besides, it can be observed that control inputs are not associated to saturation problems. In addition, the controllers can efficiently reject disturbances of ±5% in the feed flow, as can be seen in Figure 8, since the compositions return to the nominal values in a short time and without significant movements on control inputs. Finally, Figures 9 and 10 depict how disturbances in the feed composition ,with respect to toluene and xylene, respectively, are rejected without problems. These results demonstrate that the gains provided by the tuning technique gives an efficient product impurity control.

In order to complete the control test, set-point changes in the impurity compositions of output streams were implemented: Figure 11 depicts how impurities achieve new set points, although in a period slightly higher than that of the disturbance rejection; it can be noticed that even for set-point changes in the

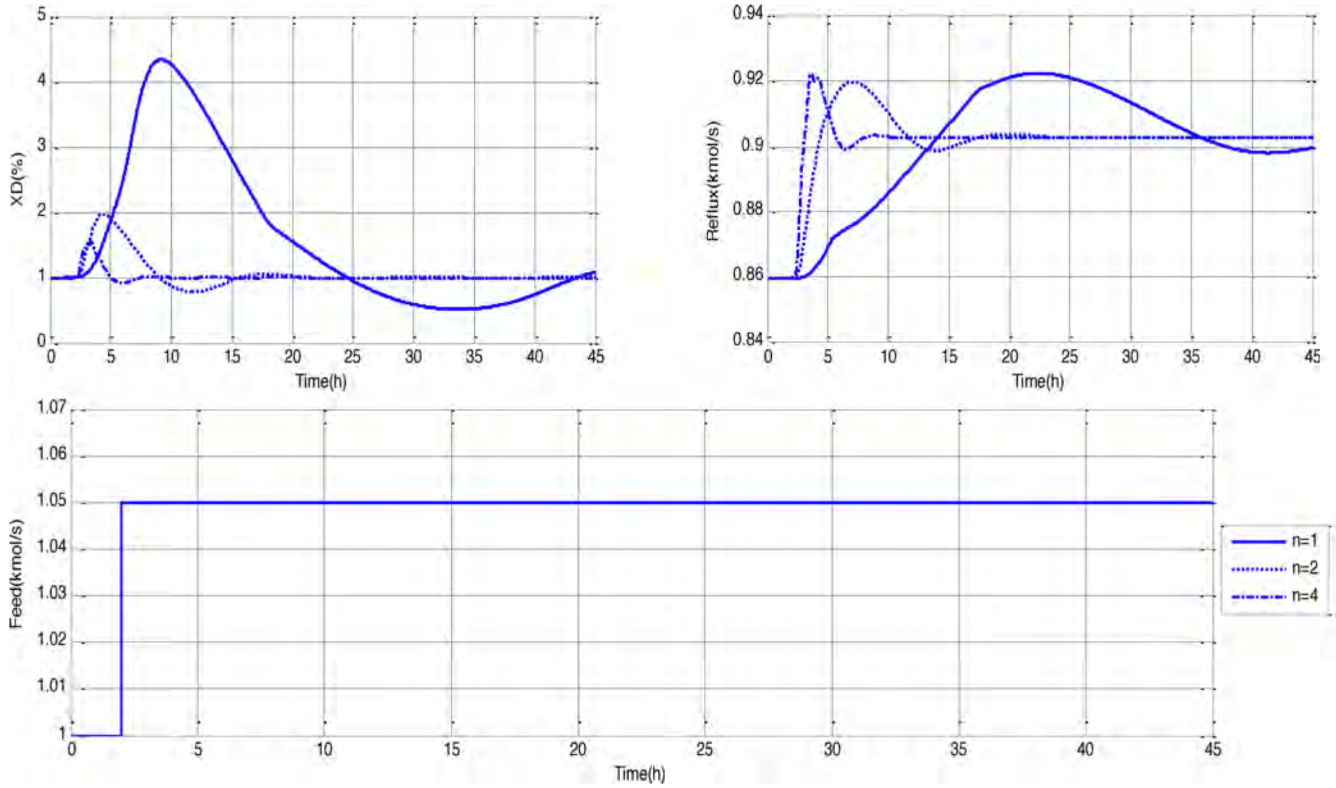

Figure 6. Performance against feed flow disturbances with different values of *n*.

