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Chromatographic and SMB Center-Cut Separations of Ternary Mixtures

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Abstract: Chromatography and SMB processes were studied to isolate only the intermediate retained component from ternary mixtures. The separation of ternary phenol and amino acid mixtures was simulated with Aspen Chromatography®. Simulation results for the phenol system with 10 μm packing showed that recycled center-cut chromatography usually produced the highest purity compared to cascades with two 4-zone SMBs and a 2-zone SMB/chromatography. For the amino acid mixture at $\Delta P_{max} = 1.0$ bar and purity-recovery index = 95%, the recycled cascade of two 4-zone SMBs had approximately a 25% larger productivity compared to the simpler recycled center-cut chromatography.

Keywords: Center-cut, chromatography, SMB

INTRODUCTION

Simulated Moving Bed (SMB) processes have generally been more economical than elution chromatography for large-scale binary and pseudo-binary (desired component is either least or most strongly adsorbed) separations (1–3). Although there is considerable interest and a few commercial units, ternary separations have not been extensively studied.

For complete, isocratic separation of a ternary mixture, two coupled binary SMBs in various configurations (e.g., Fig. 1) have been used (4–6). However, these multiple cascade systems require many columns that should be uniformly packed, have high pressure drop, and are considered to be

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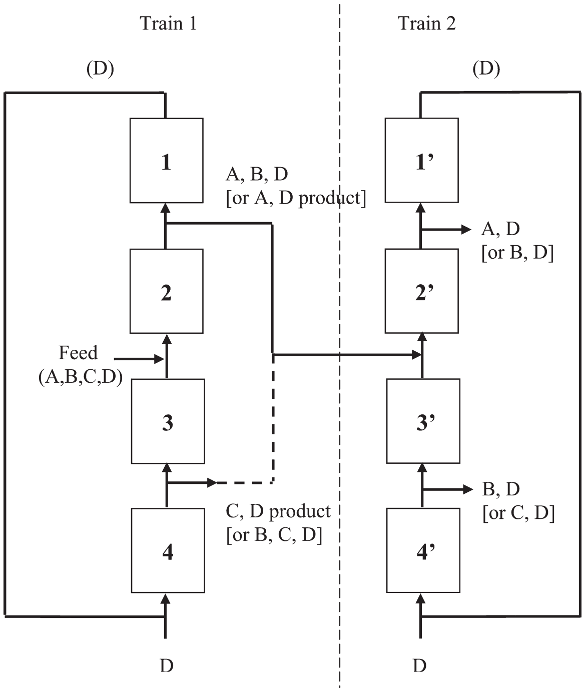


Figure 1. Cascade with two four-zone SMBs for complete ternary separation (6). Switching of ports is not shown.

expensive. Masuda et al. (7) patented a discontinuous SMB process for ternary separations that has been commercialized by Organo Corporation. A 5-zone system with a side stream that is applicable to relatively easy separations has also been extensively studied (8, 9). Hur and Wankat (10) developed a 2-zone SMB/chromatographic process for complete ternary separations, but it also requires relatively easy separations. An even simpler 2-zone SMB/chromatography system was developed for purification of only the intermediate retained component from a ternary mixture (11, 12), but desorbent to feed (D/F) requirements are relatively high.

In this paper we look at center-cut separations where only the intermediate adsorbed component is of value. Aspen Chromatography simulations are used to compare four systems:

1. a cascade of two 4-zone SMBs recovering only the intermediate retained component (called a center-cut for the remainder of this paper),
2. a recycled center-cut cascade of two 4-zone SMBs,
3. a 2-zone SMB/chromatography cascade for center-cuts, and
4. a new center-cut recycle chromatography system.

These processes are studied first for the center-cut separation of a phenolic mixture of phenol (A), 2-phenylethanol (B) and 3-phenyl-1-propanol (C) where it is assumed that the only desired product is 2-phenylethanol (B), and then for the center-cut separation of glycine (A), L-phenylalanine (B), and L-tryptophan (C) where it is assumed that the only desired product is L-phenylalanine. Throughout this paper A will be the least adsorbed substance and C the most adsorbed.

PROCESS DESCRIPTIONS

Figure 1 shows the usual cascade of two SMBs for complete ternary separations. The connections with solid lines would typically be used if the B-C separation is easier and the connections with dotted lines would typically be used if the A-B separation is easier.

Since a complete separation is not required, the D/F ratio can be reduced by not doing a complete separation in zone I or zone IV of the first train (Fig. 2) (4). For example, component A can be allowed to spread throughout the entire cascade. Since component B is the only desired product, the first

