Improving Dual Composition Control in Continuous Distillation by a Novel Column Design

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How a novel design of continuous distillation columns may impact the performance of conventional controllers when it is required to accurately control the purity of both products in a binary separation is analyzed. The proposed column layout is characterized by the presence of a middle vessel, to which two streams are fed: the liquid flow coming from the rectifying section and the feed to be separated. The actual liquid flow to the column is determined by the middle-vessel level controller. For different control configurations and conventional proportional-integral control, it is shown that using a middle-vessel column provides a way to reduce the interaction between the composition loops, in such a way that the control performance of middle-vessel columns may be made remarkably superior to that of the conventional columns. The results obtained are supported by a theoretical analysis based on the frequency-dependent relative gain array tool.

Introduction

Improving the control of distillate and bottoms compositions in continuous distillation usually results in major economic benefits. The most important argument calling for tight control of the purities of both distillation products is the energetic one. In fact, it is well known that distillation is an energy-intensive operation. According to some estimates (McAvoy, 1983), about 40% of the energy used in a typical chemical plant goes to distillation, and—for all U.S. industries—this corresponds to about 3% of the total energy consumption in the United States. Under manual control, the operators tend to overreflux towers in order to more than meet product specifications; conversely, by putting both compositions under control, overpurification is avoided and the energy waste is reduced. Tight dual-composition control can also result in other benefits, such as reduced product variability, reduction in the rate of production of off-specification products, increased production rates when a column is the bottleneck in the system, increase in the yield of a product through an increase in the average impurity levels while maintaining product specification (Riggs et al., 1993).

The strong coupling between manipulated variables, and the nonlinear stationary and dynamic behavior of distillation towers are the main issues that make dual-composition control a challenging problem. As a result, the topic of distillation control has attracted the attention of a number of researchers, both in academia and in the industry. Literally hundreds of articles have been published on distillation control over the last half century, so that it would be impossible to credit all the relevant works in this field. Therefore, we limit ourselves to the most current review and tutorial introduction to the dynamics and control of distillation columns (Skogestad, 1997), and to a recent survey article somewhat more oriented to practice (Riggs, 1998). Some textbooks on the same subject are also worth mentioning (Luyben, 1992; Kister, 1990; Buckley et al., 1985; Shinskey, 1984; Nisenfeld and Seeman, 1981).

So far, most of the contributions in the area of distillation column control have focused on such issues as the selection of the most appropriate pairing between controlled and manipulated variables, the development of linear and nonlinear advanced controllers, and the development of tuning procedures for conventional and advanced controllers. In this article, we do not really address in detail any of these issues. Rather, we are most interested in tackling the control problem from a different perspective, that is, we look at how a modification to the plant layout can be beneficial for control. Reference is made to two example columns that have been

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Table 1. Steady-State Data for Column 1

N	N_F	z_F	α	D/F	L/F	V/F	x_D	x_B	M_i/F (min)	τ_L (min)
40	21	0.5	1.5	0.5	2.706	3.206	0.99	0.01	0.5	0.063

proposed in the literature as benchmarks that illustrate the peculiar challenges of dual composition control.

The article is organized as follows. The next section briefly describes the two example columns that are referred to in the study. Some known issues on dual composition control are recalled in the third section (with reference to the first example column), in order to provide a theoretical motivation for the proposed column layout, which is illustrated in detail in the fourth section (with reference to the first example column). The fifth section presents the control results for both columns, and some additional issues and limitations for the proposed layout are discussed in the sixth section. A final section provides the conclusions to the work.

Example Columns

The first example column in taken from Skogestad (1997). This column (which will be referred to as Column 1 in the following) is an ill-conditioned, high-purity one. Steady-state data at nominal operating conditions are reported in Table 1. The symbols used throughout the text are defined either in text or in the Notation section.

As can be seem from Table 1, a constant-relative-volatility, binary separation is assumed; other assumptions are negligible vapor holdups, boiling liquid feed, constant vapor rate, tight control of the top and bottom levels (proportional-only control with a $-10\ \text{min}^{-1}$ gain), constant pressure along the column. The liquid dynamics is accounted for by the Francis weir formula with a hydraulic time constant $\tau_L = 0.063$ min. The steady-state holdup on all trays, including reboiler and condenser, is chosen as $M_i/F = 0.5$ min.

The second example column (Column 2, in the following) is a propylene/propane splitter taken from Gokhale et al. (1995a). The splitter separates a polymer-grade propylene (99.7 mol%) from a fuel-grade propane (98 mol%). With a 70 mol% propylene in the feed, the separation is achieved in a 232-real-tray column. Other features of the column are listed in Table 2.

Proportional-integral (PI) controllers, whose settings are provided by Gokhale et al. (1995a), control the top and bottom inventories. The dynamic model of the superfractionator was benchmarked against dynamic step test data from an industrial C_3 splitter, and a good reproduction of the plant data was provided by the model (Gokhale et al., 1995b).

Known Issues in Dual Composition Control

According to the L-V control configuration (also called the energy-balance configuration; Figure 1), the reflux rate is used to control the overhead purity, while the vapor boilup rate is used to control the bottoms composition (in practice, however, the heat supply to the reboiler is manipulated instead of the vapor boilup, as indicated in Figure 1). The top and bottom inventories are controlled by the distillate and bottoms rates, respectively. Although the L-V scheme may not be the best one from the point of view of coupling between control loops (Shinskey, 1984), it is the standard control structure for dual-composition control (Häggblom and Waller, 1992), because it is simple to implement and easy to understand, and therefore is easily accepted among operators. A further advantage is that this configuration is generally the least sensitive to feed composition upsets and is also the fastest responding; moreover, its performance is almost independent of the tuning of the level controllers (LCs), and this makes both the tuning of the composition controllers simpler and the control of the column easier. For these reasons, the L-V configuration will be considered in detail in this section; other control configurations will be analyzed later.

The degree of steady-state coupling between control loops is usually measured by means of the steady-state relative gain array (RGA; Bristol, 1966). For a 2×2 linear system, this matrix is fully characterized by its diagonal element λ_{11}, which is calculated as follows:

Table 2. Some Data for Column 2

No. of trays	232
Feed-tray location	64
Tray Murphree efficiency	0.85
Column diameter	3.96 m
Overhead pressure	211 psia
Overhead temperature	34.7°C
Bottom temperature	42.3°C
Reflux drum holdup	2000 lb mol
Bottom holdup	2000 lb mol
Feed quality	saturated liquid
Feed composition	70 mol %
Distillate composition	99.7 mol %
Bottoms composition	2 mol %
Feed flow rate	13.44 kg/s
Overhead flow rate	9.21 kg/s
Vapor boilup rate	131.24 kg/s
Reflux ratio	12.6

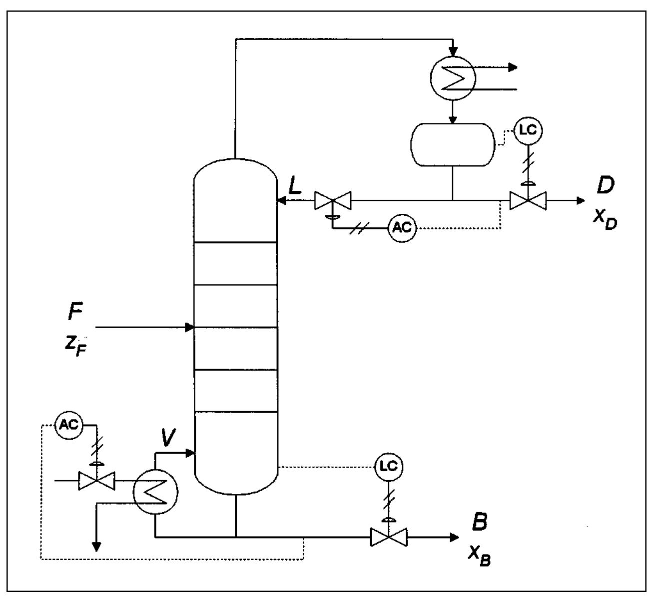

Figure 1. L-V control configuration.

$$\lambda_{11} = \frac{1}{1 - \frac{K_{12}K_{21}}{K_{11}K_{22}}}, \qquad (1)$$

where K_{ij} is the steady state gain of the transfer function element $g_{ij}(s)$ of the system, and s is the Laplace transform variable. In order to calculate the relative gain array for the nonlinear column examples, the column dynamics need to be linearized around the nominal operating point. Therefore, for the L-V configuration, one gets

$$\begin{bmatrix} \tilde{x}_D \\ \tilde{x}_B \end{bmatrix} = \begin{bmatrix} g_{11}^{LV} & g_{12}^{LV} \\ g_{21}^{LV} & g_{22}^{LV} \end{bmatrix} \begin{bmatrix} \tilde{L} \\ \tilde{V} \end{bmatrix}, \qquad (2)$$

where the $\sim$ symbol indicates a (small) deviation from the nominal steady state. It should be noted that, since distillation columns are known to exhibit nonlinear behavior, the results coming from an RGA analysis are to be regarded as qualitative only, particularly when a column is moved away from the nominal operating conditions.