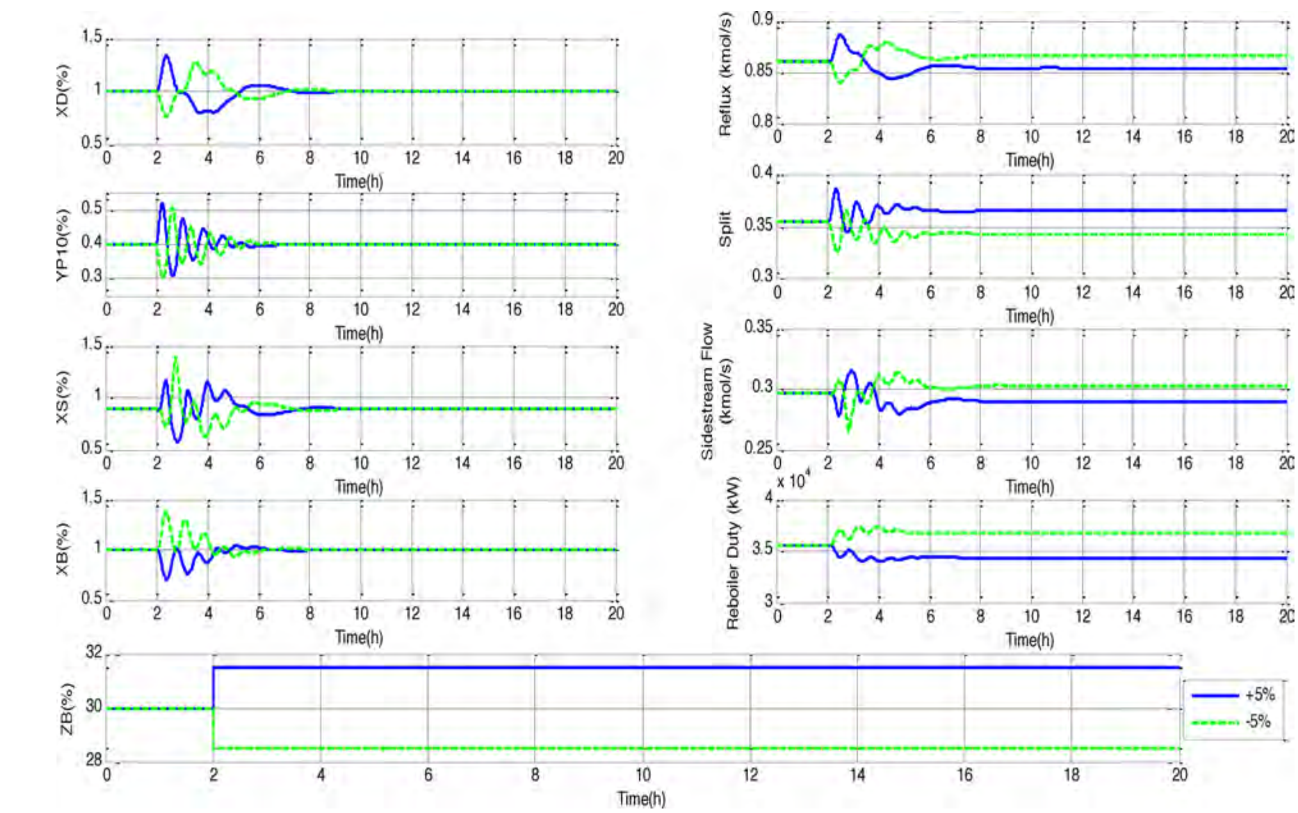

Figure 7. Performance against benzene feed composition disturbances.

composition of the three output streams, the controllers act without great effort.