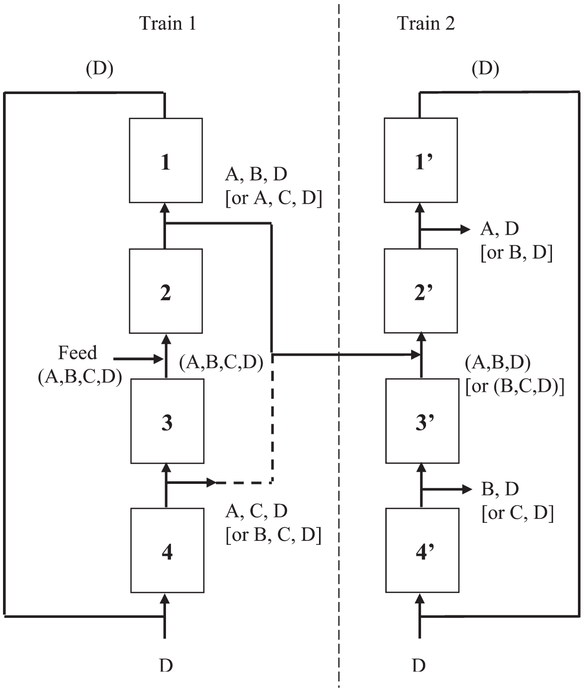
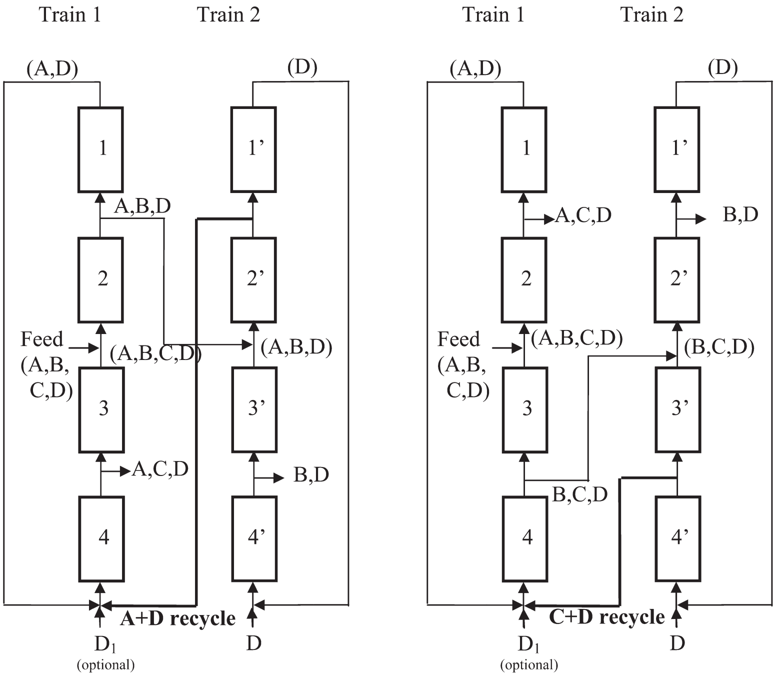


Figure 2. Cascade with two four-zone SMBs for center-cut separation (4, 5). Switching of ports is not shown.

train separates the ternary feed into two binary mixtures one of which is waste and the other is sent to the second train, which does a binary separation. Allowing one component to distribute in the first train reduces desorbent consumption although the system is still complex and expensive.

The next refinement is to add recycle of the unwanted product from the second train (Fig. 3) (11). Although this process is more complex, in the ideal case of infinitely fast mass transfer and no axial dispersion, the minimum amount of desorbent required for a center-cut separation of an isocratic, isothermal, isobaric system with linear isotherms is reduced to the thermodynamic minimum, $(D/F)_{\min} = 1.0$. The minimum is 1.0 in this case because the ternary feed is separated into only two products.

The center-cut 2-zone SMB/chromatography system is shown in Fig. 4 (11, 12). This system was based on the complete ternary separation process (10), but with components A and C produced as a mixture. This simplification makes the separation constraints less restrictive, but the two-zone system still requires a relatively large selectivity between the intermediate and most retained components.



(a) (b)

Figure 3. Recycled cascade with two four-zone SMBs for purification of only the intermediate component in ternary mixtures (11). (a) B-C separation is easier. (b) A-B separation is easier. Switching of ports is not shown.

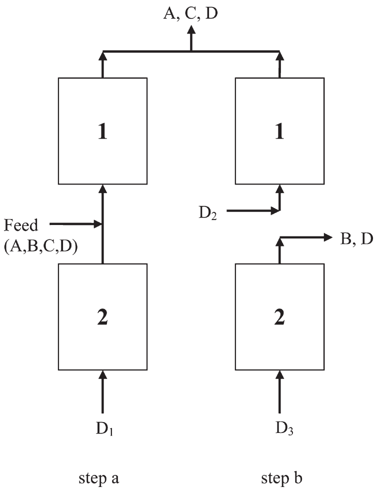


Figure 4. Center-cut, two-zone SMB/chromatography system for recovering only the intermediate component from a ternary mixture (11). Switching of ports is not shown.

As a benchmark, we also tried a chromatography system with repeated feed steps. The local equilibrium solution for this process with linear isotherms is shown in Fig. 5a. For the single porosity model with linear isotherms $q_i = K_i c_i$, the solute movement u_{si} velocity is (3),

$$u_{si} = \frac{v}{1 + ((1-\varepsilon)/\varepsilon)K_i} = G_i v \tag{1}$$

where G_i is a constant for each solute i. Since mass transfer resistance and axial dispersion are not included in this analysis, this model provides only an initial approximation. If we time the next feed step so that the A and C products overlap we obtain the local equilibrium solution shown in Fig. 5b. Since the separation is controlled by the pair of key components (A and B in Fig. 5), excess pure desorbent leaves the column between the B and C peaks. This pure desorbent can be recycled, which gives the center-cut recycle chromatography system shown in Fig. 6. In the ideal case of infinitely fast mass transfer and no axial dispersion, the minimum amount of desorbent for a center-cut separation of an isocratic, isothermal, isobaric system with linear isotherms is again the thermodynamic minimum, $(D/F)_{min} = 1.0$. In real systems with finite mass transfer rates and axial dispersion the recycled desorbent will not be completely pure, and it will probably make a difference when it is recycled. Three possibilities are shown in Fig. 7.