For Column 1 (results refer to this column in the present section), the L-V configuration provides $\lambda_{11} = 35.94$, which indicates quite a large degree of interaction between the composition control loops. However, despite the indication from λ_{11}, satisfactory control of both product purities can be achieved for this column, as was shown by Skogestad (1997). The reason for that can be explained by using the dynamic RGA (McAvoy, 1983) to evaluate the interaction between the quality loops. For 2×2 linear systems, the diagonal element $\Lambda_{11}(s)$ of the dynamic RGA matrix is calculated from

$$\Lambda_{11}(s) = \frac{1}{1 - \frac{g_{12}(s)g_{21}(s)}{g_{11}(s)g_{22}(s)}}. \qquad (3)$$

With the formal substitution $s = j\omega$, Eq. 3 enables the calculation of Λ_{11} as a function of the frequency ω. Note that $\Lambda_{11}(0) = \lambda_{11}$.

The magnitude $|\Lambda_{11}(s)|$ of Λ_{11} as a function of frequency is plotted in Figure 2 for Column 1 (solid line). It is clear that,

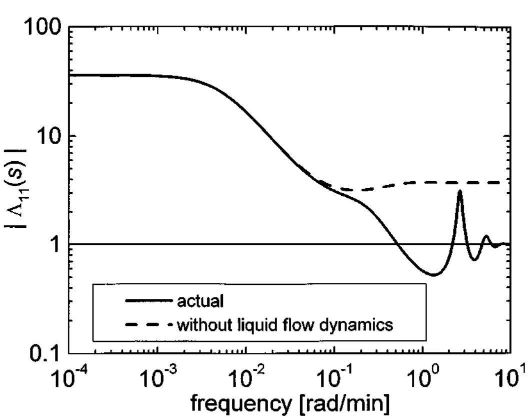

Figure 2. Effect of the liquid flow dynamics on $|\Lambda_{11}|$.
Column 1; L-V configuration.

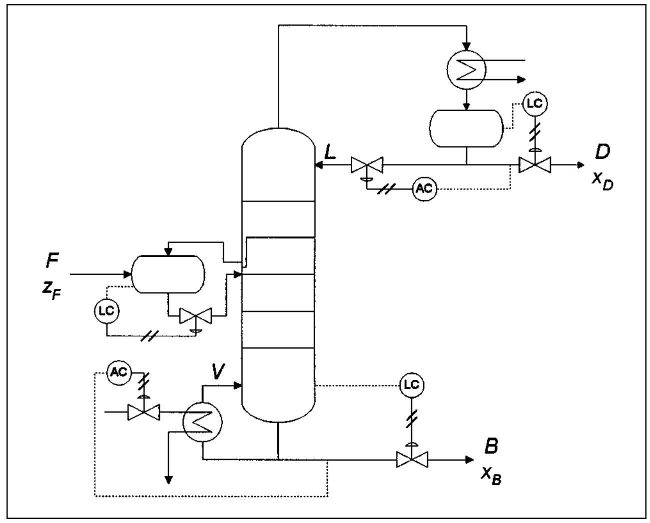

Figure 3. Middle-vessel continuous column.
L-V configuration.

although at steady state the interaction between the quality-control loops is high, it decreases rapidly at frequencies higher than $\approx 2 \times 10^{-3}$ rad/min, and crosses 1 at $\omega \approx 0.5$ rad/min.

This means that at relatively high frequencies the control loops are almost decoupled ($|\Lambda_{11}(s)| \approx 1$), and therefore it is sufficient to make the composition control loops fast to achieve good control even with the L-V configuration (Skogestad, 1997). Otherwise stated, steady-state coupling does not play a major role in the control of composition, because it is the value of $|\Lambda_{11}(s)|$ within the frequency range at which the loops operate that determines the quality of the control achieved. What is important to note is that it is the liquid flow dynamics that provides initial (that is, high-frequency) decoupling between the composition control loops. In fact, due to the dynamics of the liquid flow, it takes some times for a perturbation in the reflux rate to affect the liquid flow to the reboiler (hence, the bottoms composition), and for this reason the initial composition response is decoupled (Skogestad et al., 1990). Note, however, that since a change in the vapor boilup rate propagates in a much faster way along the column, only one-way decoupling is achieved at high frequencies.

The effect of the liquid flow dynamics is confirmed by looking at the dashed curve in Figure 2. This curve represents the profile of $|\Lambda_{11}(s)|$ as a function of frequency when the liquid flow dynamics is neglected, that is, when a variation on the reflux rate instantaneously propagates to the bottom of the column. It is clear that $|\Lambda_{11}(s)|$ settles at $\approx 3.7 > 1$ even at high frequencies, thus making the control loops more coupled.

Proposed Plant Layout

In light of the foregoing discussion, it is worth looking for an alternative column layout that is such that it can increase the overall time lag of the liquid flow, so as to reduce the interaction between the composition loops. The proposed layout is illustrated in Figure 3. In this section, we still refer

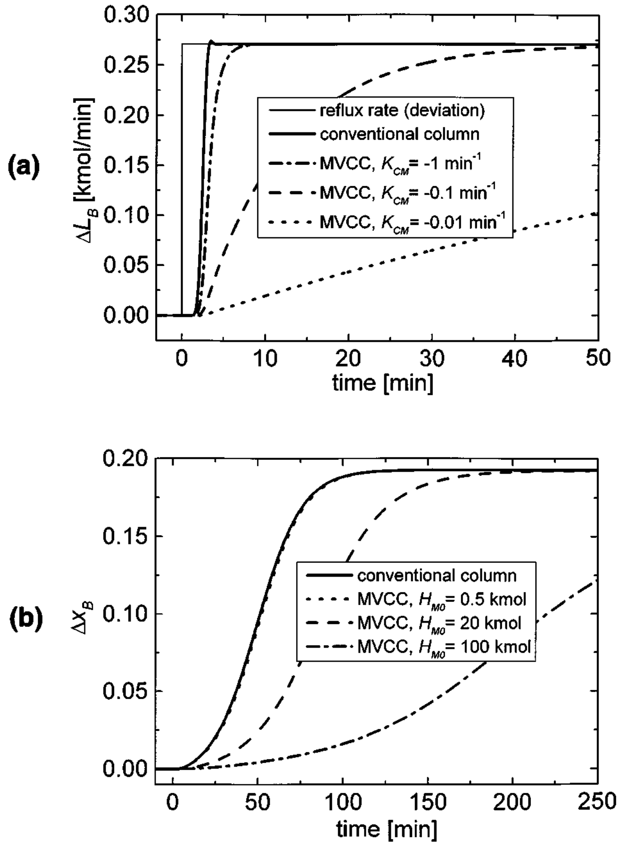

Figure 4. (a) Dynamics of the bottom liquid flow for a +10% step change of the reflux rate, and (b) dynamics of the reboiler composition for a step change $\Delta z_F = +0.1$ of the feed composition.

Column 1; L-V configuration; composition controllers switched off.

to the L-V configuration and to Column 1 in order to outline our reasoning.

A vessel is mounted at the liquid overflow of the tray above the feed tray. All the liquid flowing above the feed tray and the feed itself are sent to the vessel (we assume that the feed is available as a liquid at the bubble point, and that good mixing is provided in the vessel). The outlet flow from the vessel is determined by a proportional (P) level controller, and this flow is fed to the feed tray. We call this column middle-vessel continuous column (MVCC), in order to distinguish it from the middle-vessel batch column considered by several authors (see, for example, Barolo et al., 1998).

From a "physical" perspective, the introduction of the middle vessel causes two major effects:

• An increase in the overall time lag of the liquid flow ("hydraulic effect"). The extent of this increase is related to the gain K_{CM} of the middle-vessel level controller (Figure 4a).

• An increase of the lag in the composition dynamics ("composition effect"). The extent of this increase is related to the amount H_{M0} of liquid initially charged to the vessel (Figure 4b).

From a "theoretical" perspective, the effects of K_{CM} and H_{M0} on the column dynamics can be disclosed by considering the plots of $|\Lambda_{11}(s)|$ vs. ω, as reported in Figure 5. Figure 5a shows that, due to the "hydraulic effect" of the middle vessel, the curve of $|\Lambda_{11}(s)|$ vs. ω considerably "flattens" around $|\Lambda_{11}| = 1$ for the L-V configuration. The less aggressive the middle vessel LC, the lower the frequency at which $|\Lambda_{11}(s)|$ crosses 1, and the wider the range of frequencies at which the quality loops are decoupled. On the other hand, when $|K_{CM}|$ is very high (very fast level controller), the middle vessel has almost no effect on $|\Lambda_{11}(s)|$. For this control configuration the "composition effect" does not play a major role in loop decoupling, as is shown in Figure 5b, which confirms that the "flattening" of $|\Lambda_{11}(s)|$ is almost independent of H_{M0}. Also note that the value of $|\Lambda_{11}(0)|$ is not affected by the presence of the middle vessel, as must be, since the steady-state gains of the plant are not modified.