In order to compare the effectiveness of the tuning method, it was recalled two tuning methods: (i) the BLT frequency-domain approach,[23] which also tunes in a simultaneous way all the controllers of a control system, and (ii) the tuning approach given by Lin and Luyben[18] for DWDC columns. Here, the second approach, which is called the "sequential method",

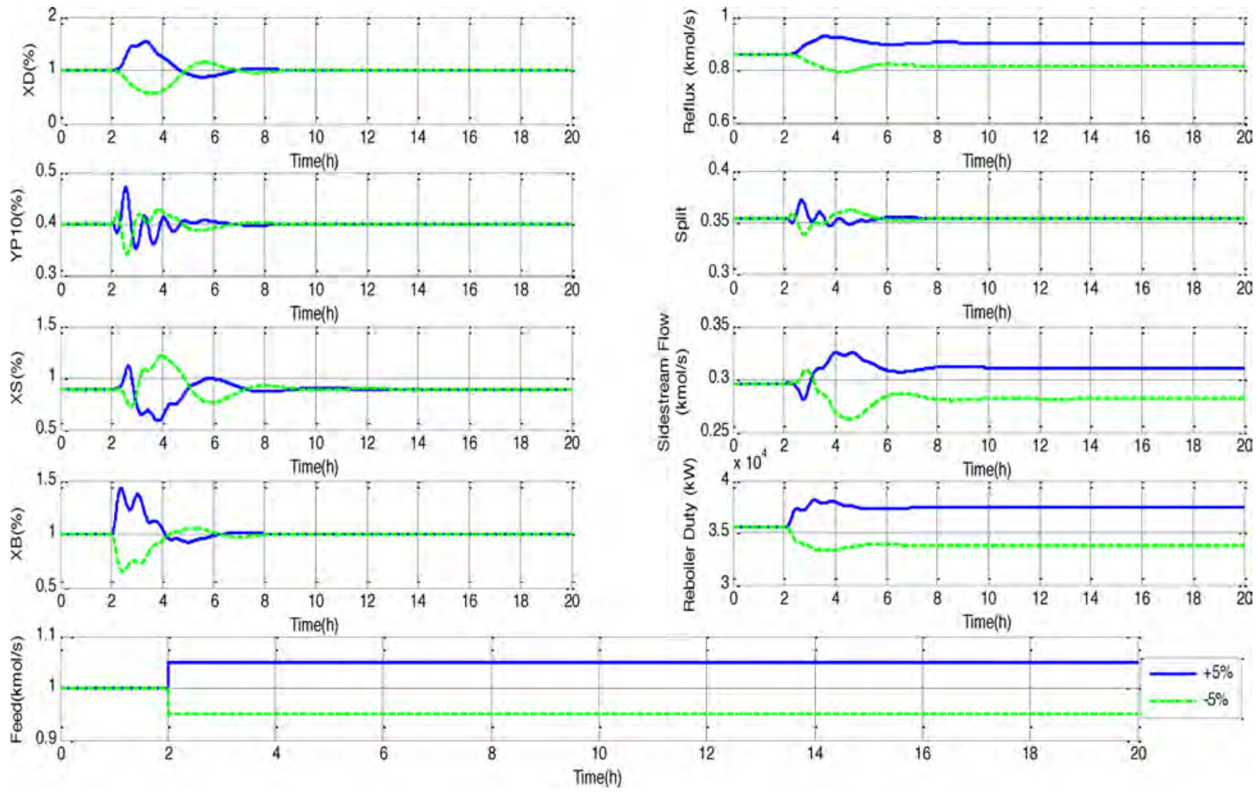

Figure 8. Performance against feed flow disturbances.