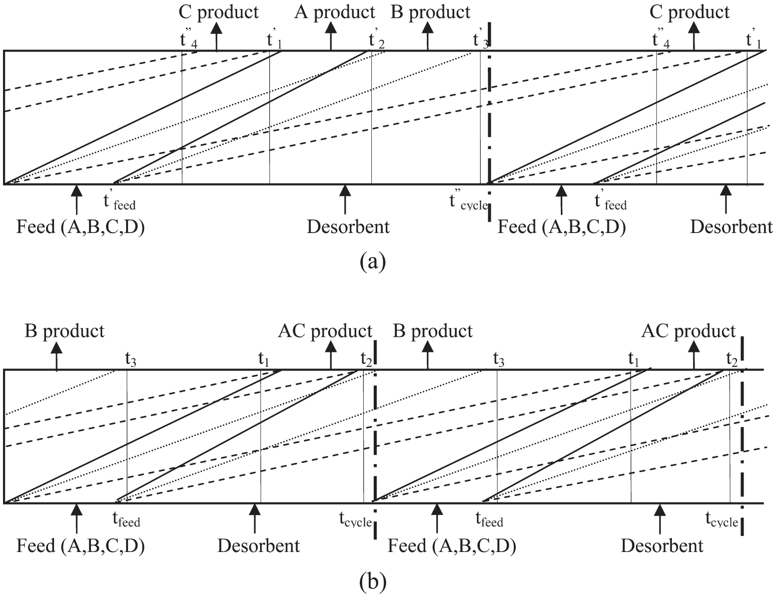


Figure 5. Local equilibrium solutions for the chromatography systems with repeated feed pulses with linear isotherms for complete ternary separation (a) and center-cut separation (b). ——— A, ... B, – – –C). These diagrams are at $D/F > (D/F)_{\min}$.

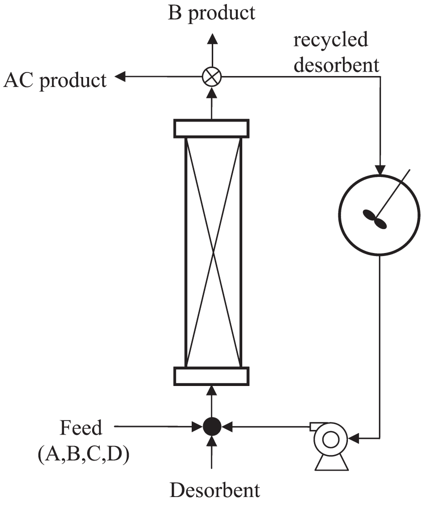
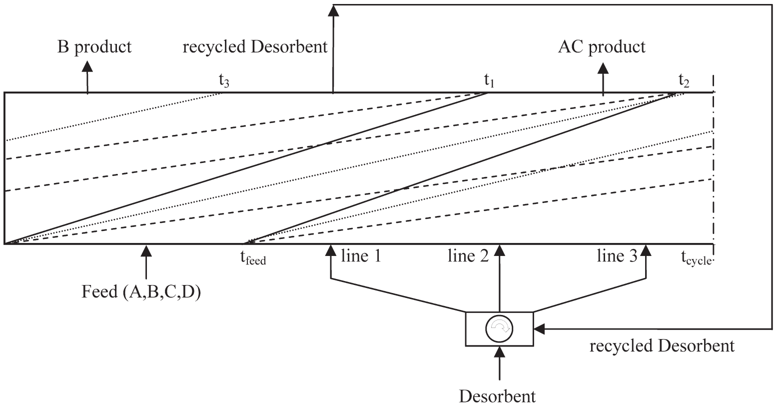


Figure 6. Center-cut, recycle chromatography to separate only the intermediate retained component B from a ternary mixture.



case no.	line 1	line 2	line 3
case 1	**recycled desorbent**	pure desorbent	pure desorbent
case 2	pure desorbent	**recycled desorbent**	pure desorbent
case 3	pure desorbent	pure desorbent	**recycled desorbent**

Figure 7. Local equilibrium solution for recycle center-cut chromatography system with linear isotherms (——— A, ... B, – – –C) with different locations for the recycled desorbent.

SIMULATIONS AND RESULTS

Phenolic System

The processes in Figs. 2, 3, 4 and 6 were simulated with the commercial Aspen Chromatography simulator. Aspen Chromatography uses the method of lines to solve the standard partial differential equations for adsorption in packed beds. Details of the equations and simulations are given by Hur (13). The initial simulations were done for separation of a phenolic mixture of phenol (A), 2-phenylethanol (B) and 3-phenyl-1-propanol (C) with a 10 μm packing. System and operating parameters are given in Table 1 (14). For the phenolic mixture, the number of theoretical plates N_p based on the apparent dispersion coefficients D_{ax} is used to evaluate the mass transfer and dispersion effects. The processes are compared at the same productivity, $3.01 \times 10^{-2}\ \text{cm}^3/\text{cm}^3 \cdot \text{min}$. The analysis and results for the center cut 2-zone SMB/chromatography system were reported previously (11). The optimized flow rates for all systems are given in Table 2.