It is now clear that, by properly choosing K_{CM}, one can improve the decoupling of the composition loops. It must be stressed that, with reference to loop decoupling, the main role of the middle vessel with the L-V configuration is to dampen the variations of the liquid flow in the stripping section of the column. This dampening effect (which is in-

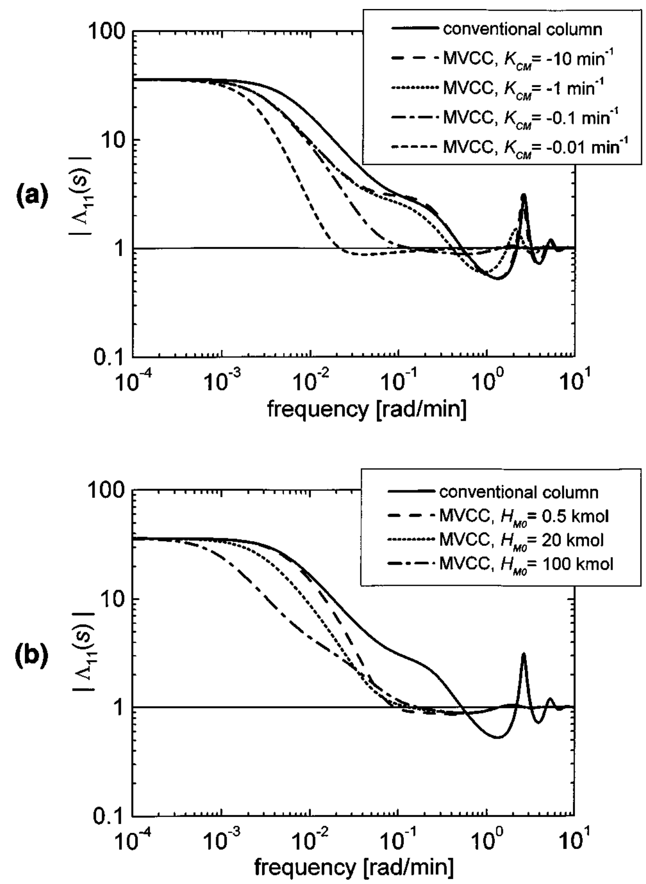

Figure 5. $|\Lambda_{11}|$ as a function of frequency for several MVCCs.

(a) $H_{M0} = 20$ kmol and different values of K_{CM}; (b) $K_{CM} = -0.1$ min^{-1} and different values of H_{M0}. Column 1; L-V configuration.

Table 3. Test Problems for the Optimal Tuning Procedure of Column 1

Test Problem	Time		
	$t_1 = 10$ min	$t_2 = 100$ min	$t_3 = 200$ min
TP1	$\Delta F = +20\%$	$\Delta z_F = +0.1$	$\Delta x_{D,sp} = +0.005$
TP2	$\Delta x_{B,sp} = -0.005$	$\Delta F = -20\%$	$\Delta x_{D,sp} = +0.005$

Note: The symbol Δ indicates a stepwise change; both tests stop after 300 min.

dependent of the actual amount of liquid inside the vessel, as long as the vessel is not full or empty) is most important for control, because the composition profile inside the column starts changing as soon as an imbalance in the liquid (or vapor) flows occurs in a plate. Thus, dampening the flow variations eventually results in dampening the composition variations, and this in turn means making composition control easier. A further issue to mention is that the additional lag introduced by the middle vessel actually slows down the open-loop dynamics of the column. However, by appropriately tuning the feedback composition controllers, the closed-loop dynamics can be made faster, as is shown in the next section.

Control Results

The control performances of Columns 1 and 2 with and without the middle vessel are compared in this section. Diagonal PI composition controllers always will be used, since this is the most frequent case in the industry. A 1-min delay on the overhead and bottom composition measurements is assumed in Column 1, while a 5-min composition measurement delay is assumed for Column 2.

Column 1

In order to keep the results from being affected by an ''unfair'' tuning of the quality controllers, the controller parameters were determined by an optimizing technique. A series of step disturbances and setpoint changes were considered (see Table 3, test problem TP1), and the controller tuning parameters were determined in such a way as to obtain a minimum of the following objective function:

$$\varphi_1 = q \times \text{ISE} + \text{VT}_V \qquad [\text{kmol/min}], \tag{4}$$

where $q = 1 \times 10^4$ kmol/min^2 is a dimensional scaling factor, ISE is the integral of squared error on composition, defined as

$$\text{ISE} = \sum_{i=1}^{N_t} \left(\int_{t_i}^{t_{i+1}} (x_{B,sp} - x_B)^2 dt + \int_{t_i}^{t_{i+1}} (x_{D,sp} - x_D)^2 dt \right) \quad [\text{min}], \tag{5}$$

and VT_V is the boilup valve travel, defined by

$$\text{VT}_V = \sum_{j=1}^{N_c} |V(j) - V(j-1)| \qquad [\text{kmol/min}]. \tag{6}$$

The valve travel (Ramchandran and Rhinehart, 1995) was included in the objective function in order to account not only for the composition response, but also for the ''amount of work'' done by the control system. As a further comment to the notation used in Eqs. 5 and 6, N_t is the total number of step disturbances and setpoint changes ($N_t = 3$), t_i and t_{i+1} are the start and stop times for the ith change, t_{N_t+1} is the total simulation time (300 min), $V(j)$ is the value of the boilup rate at the jth control action, and N_c the total number of control actions performed.

It should be noted that, while this tuning procedure ensures a fair comparison of the controller performance for the conventional column and the MVCC, it does not necessarily guarantee that a robust tuning is achieved. We disregard the issue of robust tuning for the moment; however, some considerations on controller robustness are stated later.

L-V Configuration. Table 4 summarizes the results of the tuning for the conventional column and for several MVCCs with the L-V configuration. A graphical comparison of the control performance of the conventional column and the MVCC ($K_{CM} = -0.1$ min^{-1} and $H_{M0} = 20$ kmol) is shown in Figure 6. It is clear that the MVCC provides a better control performance than the conventional column, as is also confirmed by the analysis of the values of the objective function φ_1, reported in Table 4. In particular, a much more decoupled behavior is obtained in response to the first step disturbance and to the distillate setpoint change. A slightly larger settling time of the distillate composition in the MVCC follows the feed flow disturbance; however, the rise and settling

Table 4. Results of the Optimal Tuning for the Conventional Column and for Several MVCCs

Column	H_{M0} [kmol]	K_{CM} [min^{-1}]	K_{CD} [kmol/min]	τ_{ID} [min]	K_{CB} [kmol/min]	τ_{IB} [min]	φ_1 [kmol/min]
Conventional*	—	—	62.9	4.48	−65.2	2.52	5.011
Conventional	—	—	24.7	1.13	−104	4.03	4.104
MVCC	20	−0.1	92.9	4.46	−109	3.02	1.659
MVCC	0.5	−0.1	95.3	4.51	−107	2.85	1.650
MVCC	100	−0.1	91.7	4.51	−115	3.11	1.650
MVCC	20	−0.01	239	13.3	−87.3	4.24	0.7731
MVCC	20	−1	26.7	1.28	−116	3.93	3.022
MVCC	20	−10	22.2	1.00	−108	4.26	3.870

*Liquid flow dynamics neglected.
Note: Column 1; L-V configuration; test problem TP1.

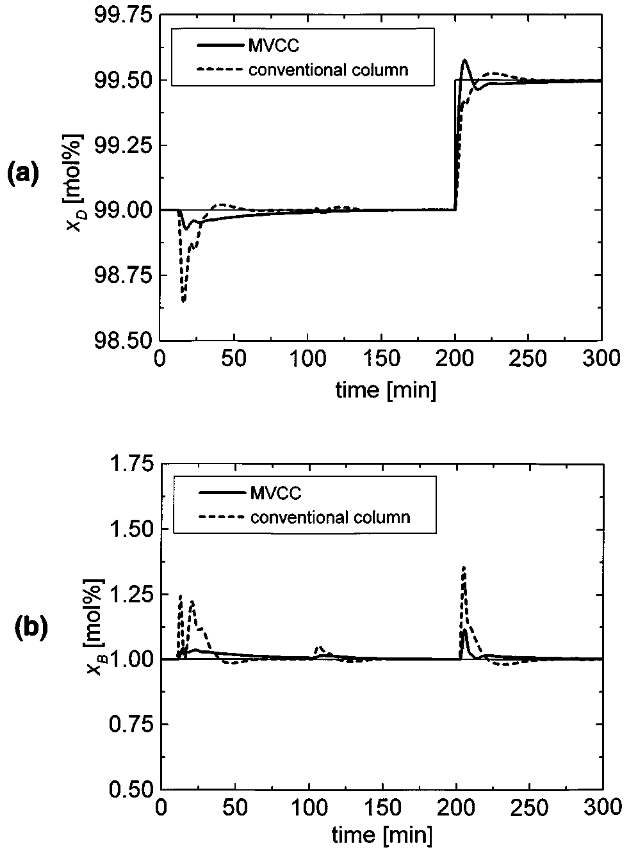

Figure 6. Profiles of the (a) distillate composition and (b) bottoms composition for the conventional column and the MVCC.