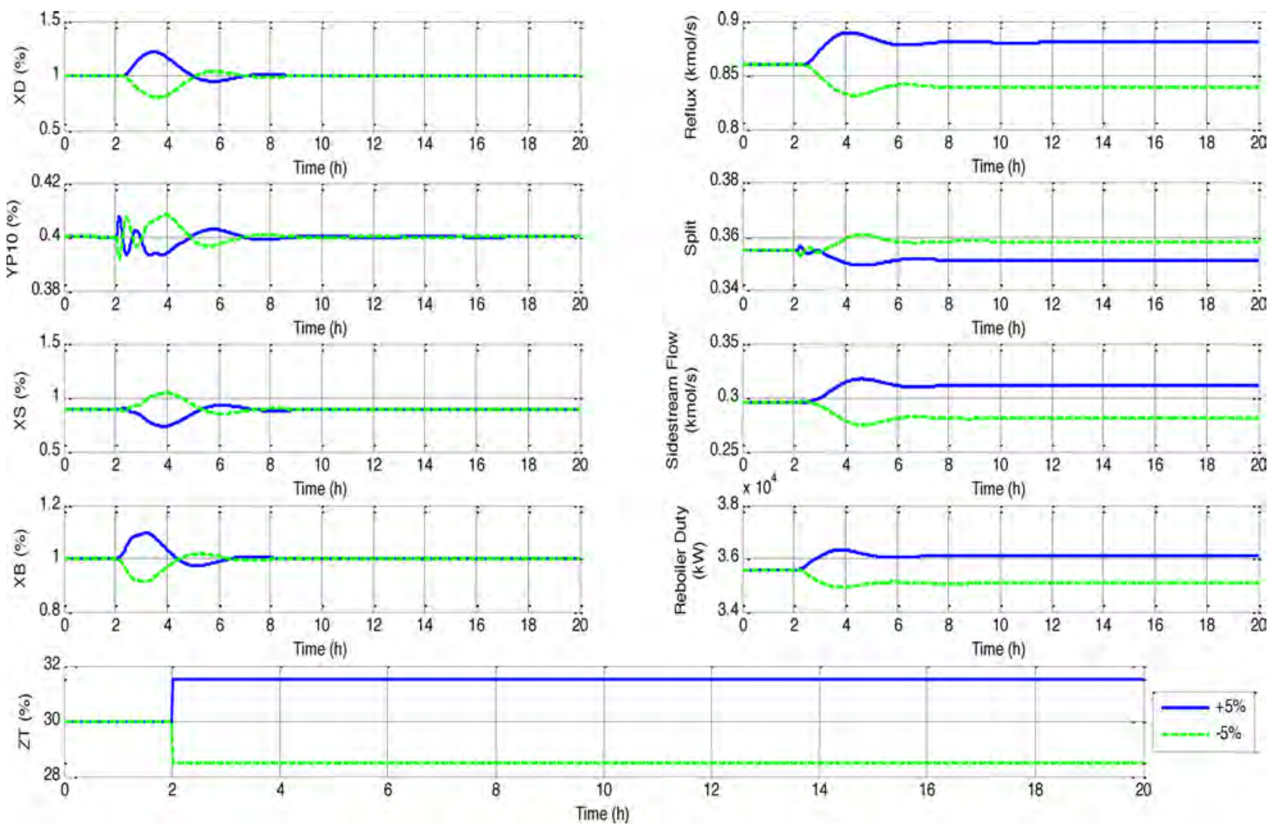

Figure 9. Performance against toluene feed composition disturbances.

because of the tuning of controllers, is carried out one-by-one in a certain sequence, based on the Tyreus–Luyben tuning method. The application of the BLT method was based on a 4×4 transfer function matrix, where every transfer function of first order plus delay time was identified from output responses for step changes in every control input. For the sequential