For the recycled cascade with two four-zone SMBs (Fig. 3), the concentrations and fractions in stream AB and in recycled stream A varied throughout the switching time if the trains are directly connected without buffer tanks. This can result in irregular oscillation in product concentrations. It is desirable

Table 1. System and operating parameters. Data for equilibrium, and mass transfer for phenolic system (14)

	Phenolic system phenol (A), 2-phenylethanol (B) and 3-phenyl-1-propanol (C)
Length of column (L)	25 cm
Column diameter (d)	0.46 cm
Voidage (ε)	0.54
Particle radius (R)	5 μm
Density (ρ)	1.0 g/cm^3
Viscosity (μ)	1.9 cp
Mass transfer/dispersion	$N_{pA} = 3500$
	$N_{pB} = 4000$
	$N_{pC} = 6000$
Linear isotherm at T = 21°C	$K_A = 2.15$, $G_A = 0.654$
	$K_B = 3.61$, $G_B = 0.454$
	$K_C = 6.85$, $G_C = 0.271$
Feed concentration	5 g/l

to have a constant average concentration so that a cyclic steady state is obtained. In general, stirred tanks between the two trains can be used to reduce the oscillation and to keep the average concentrations constant. If cycle times are adjusted so that the switching times are congruent, only a small tank was needed to remove the oscillation, and the system quickly reached the cyclic steady state (13). In this study all columns are identical to keep the productivity constant, and the stirred tank is large enough to remove the oscillation.

The standard cascade with two four-zone SMBs (Fig. 1) and the recycled cascade with two four-zone SMBs (Fig. 3) were optimized sequentially since application of a genetic algorithm to the entire system resulted in run time errors (10). Train 1 was simulated with various D/F values, and then four D/F values were chosen in between the minimum D/F and the D/F which gave an almost constant purity-recovery index (PRI) for train 1. The PRI is defined as,

$$\text{PRI} = \text{purity recovery index} = (\text{Purity}_i + \text{Recovery}_i)/2 \qquad (2)$$

Then, train 2 was simulated with the results of train 1 to find the maximum purity-recovery indices by changing flow rates. The recycled cascade was first optimized without recycle, and then the recycle stream was connected. Therefore, the operating conditions may not be the global optimum for the recycled cascade.

Figure 8 shows the results for the three SMB systems. Minimum D_{total}/F was decreased from 2.9 for the standard cascade for complete ternary separations (Fig. 1) to 2.0 for the center-cut cascade (Fig. 2), and is further

Table 2. Optimized switching times and flow rates (cm^3/min) for phenol system

		1st train					2nd train						
D_{total}/F	t_{sw} (min)	Q_{R1}	Q_{D1}	Q_{AB}	Q_C	$t_{sw'}$ (min)	Q_{R2}	Q_{D2}	Q_A	Q_B	B purity (%)	B yield (%)	PRI (%)
(a) Cascade with two four-zone SMBs for complete ternary separation (Fig. 1) ($Q_{feed} = 1.0\ cm^3/min$, $C_A = C_B = C_C = 5.0\ g/l$)													
2.90	6.19	1.026	1.451	1.451	1.000	1.92	3.303	1.451	1.451	1.451	94.5	95.0	94.7
3.28	5.94	1.059	1.550	1.497	1.053	1.73	3.622	1.727	1.591	1.632	97.1	97.1	97.1
4.00	5.19	1.173	1.900	1.659	1.241	1.48	4.189	2.100	1.840	1.919	98.8	98.3	98.5
5.00	5.19	1.173	1.900	1.659	1.241	1.17	5.122	3.100	2.250	2.509	99.5	99.2	99.4
7.00	4.54	1.304	2.300	1.845	1.455	0.85	6.864	4.700	3.015	3.529	99.9	99.9	99.9

		1st train					2nd train						
D_{total}/F	t_{sw} (min)	Q_{R1}	Q_{D1}	Q_{AB}	Q_{AC}	$t_{sw'}$ (min)	Q_{R2}	Q_{D2}	Q_A	Q_B	B purity (%)	B yield (%)	PRI (%)
(b) Cascade with two four-zone SMBs for B purification (Fig. 2) ($Q_{feed} = 1.0\ cm^3/min$, $C_A = C_B = C_C = 5.0\ g/l$)													
2.00	6.19	1.477	1.000	1.000	1.000	2.79	2.277	1.000	1.000	1.000	95.2	92.9	94.0
3.00	5.63	1.587	1.200	1.075	1.125	1.94	3.124	1.800	1.372	1.503	99.2	97.4	98.3
4.00	5.19	1.173	1.900	1.659	1.241	1.48	4.189	2.100	1.840	2.350	99.3	98.7	99.0
5.00	4.54	1.304	2.300	1.845	1.455	1.23	4.998	2.700	2.195	3.117	99.8	99.1	99.5
6.30	4.54	1.304	2.300	1.845	1.455	0.95	6.211	4.000	2.728	3.707	99.9	99.7	99.8
7.30	4.54	1.304	2.300	1.845	1.455	0.82	7.145	5.000	3.138	3.706	99.9	99.8	99.8

(*continued*)