Column 1; L-V configuration; $K_{CM} = -0.1\ \text{min}^{-1}$; $H_{M0} = 20$ kmol; test problem TP1.

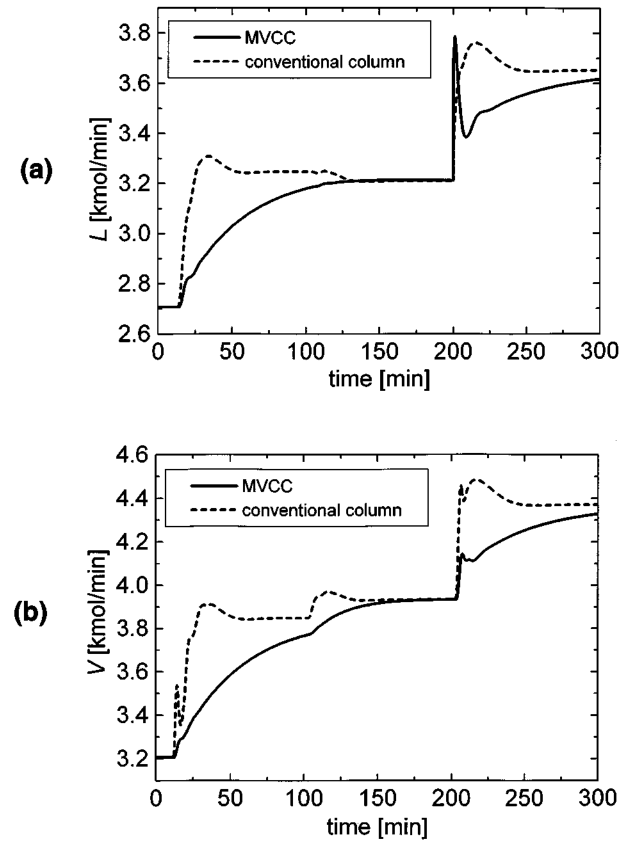

Figure 7. Profiles of the (a) reflux rate and (b) boilup rate for the conventional column and the MVCC.

Column 1; L-V configuration; $K_{CM} = -0.1\ \text{min}^{-1}$; $H_{M0} = 20$ kmol; test problem TP1.

times of the distillate composition response in the servo problem are shorter in the MVCC.

The effect of the middle vessel on the tuning of the quality controllers can be investigated by analyzing the results of Table 4. As for the bottom controller, it is tuned quite aggressively for both the MVCC and the conventional column, and no substantial difference exists for the two columns (however, as expected the bottom controller must be significantly detuned if the liquid flow dynamics is neglected). Instead, a marked difference exists in the tuning of the overhead composition controller. In fact, this controller is much more aggressive in the MVCC than in the conventional column, because the two sections of the column are hydraulically decoupled in the MVCC.

The manipulated variable profiles are plotted in Figure 7 for both columns. Although the MVCC overhead composition controller is tuned more tightly than in the conventional column, the reflux and boilup profiles evolve smoothly in the MVCC, because in this column the quality loops are decoupled over a wide range of frequencies.

The profile of the middle-vessel holdup is plotted in Figure 8 against time. The particular disturbance and setpoint step sequence is such that the middle-vessel holdup always increases during test problem TP1; this is not a general result, of course. The initial large variation in the middle-vessel holdup is due to the large increase in the "external" feed rate (+20%): since the middle-vessel level is controlled by a P-only controller, a sufficient level offset must build in the vessel for discharging the proper liquid rate in the stripping section of the column.

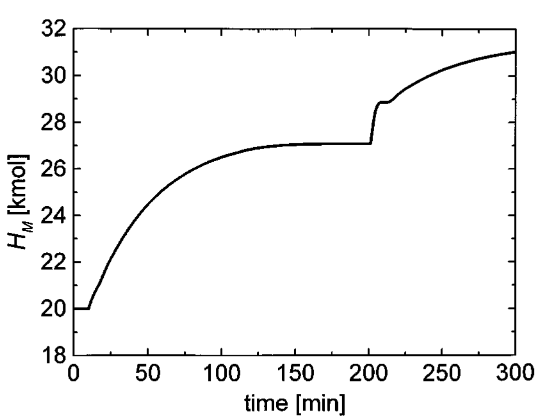

Figure 8. Profile of the middle-vessel holdup.

Column 1; L-V configuration; $K_{CM} = -0.1\ \text{min}^{-1}$; $H_{M0} = 20$ kmol; test problem TP1.

Table 4 reveals that the holdup of the middle vessel has indeed a negligible effect on the control performance. Even in the (deliberately unrealistic) case of an initial-vessel holdup equal to the initial-tray holdup ($H_{M0} = 0.5$ kmol), the optimal value of the objective function does not change appreciably. Moreover, the tuning constants of the quality controllers appear to be almost independent of the middle-vessel holdup. On the other hand, as expected, the controller performance does depend on the tuning of the middle-vessel level controller. When tight level control is provided ($K_{CM} = -10$ min^{-1}), the control performance of the MVCC ($\varphi_1 = 3.870$ kmol/min) is not too different from that of the conventional column ($\varphi_1 = 4.104$ kmol/min). The MVCC performance is gradually improved as the middle-vessel LC is detuned; in doing this, the overhead composition controller becomes more and more aggressive.

As was noted previously, the adopted tuning procedure provides a way for fairly comparing the performance of the control systems in the two columns, and for studying the effects of the middle-vessel LC tuning and middle-vessel holdup on the overall control response. However, the tunings achieved in this way may not be sufficiently robust to cope with markedly different control problems. For this reason, the control performance of the conventional column and of the MVCC were evaluated with a more robust tuning of the composition controllers. For the conventional column, the robust controller settings were taken from Skogestad (1997), while for the MVCC a satisfactory set of parameters was determined by trial and error. These settings are summarized in Table 5, along with the related values of φ_1 during test TP1. Note that in this case, the bottoms loops are substantially detuned for both columns, as expected. A comparison of the values of φ_1 makes clear that the MVCC still gives a better response to TP1 with these robust parameters.

A second, significantly different control problem (test problem TP2; see Table 3) was then considered with these tunings. The relevant results are reported in Figure 9. Again, the improvement achieved with the MVCC is remarkable, particularly in the rejection of the feed flow disturbance.

D-V Configuration. As an example of the so-called "material-balance" control schemes, we consider the D-V configuration. Plots of $|\Lambda_{11}(s)|$ as a function of frequency for the conventional column and for several MVCCs are shown in Figure 10.

It appears that the steady-state interactions are also quite high ($\lambda_{11} = 0.45$) for this control configuration. For the MVCC, the shape of the curves depends on the tuning of the middle-vessel LC (Figure 10a). When this LC is tuned tightly ($|K_{CM}| \geq 1$ min^{-1}), there is not much of a difference between the conventional column and the MVCC; making the level control looser ($|K_{CM}| = 0.1$ min^{-1}) improves the loop decoupling, since $|\Lambda_{11}(s)|$ flattens around 1; however, a further reduction of the level controller gain ($|K_{CM}| = 0.01$ min^{-1}) promotes interaction between the composition loops. This behavior may be attributed to interactions between inventory control and composition control, an issue that is known to arise when the material balance configurations are employed for composition control (Yang et al., 1993). Figure 10b shows that the middle-vessel holdup somewhat affects the shape of $|\Lambda_{11}(s)|$.

Table 5. Robust Settings for the Conventional Column and for the MVCC

Column	K_{CD} [kmol/min]	τ_{ID} [min]	K_{CB} [kmol/min]	τ_{I_B} [min]	φ_1 [kmol/min]
Conventional	26.1	3.76	−37.5	3.31	6.799
MVCC	175	17.5	−41.0	2.73	2.306

Note: Column 1; L-V configuration; $K_{CM} = -0.1$ min^{-1}; $H_{M0} = 20$ kmol; test problem TP1.