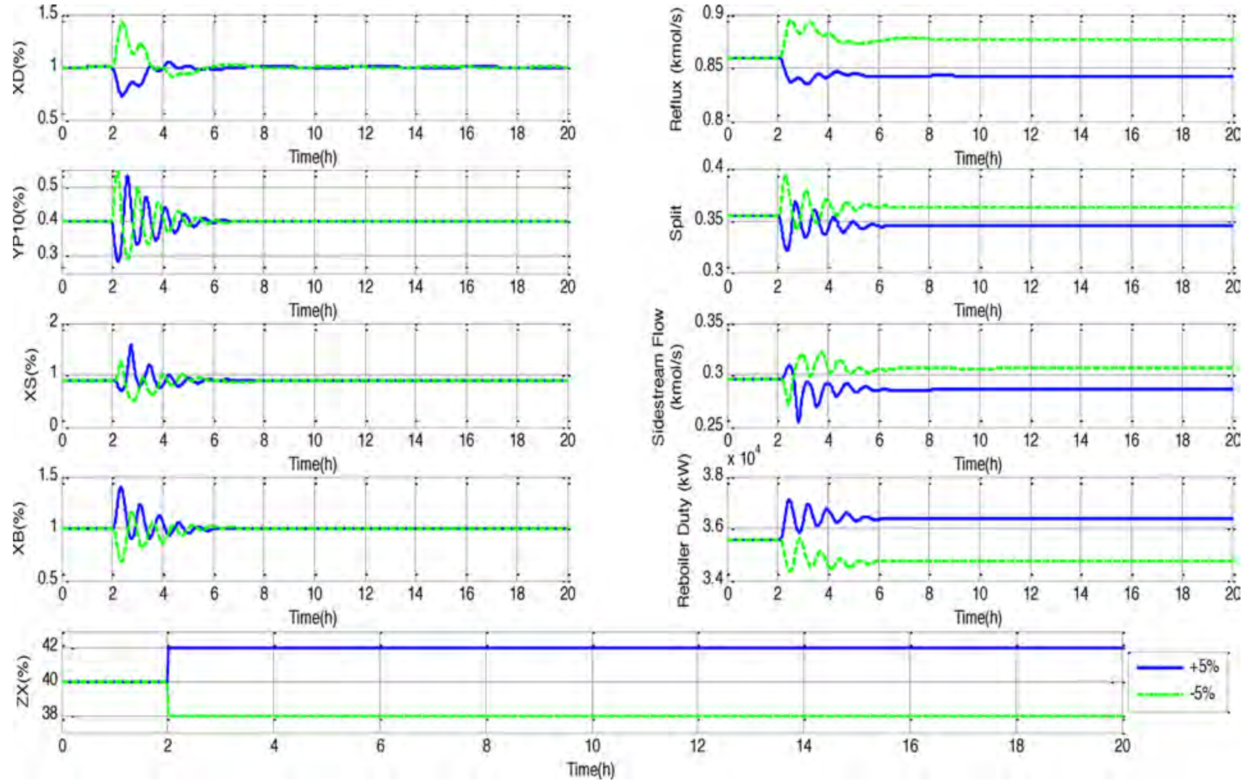

Figure 10. Performance against *o*-xylene feed composition disturbances.