Table 2. Continued

		1st train					2nd train							
D_{total}/F	t_{sw} (min)	Q_{R1}	Q_{D1}	Q_{AB}	Q_{AC}	$t_{\text{sw}'}$ (min)	Q_{R2}	Q_{D2}	Q_{A}	$Q_{\text{A recycle}}$	Q_{B}	B purity (%)	B yield (%)	PRI (%)
(c) Recycled cascade with two four-zone SMBs for B purification (Fig. 3) ($Q_{\text{feed}} = 1.0$ cm^3/min, $C_{\text{A}} = C_{\text{B}} = C_{\text{C}} = 5.0$ g/l)														
1.00	6.19	1.477	0.000	1.000	1.000	2.79	2.277	1.000	0.000	1.000	1.000	93.1	93.1	93.1
2.16	5.19	1.173	0.060	1.659	1.241	1.48	4.189	2.100	0.000	1.840	1.919	98.3	98.9	98.6
2.80	4.54	1.304	0.105	1.845	1.455	1.23	4.998	2.700	0.000	2.195	2.350	99.3	99.5	99.4
4.00	4.54	1.304	0.000	1.845	1.455	0.95	6.211	4.000	0.428	2.300	3.117	99.8	99.9	99.8
5.00	4.54	1.304	0.000	1.845	1.455	0.82	7.145	5.000	0.838	2.300	3.707	99.9	99.8	99.8
7.00	4.54	1.304	0.000	1.845	1.455	0.63	9.011	7.000	1.658	2.300	4.887	99.9	99.8	99.9

D_{total}/F	t_{sw} (min)	Q_{AC2}	Q_{D1}	Q_{AC1} ($= Q_{\text{D2}}$)	Q_{B} ($= Q_{\text{D3}}$)	B purity (%)	B yield (%)	PRI (%)
(d) Center-cut two-zone SMB/chromatography system (Fig. 4) ($Q_{\text{feed}} = 0.5$ cm^3/min, $C_{\text{A}} = C_{\text{B}} = C_{\text{C}} = 5.0$ g/l, $t_{\text{a}} = t_{\text{b}} = t_{\text{sw}}/2$)								
3.28	11.16	1.027	0.527	0.611	0.500	98.2	93.4	95.8
4.00	9.44	1.150	0.650	0.710	0.641	98.9	99.6	99.2
5.00	7.89	1.225	0.725	0.963	0.813	99.5	99.9	99.8
7.00	5.46	1.817	1.317	1.277	0.906	99.6	99.9	99.8

D_{total}/F	Q (cm^3/min)	t_{feed} (min)	t_3 (min)	t_1 (min)	t_2 (min)	t_{cycle} (min)	B purity (%)	B yield (%)	PRI (%)
(e) Center-cut chromatography system without desorbent recycle (Fig. 5b) ($C_A = C_B = C_C = 5.0$ g/l)									
2.22	0.403	6.93	7.33	15.78	0.40	22.31	94.2	92.4	93.3
3.00	0.500	4.49	5.35	12.16	17.73	17.96	98.4	98.7	98.6
4.00	0.625	2.87	3.92	9.36	13.83	14.37	99.6	100.0	99.8
5.00	0.750	2.00	3.07	7.60	11.32	11.97	99.8	100.0	99.9
8.00	1.126	0.95	1.52	3.44	7.62	8.54	99.9	100.0	100.0

D_{total}/F	Q (cm^3/min)	t_{feed} (min)	t_3 (min)	t_1 (min)	t_2 (min)	$t_{recycle}$ (min)	t_{cycle} (min)	B purity (%)	B yield (%)	PRI (%)
(f) Center-cut chromatography system with desorbent recycle (Figures 6 and 7) ($C_A = C_B = C_C = 5.0$ g/l)										
1.00	0.403	6.93	7.33	15.78	0.40	13.86	22.31	92.1	92.4	92.3
1.49	0.500	4.49	5.35	12.16	17.73	11.16	17.96	98.2	98.7	98.5
2.10	0.625	2.87	3.92	9.36	13.83	8.92	14.37	99.6	100.0	99.8
2.73	0.750	2.00	3.07	7.60	11.32	7.44	11.97	99.9	100.0	100.0
5.97	1.126	0.95	1.52	3.44	7.62	6.61	8.54	99.9	100.0	100.0

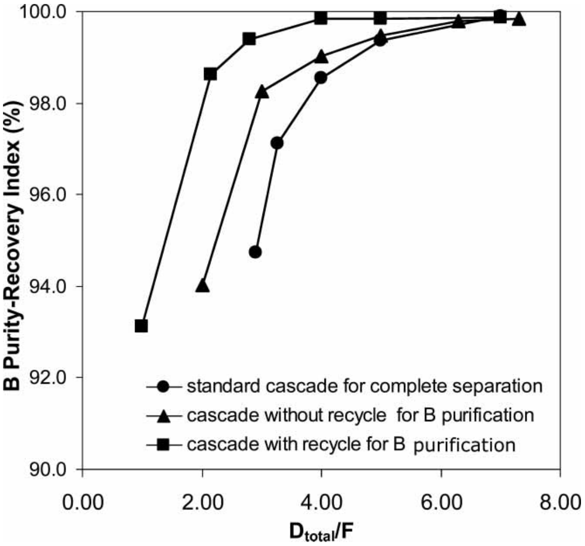


Figure 8. Results for phenol separations for the standard SMB cascade for complete ternary separation (Fig. 1), center-cut SMB cascade (Fig. 2), and the recycled, center-cut SMB cascade (Fig. 3). The SMB systems have one column per zone.

reduced to 1.0 for the recycled center-cut cascade (Fig. 3) [each curve starts at $(D_{\text{total}}/F)_{\min}$]. The purity-recovery index at $(D_{\text{total}}/F)_{\min}$ decreased in the recycled cascade because the fraction of A in the AB product stream increases. However, the recycled system has a higher PRI for B than the other two cascades at the same D_{total}/F and same productivity. This is particularly significant at low desorbent rates. Only the recycled SMB system will be compared to the other processes.