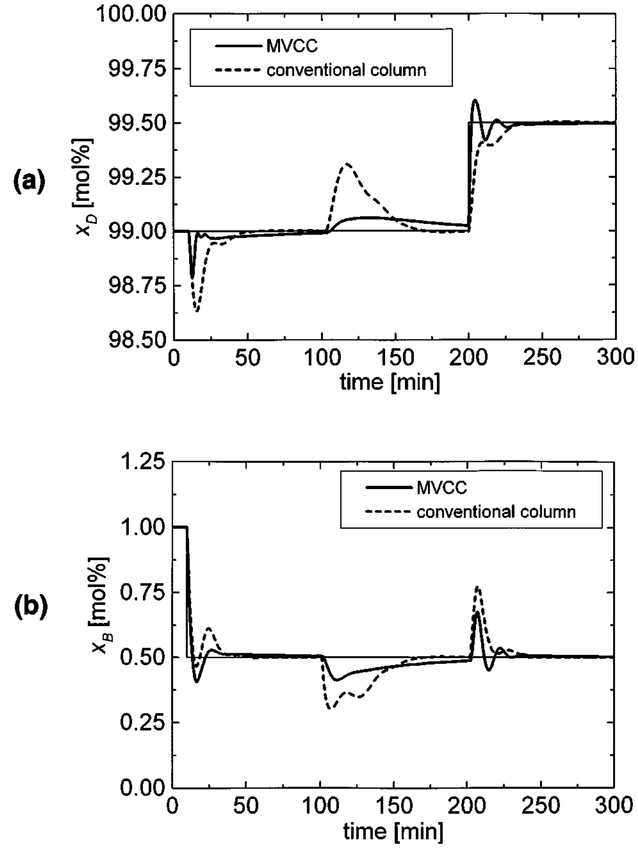

Figure 9. Profiles of (a) distillate composition and (b) bottoms composition for the conventional column and the MVCC.

Column 1; L-V configuration; $K_{CM} = -0.1$ min^{-1}; $H_{M0} = 20$ kmol; test problem TP2; robust tuning of the composition controllers.

The optimal control performance for the conventional column and the MVCC are shown in Figure 11. The control performance of the MVCC is clearly superior to that of the conventional column, which is also confirmed by the values of the performance index φ_1 in Table 6 under the heading "tight" control of the top level.

Note that, as was mentioned before, the performance of the material balance and ratio control configurations may indeed be affected by the tuning of the top- and bottom-level controllers. It is well known that loose level control usually worsens the control of composition (Yang et al., 1993). However, when a material-balance configuration is used, it is not always possible to tightly control the column inventories, be-

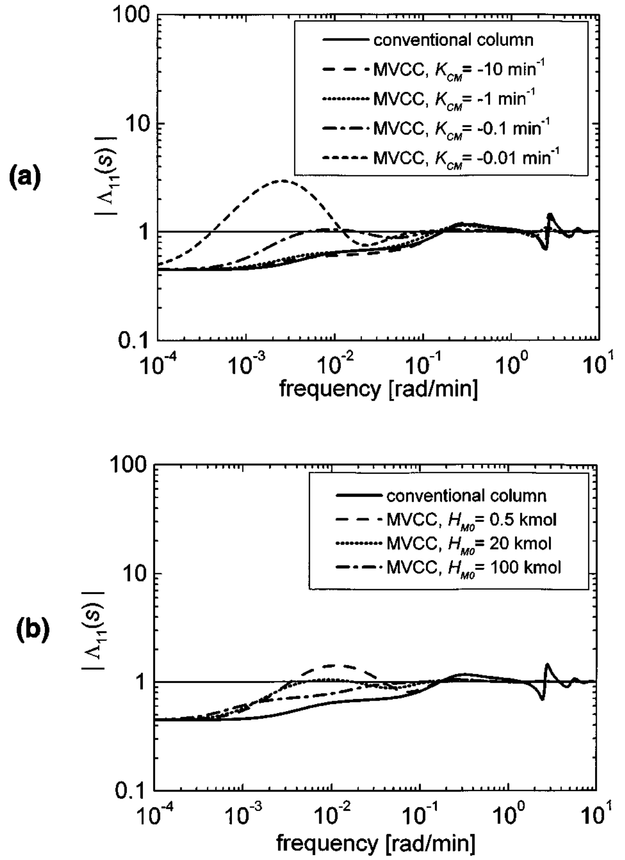

Figure 10. $|\Lambda_{11}|$ **as a function of frequency for the conventional column and several MVCCs.**

(a) $H_M = 20$ kmol and different values of K_{CM}; (b) $K_{CM} = -0.1\ \text{min}^{-1}$ and different values of H_{M0}. Column 1; D-V configuration.

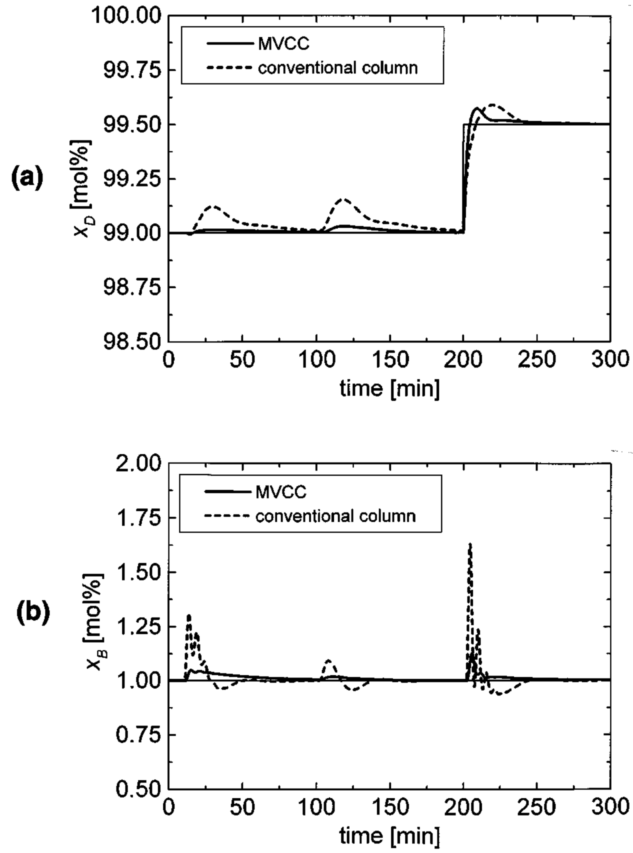

Figure 11. Profiles of the (a) distillate composition and (b) bottoms composition for the conventional column and the MVCC.

Column 1; D-V configuration; $K_{CM} = -0.1\ \text{min}^{-1}$, $H_{M0} = 20$ kmol; test problem TP1.

cause tight level control would pass excessive flow variations back into the column, thus promoting interaction between the quality loops.

Therefore, in order to analyze the effects of loose tuning of the reflux drum LC, the gain of this controller was reduced to 0.3 min^{-1} (absolute value), while the composition controllers were tuned optimally using the usual procedure.

As is shown in Table 6, loosening the control of the reflux-drum level degrades the control performance in both the conventional column and the MVCC, but the MVCC performs significantly better even in the presence of loose top-level control. However, note that, due to the decoupling achieved in the MVCC, it may not be necessary in practice to loosen the control of the accumulator level. This issue is discussed further with respect to the control performance of Column 2.

(L/D)-(VB) Configuration. The (L/D)-(V/B) configuration (also called the double-ratio configuration) was shown to be the best one for controlling Column 1 (Skogestad, 1997). The superior characteristics of this configuration can be understood by considering the plots $|\Lambda_{11}(s)|$ vs. ω illustrated in Figure 12a. The solid line shows that $|\Lambda_{11}(s)|$ is close to 1 over a wide range of frequencies for the conventional column. In this case, decoupling is mainly due to the double-ratio nature of the control scheme, rather than to the effect of the liquid flow dynamics. This is clear by looking at the dotted line of Figure 12a, which plots $|\Lambda_{11}(s)|$ in the hypothetical case of instantaneous liquid flow dynamics: no substantial differences from the "real" column are observed. Therefore, the effect of the additional dynamics introduced by the middle vessel also is marginal for this configuration, as confirmed by the profiles of the MVCC lines in Figure 12a.

On the other hand, the "composition effect" realized by the middle vessel is more pronounced in this case (Figure

Table 6. Comparison of the Optimal Control Performance of the Conventional Column and MVCC for Two Control Configurations and Different Tuning of the Top LC

Configuration	Column	Top-Level Control	φ_1 [kmol/min]
D-V	Conventional	Tight	5.557
D-V	MVCC	Tight	1.683
D-V	Conventional	Loose	6.391
D-V	MVCC	Loose	2.534
(L/D)−(V/B)	Conventional	Tight	2.908
(L/D)−(V/B)	MVCC	Tight	1.495

Note: Column 1; $K_{CM} = -0.1\ \text{min}^{-1}$; $H_{M0} = 20$ kmol; test problem TP1.