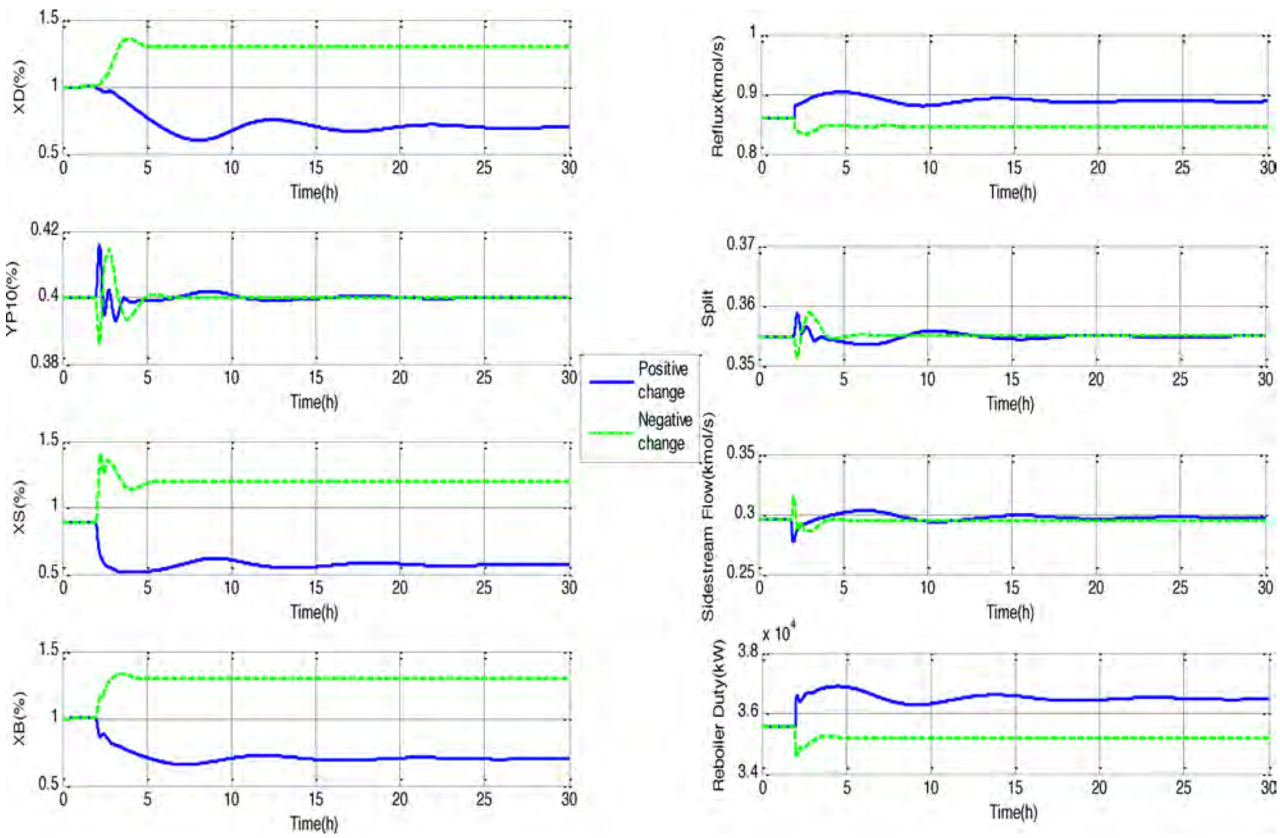

Figure 11. Performance when all set points are changed at the same time.

method, by directly implementing the Tyreus−Luyben tuning method in Aspen Dynamics, the control loops were tuned in the following order: first, (Q, x_B); second, (R, x_D); third, (F_S, x_S), and fourth, (S_L, y_{P10}).

The values of the controller gains obtained by the three methods are given in Table 3. It can be observed that controller gains from the pole-assignment method are quite similar to the corresponding gains from the sequential method (more with respect to proportional gains); however, with respect to the BLT method, no similarity seems to exist. Figure 12 depicts the performance provided for the BLT and pole-assignment methods in a case of disturbance where the corresponding controllers exhibited their better performance among the cases simulated. The same scenario is shown in Figure 13, but the performances provided by the pole-assignment and sequential methods are compared. It can be observed that the performances provided by the three methods are similar; however, the

Table 3. Controller Gains of Tested Tuning Methods

	Pole Assignment		BLT Method		Sequential Method	
loop	K_C (%/%)	τ_I (h)	K_C (%/%)	τ_I (h)	K_C (%/%)	τ_I (h)
(R, x_D)	0.0771	0.9248	0.125	0.1760	0.07189	1.606
(S_L, y_{P10})	0.2029	0.3035	0.0682	0.8272	0.1669	0.836
(F_S, x_S)	0.1667	0.7647	0.1023	0.8272	0.125	0.946
(Q, x_B)	0.08235	0.6048	0.017	1.5312	0.07212	1.232