The local equilibrium solution for a complete ternary chromatography process was shown in Fig. 5. The general separation constraints for this process are easily derived with the local equilibrium model (13). If the new feed is introduced after component C exits the column, the minimum D/F for the phenolic mixture is 5.50. If the new feed is timed to produce A product just after C is produced (Fig. 5a), the minimum D/F decreases to 3.22, which is a 41% reduction. For the center-cut separation, A and C concentration profiles can be overlapped to further reduce the desorbent consumption (Fig. 5b). This also reduces the time for one complete cycle so that productivity increases,

$$\text{productivity} = \frac{Q(t_{feed}/t_{cycle})}{\text{adsorbent volume}} \tag{3}$$

Additional reduction in desorbent use is possible by recycling desorbent as shown in Fig. 6. Although a tank is required and the recycled desorbent may

Table 3. Simulation results for phenol separation with different locations of the recycled desorbent for $D_{\text{total}}/F = 1.0$ and $d_p = 10$ μm (Fig. 7)

Case no.	B purity (%)	B yield (%)	PRI (%)
Case 1	86.7	92.9	89.8
Case 2	89.2	92.5	90.9
Case 3	92.1	92.4	92.3

not be pure, $(D/F)_{\min} = 1.0$ with desorbent recycle. Center-cut chromatography with desorbent recycle was tested with three different cases (Fig. 7) at $D/F = 1.0$. Table 3 shows that case 3 (returning the recycled desorbent immediately before the next feed pulse) has the highest B purity and recovery. Thus, case 3 was used for all remaining simulations and it was assumed that all desorbent exiting the column between t_1 and t_2 is recycled. A genetic algorithm was used to maximize the purity-recovery index for the center-cut chromatography with fixed D_{total}/F values. The optimized flow rates are given in Table 2f.

In Fig. 9, center-cut chromatography with desorbent recycle is compared to center-cut chromatography without desorbent recycle. Desorbent recycle reduces $(D_{\text{total}}/F)_{\min}$ from 2.2 to 1.0. Because of dispersion, the recycled desorbent will contain A and C components that will contaminate B product. Thus, recycled chromatography has a lower PRI than chromatography

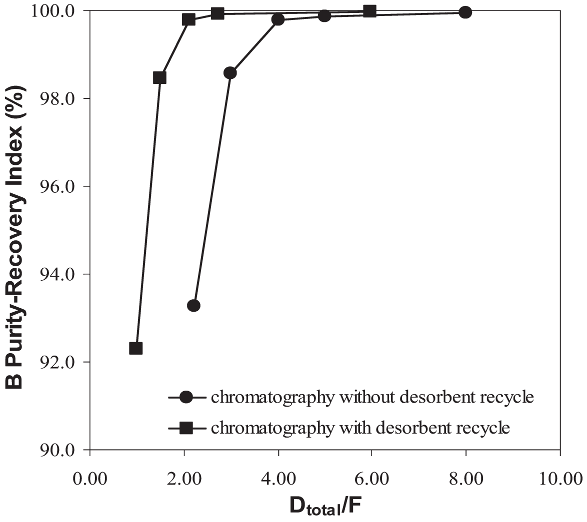


Figure 9. Results for phenol separations for center-cut chromatography (Figs. 6 and 7) without and with recycle. Operating times are optimized for each D_{total}/F value (Table 2).

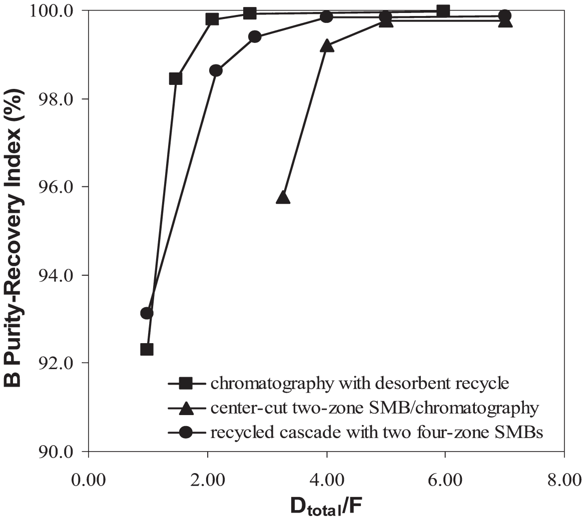


Figure 10. Results for center-cut separation of phenols for recycled, center-cut SMB cascade (Figure 3), center-cut two zone-SMB/chromatography (Figure 4), and recycled, center-cut chromatography (Fig. 6). The SMB systems have one column per zone. Particle size is $d_p = 10\ \mu m$, and flow rates are optimized for each D_{total}/F value (Table 2).

without recycle at their $(D_{total}/F)_{min}$ values, although at the same D/F value, the recycle system has a higher PRI. Thus, only the recycle system will be compared to the other systems.