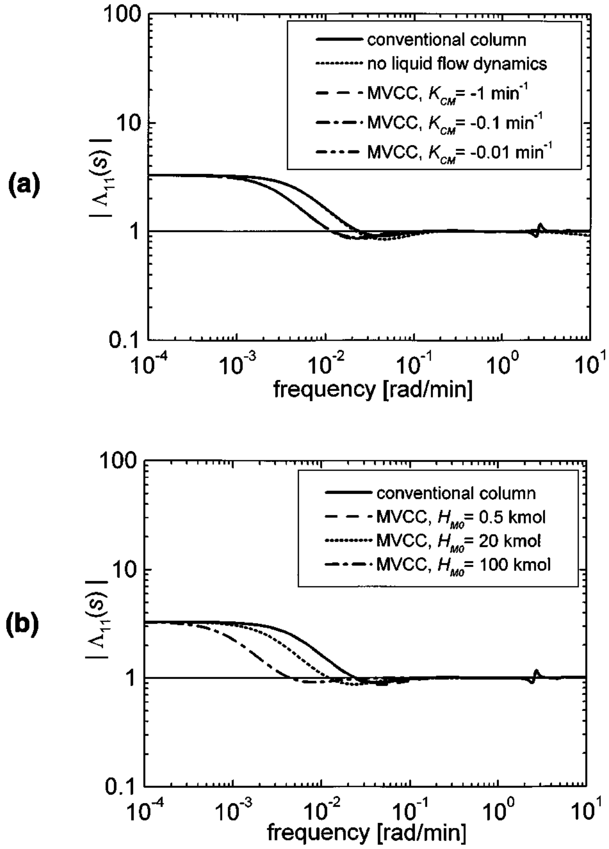

Figure 12. $|\Lambda_{11}|$ as a function of frequency for the conventional column and several MVCCs.

(a) $H_{M0} = 20$ kmol and different values of K_{CM}; (b) $K_{CM} = -0.1$ min^{-1} and different values of H_{M0}. Column 1; (L/D)-(V/B) configuration.

12b). The control results for optimal tuning of the MVCC and conventional column composition controllers are shown in Table 6. As expected, the double-ratio configuration displays a better control performance for the conventional column than the L-V configuration; inserting the middle vessel provides a further improvement.

Note that, although the double-ratio configuration often provides better control than the other configurations, its use is not as frequent as that of the energy or material-balance schemes. In fact, all the flow rates (D, L, B, V) need to be measured for implementation of the double-ratio configuration, which makes it sensitive to sensor failure. Moreover, as happens for the material-balance schemes, its performance is affected by the tuning of the top- and bottom-level controllers.

Column 2

The propylene/propane splitter was considered as an example column because it represents a severe test for assessing the performance of the middle-vessel configuration. In fact, the large column diameter (that is, large hydraulic time constant of the trays) and the very large number of stages inherently reduce the "hydraulic" coupling between the top and the bottom of the column, even without inserting a middle vessel.

The L-B configuration is used for dual composition control in this superfractionator (Gokhale et al., 1995a,b). However, the use of this material-balance scheme makes the composition control loops interact with the inventory loops, and this in turn makes dual composition control harder. This is particularly true for this column, where the bottom-level loop is loosely tuned (Gokhale et al., 1995a).

The test scenarios indicated by Gokhale et al. (1995b) were used to tune and test the controllers:

- *Test scenario 1* (TS1): A setpoint change to 99.85% propylene in the overhead product at $t = 100$ min, followed by a setpoint change to 99.55% at $t = 1{,}000$ min.
- *Test scenario 2* (TS2): A ramp change in pressure from 211 to 226 psia from $t = 100$ min to $t = 160$ min, followed by a step change in feed composition to 65% at $t = 1{,}000$ min.
- *Test scenario 3* (TS3): Negative and positive 5 mol% step changes in feed composition with changes applied every 250 min. At $t = 250$ min, the feed composition z_F is decreased to 65% propylene; at $t = 500$ min, z_F is set to 70%; at $t = 750$ min, z_F is set to 75%; at $t = 1{,}000$ min, z_F is set to 70%, and so on.

The duration of each test was 2,000 min; the setpoint profiles of test TS1 were passed through a first-order filter with a time constant of 20 min in order to avoid spiking of the manipulated variables. The controllers were tuned for TS1, and further tested on scenarios 2 and 3. In order to provide a fair comparison between the control performance of the conventional column and the MVCC, the composition-controller settings were obtained by an optimization technique similar to that developed for Column 1. It should be observed, however, that control of the distillate purity is more important than that of the bottoms purity for this superfractionator, and in practice the control objective in evaluating controller performance should be the variability in the propylene product, while keeping the bottom product only in the vicinity of the target setpoint (Gokhale et al., 1995a). Several objective functions were tested for this performance requirement, and the following composite function was eventually selected:

$$\varphi_2 = q_1 \times \mathrm{ITSE}_{x_D} + q_2 \times \mathrm{ITAE}_{x_B} + q_3 \times \mathrm{VT}_L \qquad [\text{lb mol} \times \text{s}^2], \tag{7}$$

where the q_i are dimensional weighting coefficients (see Table 7), ITSE_{x_D} is the integral of time-weighted squared error on x_D, ITAE_{x_B} is the integral of time-weighted absolute error on x_B, and VT_L is the reflux valve travel.

The optimal tuning procedure was performed for the conventional column and for an MVCC with $H_{M0} = 10{,}000$ lb mol ($\sim 14{,}000$ ft^3, at the nominal operating conditions), and $K_{CM} = -0.002$ s^{-1} (these values of the middle-vessel holdup and level controller gain will be retained in all of the follow-

Table 7. Weighting Coefficients for Use with Eq. 7

q_1 [lb mol]	q_2 [lb mol]	q_3 [s^3]
2.67×10^3	2.0	1.1×10^5

Table 8. Tuning of the Composition Controllers for the Conventional Column and for the MVCC

Column	Bottom-Level Control	K_{CD} [lb mol/s]	τ_{ID} [min]	K_{CB} [lb mol/s]	τ_{IB} [min]	Comp. Controller Tuning	$10^{-3} \times \varphi_2$ [lb mol$\times$s^2]
Conventional	Loose	232.15	75	1.7	400	Gokhale et al. (1995b)	1984
Conventional	Loose	303.1	29.3	10.93	5474	Optimal	775.1
MVCC	Loose	178.9	27.8	6.43	167	Optimal	560.4
Conventional	Tight	232.15	75	1.7	400	Gokhale et al. (1995b)	1396
Conventional	Tight	303.1	29.3	10.93	5474	Suboptimal	633.3
MVCC	Tight	178.9	27.8	6.43	167	Suboptimal	434.9

Note: Column 2, test scenario 1.

ing MVCC runs). The tuning results are summarized in Table 8 under the heading "loose" control of the bottom level.

The control response during TS1 is illustrated in Figure 13. It is apparent that, although the control of the bottom purity is not too different between the optimally tuned conventional column and the MVCC, the control of distillate composition is better in the MVCC, since this column settles to the new steady states in a considerably shorter time than the conventional column. Moreover, the profiles of the reflux and vapor rates are much smoother in the MVCC, and this leads us to argue that the optimal tuning for the conventional column might not be advisable in practice.

In fact, since the boilup rate varies quite markedly before the conventional column can attain a new steady state, it is likely that these wide vapor flow variations would alter the column fluid-dynamic regime, which in turn would affect both the separation efficiency and the stability of operation of the top cooling system. This is the reason why the curves related to the tunings of Gokhale et al. (1995b) have been reported on Figure 13, too. These tunings (which will be called "origi-