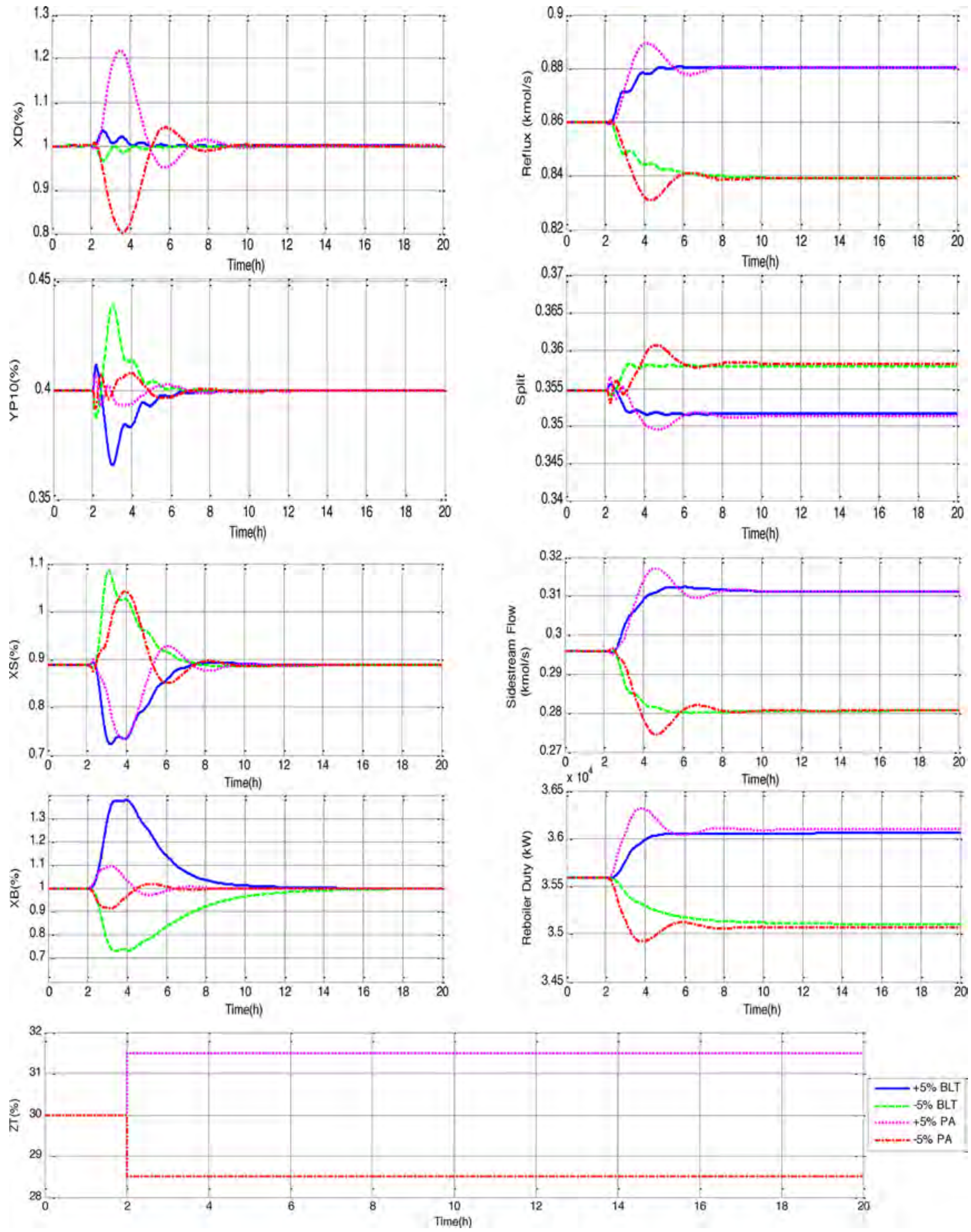

Figure 12. Performance provided by the pole-assignment (PA) and BLT tuning methods against toluene feed composition disturbances.