A comparison of the center-cut two zone-SMB/chromatography (Fig. 4), the recycled, center-cut, two four-zone SMBs (Fig. 3), and the recycled, center-cut chromatography (Fig. 6) systems is shown in Fig. 10 for separation of the phenolic mixture. The PRI for component B for the recycle center-cut chromatography was almost constant for $D_{total}/F \geq 2.73$, while the PRI values of the recycled center-cut SMB cascade and the center-cut two-zone SMB/chromatography increased until $D_{total}/F = 4.0$ and 5.0, respectively. The three systems had the similar purity-recovery index for $D_{total}/F \geq 5.0$. For this phenolic system with very small particles and very high plate numbers, center-cut chromatography has better separation than the SMB systems with one column per zone except at $D_{total}/F = 1.0$.

Table 4 compares the values of $(D_{total}/F)_{min}$, the required D_{total}/F to obtain a PRI of 99%, and the pressure drop with a PRI of 99% for the six systems. For the phenolic separation with 10 μm particles, the recycle, center-cut chromatography shows high performance in all aspects. It uses less desorbent than the other systems, it uses fewer columns, and its pressure drop at PRI = 99.0% is significantly smaller than the SMB systems with one column per zone.

Table 4. Comparison of systems for separation of phenols at productivity $= 3.01 \times 10^{-2}$ cm^3/cm^{3}min and $d_p = 10$ μm

	Complete ternary separation, two 4 -zone SMBs	Center-cut SMB cascade with 1 column/zone	Recycled, center-cut SMB with 1 column/zone	Center-cut, 2-zone SMB/chromatography	Center-cut chromatography without desorbent recycle	Center-cut chromatography with desorbent recycle
$(D_{total}/F)_{min}$	2.90	2.00	1.00	3.28	2.22	1.00
D_{total}/F for 99.0% PRI	4.56	4.00	2.47	4.00	3.33	1.72
ΔP_{max} (bar) for 99.0% PRI	67	60	66	11	5	5
(number of column)$_{min}$	8	8	8	2	1	1

For binary four-zone SMBs, it is well known that purity can be improved by using multiple columns per zone. Different column configurations were tested for the center-cut SMB systems (Table 5). The total column length was fixed so that the productivity was constant. Although adding more columns did not improve the PRI of the center-cut two-zone SMB/chromatography system, both purity and recovery increased for the recycled, center-cut SMB cascade when two columns per zone were used. Comparing Tables 5 and 2f shows that the recycled center-cut SMB with two columns per zone has a better separation than the recycled center-cut chromatography at low D/F and almost the same separation at high D/F.

The results of these simulations for the phenolic system with 10 μm particles show that the recycled, center-cut chromatography had the best separation when compared to the SMB systems with one column per zone except at very low D/F. This is the simplest system, and it uses less desorbent than the other systems at the same productivity. Moreover, it operates with approximately 90% lower pressure drop compared to the systems with two SMBs for 99.0% PRI. However, with larger particles the effects of dispersion and mass transfer resistance are expected to become important, and desorbent consumption is expected to rapidly increase because the A-B and B-C mass transfer zones exit the column.

Amino Acid Mixture

Particle diameter affects mass transfer rates and pressure drops. The ternary mixture of amino acids, glycine (A), L-phenylalanine (B), and L-tryptophan (C), was chosen as a model system because equilibrium and mass transfer data is available for a PVP resin with a particle size of $d_p = 422.5$ μm (12).

Table 5. Purity and recovery of B for phenolic system with multiple columns per zone for the center-cut 2-zone SMB/chromatography and recycled, center-cut SMB cascade at their minimum D_{total}/F values. Productivity = 3.01×10^{-2} cm^3/cm^{3}min

	Center-cut two-zone SMB/ chromatography $(D_{total}/F)_{min} = 3.28$				Recycled center-cut SMB cascade $(D_{total}/F)_{min} = 1.0$	
Column configurations	1-1	2-1	1-2	2-2	1-1-1-1	2-2-2-2
Purity of B in B product (%)	98.2	97.5	97.2	93.4	93.1	95.0
Recovery of B in B product (%)	93.4	94.1	92.1	93.0	93.1	94.7
PRI of B (%)	95.8	95.8	94.6	93.2	93.1	94.9
PRI of B (%) @ $(D_{total}/F) = 3.28$	—	—	—	—	99.7	99.9

The effect of particle size on mass transfer is usually determined from an equation similar to the following (15),

$$\frac{1}{k_{eff,i}} = \frac{R^2}{15\varepsilon_b D_{p,i}} + \frac{R}{3\,k_{f,i}} \tag{3}$$

The effective intra-particle diffusivity D_p will be constant if the internal structure of the adsorbent such as porosity and tortuosity do not change with particle size (16), and can be determined from frontal tests. The film mass-transfer coefficient k_f can be estimated from correlations such as the Wilson and Geankopolis (17) equation,

$$\frac{k_f}{v}\left(\frac{\mu}{\rho D_{AB}}\right)^{2/3} = 1.09\left(\frac{\varepsilon\rho\, vd_p}{\mu}\right)^{-2/3} (0.0016 < Re < 55) \tag{4}$$