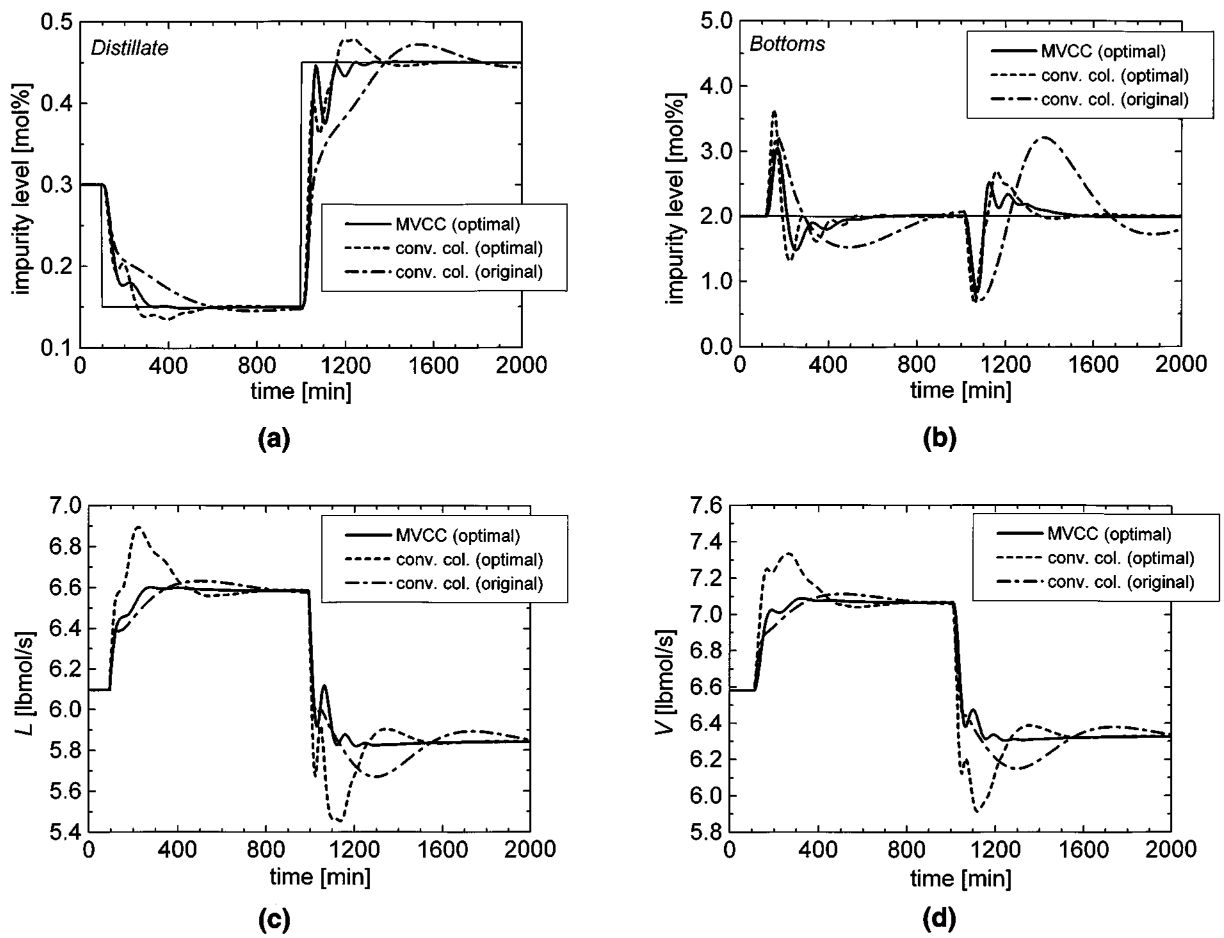

Figure 13. Profiles of (a) distillate composition, (b) bottoms composition, (c) reflux rate and (d) boilup rate for the conventional column (optimal and original tuning of the composition controllers) and the MVCC (optimal tuning of the composition controllers).

Column 2, test scenario 1.

nal" in the following) provide a sounder term of comparison for the performance of the MVCC. Figures 13a and 13b clearly show that the improvement of the MVCC configuration for dual composition control is much more marked when compared to the original tunings, and this is achieved without any loss of performance in terms of smoothness of the control action (Figures 13c and 13d).

The fact that the vapor boilup profile evolves so smoothly in the MVCC also suggests another consideration. In fact, it was noted earlier that the bottom-level controller is tuned loosely in this column. Loose tuning is necessary to keep the bottom-level controller from spiking the vapor boilup rate. Figure 13d suggests that the bottom LC can be made more aggressive in the MVCC, without expecting large modifications of the boilup profile. A faster tuning of the bottom LC was achieved in the MVCC by increasing the absolute value of the controller gain five times with respect to the original value; no further tuning of the composition controllers was performed. The control results for TS1 and this new setting of the bottom LC are shown in Figure 14.

The improvement in the control performance is indeed very large. Tightening the control of the bottom level provides a way to decouple the bottom inventory loop from the composition loop, and this in turn almost eliminates the interaction between the composition loops. On the other hand, although a decrease in the value of the objective function ($\varphi_2 = 1{,}396 \times 10^3$ lb mol$\times$s^2; Table 8, "tight" bottom-level control) is exhibited when the bottom LC is made more aggressive in the conventional column (with the original tuning of the composition controllers), the control performance of this column is still remarkably inferior to that of the MVCC. Tight level control in the conventional column, with suboptimal tuning of the composition controllers, was shown to improve the bottom composition response, but on the whole the control performance ($\varphi_2 = 633.3 \times 10^3$ lb mol$\times$s^2) was still inferior to the performance of the MVCC, with either loose or tight bottom-level control in the MVCC. This is evidence that the role of the middle vessel is crucial for providing decoupled dual composition control in the superfractionator. Only a minor loss of performance was noticeable in the MVCC when the initial middle-vessel holdup was decreased; satisfactory results were obtained with H_{M0} down to ~ 2,000 lb mol.

The MVCC and conventional column were further compared in the regulatory problem of test TS2, and the relevant results are illustrated in Figure 15. Again, the MVCC control response is superior to that of the conventional column, par-

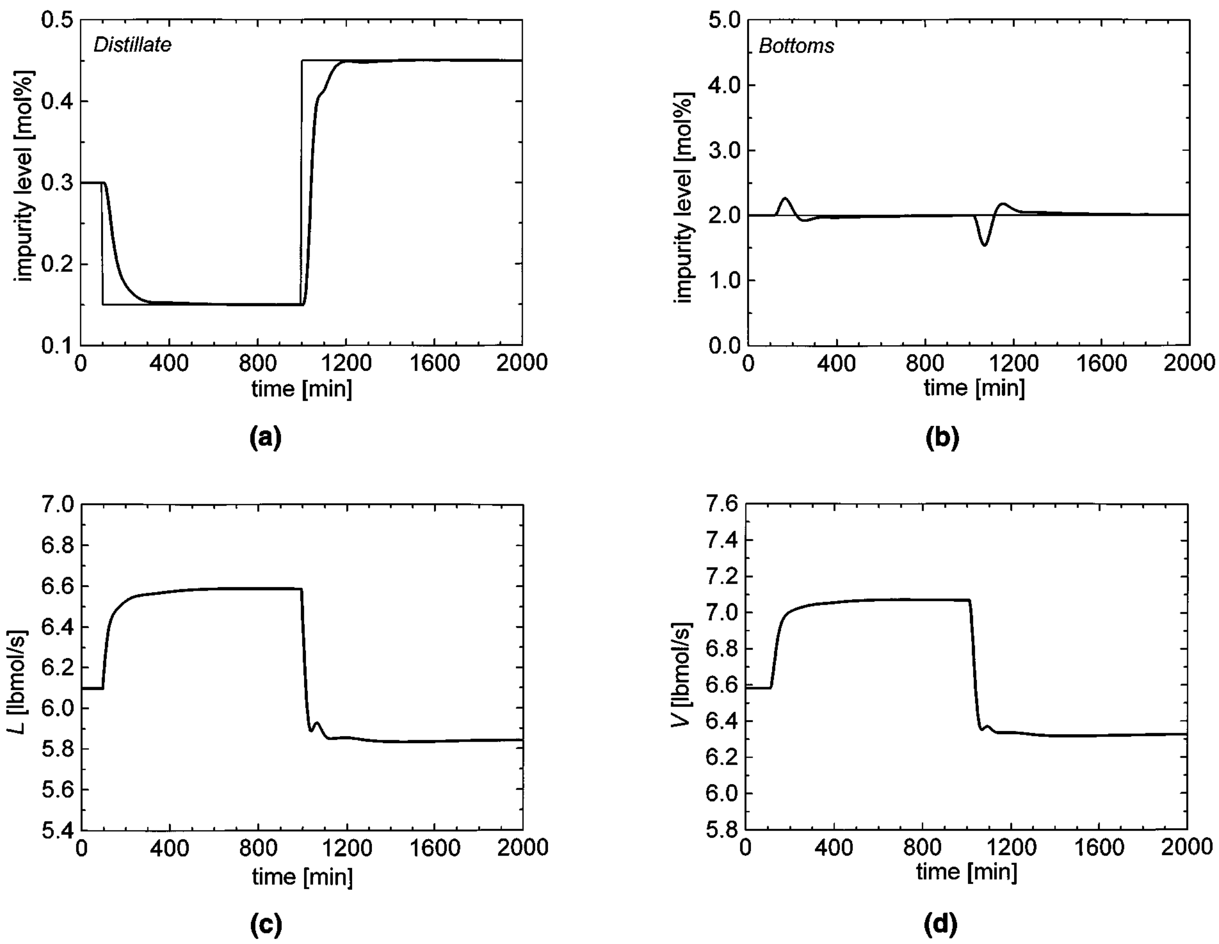

Figure 14. Profiles of (a) distillate composition, (b) bottoms composition, (c) reflux rate, and (d) boilup rate for the MVCC (tight control of bottom level; suboptimal tuning of the composition controllers).

Column 2, test scenario 1.

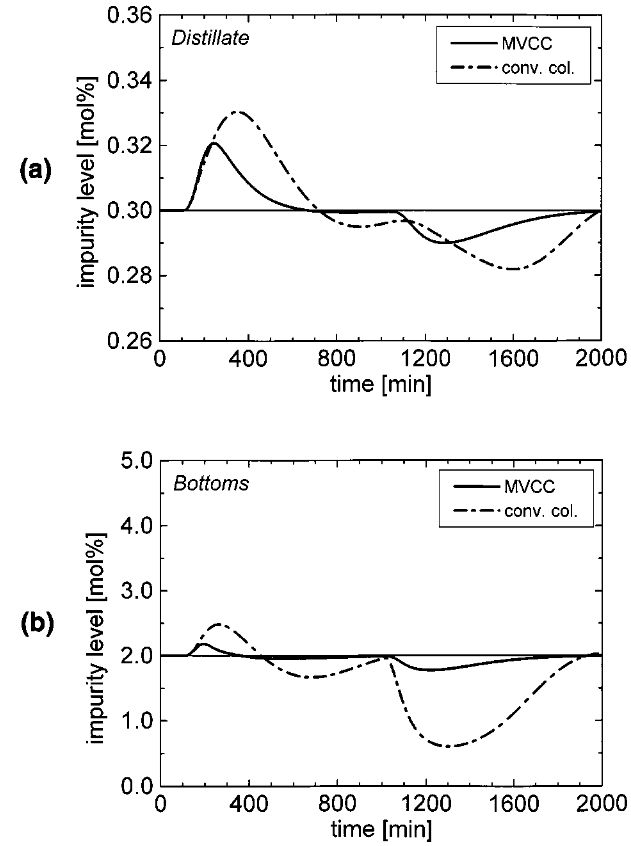

Figure 15. Profiles of (a) distillate composition and (b) bottoms composition for the conventional column (original tuning of the composition controllers) and the MVCC (tight control of bottom level; suboptimal tuning of the composition controllers).