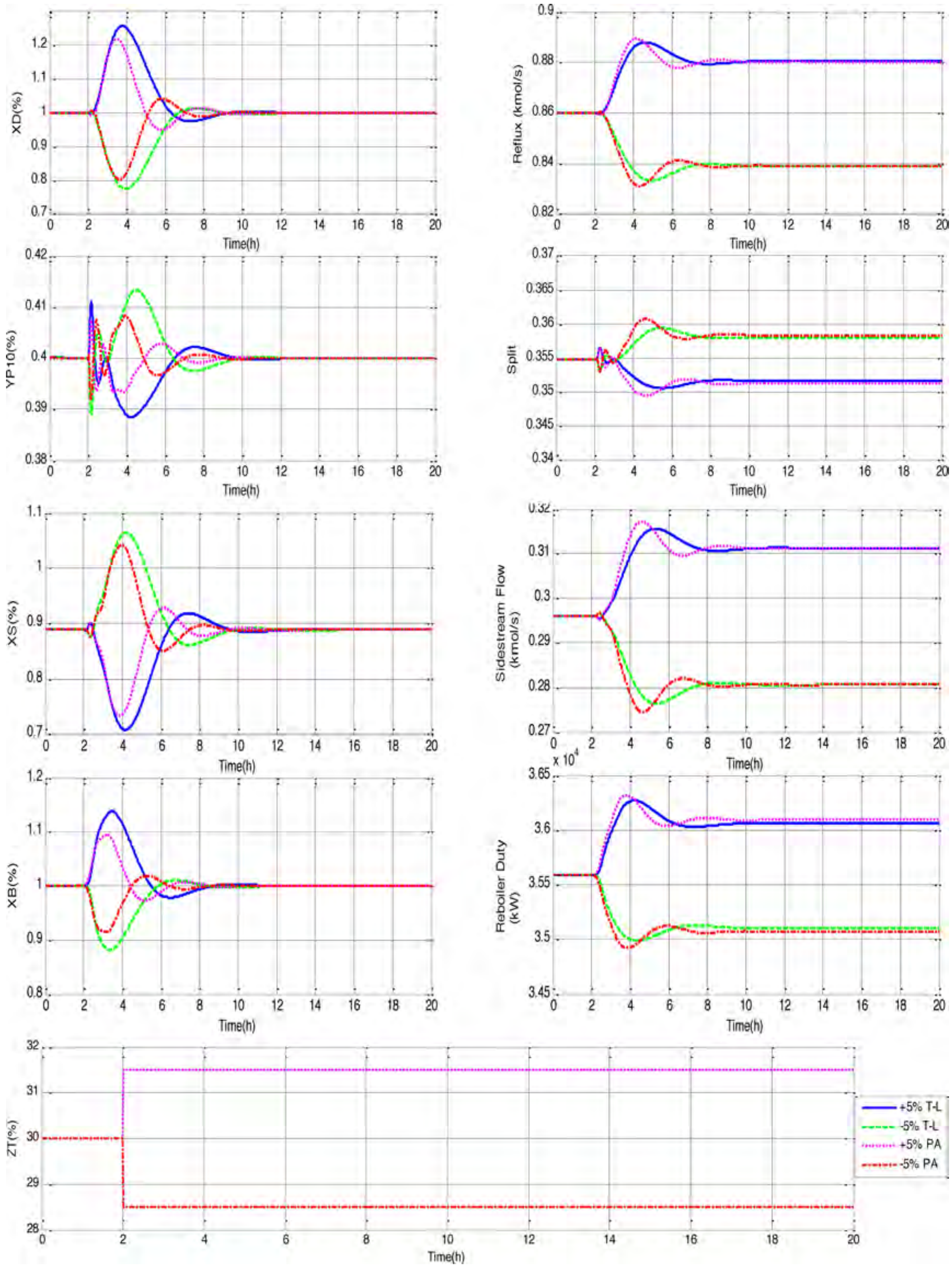

Figure 13. Performance provided by the pole-assignment (PA) and sequential tuning methods against toluene feed composition disturbances.

application of the tuning method presented in this work is much easier and more straightforward.

5. CONCLUSIONS

In this paper, a systematic technique to tune proportional–integral (PI) controllers for DWDCs was developed. This technique straightforwardly determines effective gains within a framework of convergence rates that can be manipulated, and it allows for a simultaneous tuning of all controllers, which significantly diminishes the trial-and-error activity of current techniques. The performance of controllers tuned by this technique is illustrated via simulation on both control problems of regulation and servo-control, showing efficient behaviors of the DWDC control system.

This technique has been applied for an ideal binary distillation column with good results (http://www.revistaequim.com/numeros/32/control.htm), and it is presumed to be useful for any multiple input–multiple output (MIMO) control system whose dynamics of corresponding input–output pairs can be appropriately described by first-order models.

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Notes

The authors declare no competing financial interest.

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