Column 2, test scenario 2.

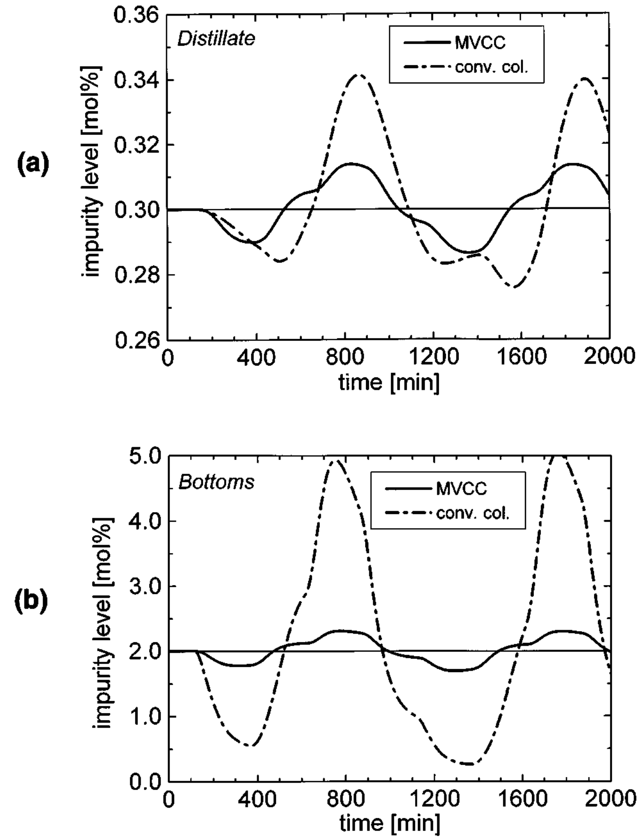

Figure 16. Profiles of (a) distillate composition and (b) bottoms composition for the conventional column (original tuning of the composition controllers) and the MVCC (tight control of bottom level; suboptimal tuning of the composition controllers).

Column 2, test scenario 3.

ticularly in the control of the quality of the bottoms. The same conclusion can be drawn for TS3, whose results are shown in Figure 16.

Further Remarks

1. Since this study is mainly devoted to analyzing the impact of a new column layout on the performance of conventional controllers for dual composition control, we have not tried to find a criterion for optimally choosing the values of either the middle-vessel level controller gain or the middle-vessel initial holdup. Although it has been shown that for the L-V configuration the choice of the vessel holdup is not a concern, the value of H_{M0} may affect the decoupling nature of the MVCC when a material-balance control configuration is used, as was shown in Figure 10b. An analysis of the plots of $|\Lambda_{11}(s)|$ may be useful in order to determine a "workable" value for H_{M0}. As starting point for trayed columns, one can choose H_{M0} equal to the total tray holdup; however, this is by no means a recommended value, and the issue of the choice of H_{M0} should be investigated in more detail in future studies.

2. Both of the columns explored had liquid feeds. It is well known that any disturbance entering a column through a vapor feed primarily propagates up to the top rather than down to the bottom; this inherently improves the bottom composition response and worsens the top composition response (Cantrell et al., 1995). However, it was verified that, with a vapor feed, an MVCC still guarantees significant improvements in the overall control response. In fact, since the top loop can be tuned fast enough in an MVCC, rejecting a vapor feed disturbance from the top of the MVCC is easy. Moreover, the bottom composition loop does not suffer from the action of the top controller, because the middle vessel almost suppresses dynamic coupling.

3. Although a large-vessel holdup provides a way of smoothing composition disturbances entering the column through the "external" feed if this feed is liquid, from a practical point of view the middle-vessel holdup should be chosen as small as possible. This is not only to reduce capital costs and safety concerns (see below), but also because, since a P-only LC is used to drive the liquid flow to the stripping section, the level transmitter must have enough sensitivity to allow a good measure of the level offset with the actual value

of the vessel holdup and the selected gain of the level controller. The LC can be equipped with a very mild integral action, if one desires that the level be driven back to the setpoint in the long term. In any case, high- and low-level alarms should be provided to keep the vessel from running full or empty.

4. The procedure adopted for tuning the composition controllers is based on minimization of a performance function φ, which accounts for both the composition response of the column and the amount of work done by the control system. Due to the highly nonlinear dependence of φ from the tuning parameters, the φ hypersurface is quite complex, and therefore we cannot guarantee that all of the optimization runs have indeed reached a global minimum of φ. In any case, the optimization procedure was repeated several times, starting from different initial points in order to reduce the risk of entrapment in local minima. Moreover, the results obtained are consistent with what one expects from a theoretical analysis.

5. Although conventional PI controllers were used throughout the article, PI controllers acting on logarithmic transforms of compositions were also tried, for both Column 1 and Column 2, but these controllers yielded results practically equivalent to those obtained with the conventional controllers.

6. If single composition control is requested, interaction between control loops is not an issue, of course. Therefore, there is no advantage in using an MVCC in that case. However, using an MVCC instead of a conventional column may make dual composition control more attractive, because controlling both purities might well be easier and cheaper in terms of energy requirements.

7. The issues of cost and safety deserve attention at this point. It must be recognized that, before definitely stating that an MVCC is superior to a conventional column, one should wonder whether on not the control improvement is worth the economic and safety penalties. In fact, outfitting a new MVCC results in higher investment costs, because an additional (possibly large) vessel, as well as transfer and mixing pumps, must be installed. Safety concerns are increased, too, as the process inventories increase and the middle vessel may need to be operated at high pressure (if the distillation pressure itself is high).

Conclusions

In this article we have analyzed how a novel design of trayed continuous distillation columns can impact the performance of conventional proportional-integral controllers when it is required to accurately control the purity of both products in a binary separation. The proposed column layout is characterized by the presence of a middle vessel, to which two streams are fed: the liquid flow coming from the rectifying section and the feed flow to be separated. The middle-vessel level controller provides the actual liquid flow to the column.

The control performance of this MVCC configuration has been compared to that of two conventional benchmark columns for different control configurations. It has been shown that using an MVCC provides a way of reducing the interaction between the quality loops, in such a way that the control performance of the middle-vessel column can be made remarkably superior to that of the conventional columns, whatever the control configuration. The results obtained were supported by a theoretical analysis based on the frequency-dependent relative gain array tool.

For the L-V configuration (the standard control scheme in industry), it has been shown that the main effect accomplished by the middle vessel is to hydraulically decouple the stripping section from the rectifying section (''hydraulic effect'' of the middle vessel). Instead, for the double-ratio configuration, the middle vessel mainly acts in such a way that the open-loop composition dynamics is made slower (''composition effect'' of the middle vessel). For the material balance control configurations (either L-B or D-V), the situation is somewhat in between. In this case, the interaction of inventory control with composition control may result in a partial loss of performance of the MVCC; however, it was shown that by properly choosing the vessel holdup and level controller gain, the MVCC significantly outperforms the conventional column for the material balance schemes, too. For the material-balance schemes, the impact of the middle vessel on the tuning of the top and bottom inventory controllers was also discussed.

The results presented appear very promising, especially in the light of today's competitive pressures, which require process plants to achieve not only high yields but also excellent product quality and low energy consumption.

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Notation

D = distillate molar rate
F = feed molar rate
K_{CD}; K_{CB} = gains of the PI controllers of distillate and bottoms composition, respectively
K_{ij}^{LV} = same as K_{ij}, but for the L-V control configuration
L = reflux molar rate
L_B = molar rate of liquid flowing from the bottom tray
M_i = liquid molar holdup on tray i
N = number of ideal stages
N_F = feed stage
q = dimensional weighting coefficient
V = vapor boilup molar rate
x_D; x_B = distillate and bottoms composition, respectively
$x_{D,sp}$; $x_{B,sp}$ = setpoint of the distillate and bottoms composition, respectively
α = relative volatility
Δ = step change
φ; φ_1; φ_2 = performance functions
τ_{ID}; τ_{IB} = integral time constants of the proportional-integral controllers of distillate and bottoms composition, respectively

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