To estimate the diffusivity of L-phenylalanine and L-tryptophan in water the Wilke and Chang (18) equation was used. The axial dispersion coefficients D_{ax} are calculated with the Chung and Wen correlation (19),

$$\left(\frac{d_p v}{D_{ax}}\right) = \frac{0.2}{\varepsilon} + \frac{0.011}{\varepsilon}\left(\frac{\varepsilon\rho\, vd_p}{\mu}\right)^{0.48} (10^{-3} < Re < 10^3) \tag{5}$$

The linear isotherm constants were measured as $K_A = 0.116$, $K_B = 1.134$, $K_C = 5.964$ and the total porosity was 0.70 (12). Table 6 shows the calculated values for $D_{\text{Phe-H2O}}$ and $D_{\text{Trp-H2O}}$ at the operating temperature of 50°C, diffusivity coefficients D_p and film mass transfer coefficients k_f, and the effective mass transfer rates ($a_p k_{eff}$) with various particle sizes. Since the mass transfer resistance of glycine was very small for $d_p = 422.5$ μm, it was assumed to be negligible for $d_p < 422.5$ μm and $(a_p k_{eff})_{gly} = 10^4$ cm^2/min, which is the default value for very fast mass transfer in Aspen Chromatography 2004, was used. This value is high enough that increases do not change the simulation results. For Aspen Chromatography simulations, the feed concentration was 1.0 g/l for each of the three amino acids and productivity was 4.07×10^{-3} cm^3/cm^{3}min for all systems.

Figure 11 shows the effects of particle size on separation performance for amino acid separations with recycled center-cut chromatography, center-cut two-zone SMB/chromatography, center-cut SMB cascade, and recycled center-cut SMB cascade. The operating conditions shown in Table 7 are optimized at $D_{total}/F = 2.0$ in the same manner used for the phenolic separations. Recycled center-cut chromatography has higher PRI values for $d_p < 50$ μm than the center-cut SMB cascade with one column per zone while the recycled center-cut SMB cascade with one column per zone shows better separation for the entire range of d_p. The center-cut two-zone SMB/chromatography system has low PRI values because the system is simulated at $D_{total}/F < (D_{total}/F)_{min} = 3.41$.

Table 6. Diffusivities and mass transfer coefficients for the effective mass transfer coefficients for amino acid separations

Particle size (μm)	422.5	211.3	105.6	42.3	21.1	10.6
D_p (cm^2/min)						
Phe	0.000163					
Trp	0.000266					
$D_{i\text{-}H2O}$ (cm^2/min)						
Phe	0.000665					
Trp	0.000749					
k_f (cm/min)						
Phe	0.228	0.362	0.575	1.060	1.682	2.671
Trp	0.211	0.335	0.532	0.980	1.555	2.465
$a_p\ k_{eff}$ (cm^2/min)						
Phe	2.76 ± 0.01	10.8 ± 0.4	42.0 ± 1.4	251 ± 8	963 ± 31	3660 ± 120
Trp	4.20 ± 0.43	16.3 ± 1.7	62.5 ± 6.4	364 ± 37	1360 ± 140	5040 ± 520

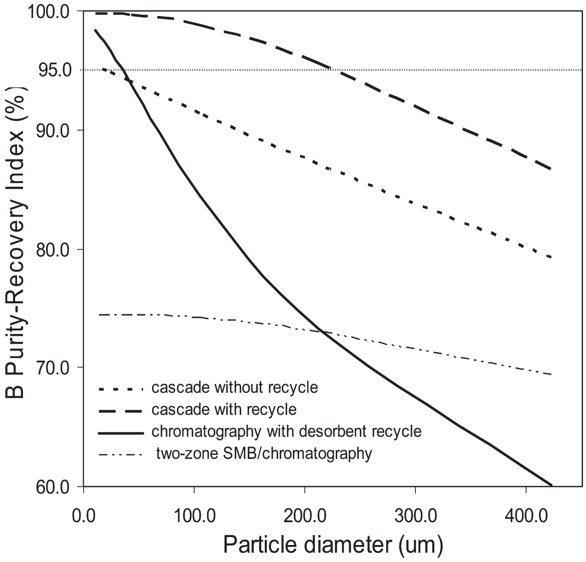


Figure 11. Effect of particle size for amino acid separation for the cascade with two four-zone SMBs (Fig. 2), recycled cascade with two four-zone SMBs (Fig. 3), center-cut two-zone SMB/chromatography (Fig. 4), and center-cut chromatography with desorbent recycle (Fig. 6). The SMB systems have one column per zone. Operating conditions are in Table 7.

The recycled center-cut chromatography system has the advantage of low pressure drop. To compare systems at the same pressure drop, we assumed that the maximum pressure limit is 1.0 bar for the adsorbent PVP and that pore diffusion controls. Then SMB scaling rules (13, 20) were used to utilize this maximum pressure drop. For $\mathrm{PRI} = 95.0\%$ and $\Delta P_{\max} = 1.0$ bar, the scaling factors were varied with fixed column length and diameter. The results are presented in Table 8. The recycled center-cut chromatography system shows almost 7 times higher productivity for approximately the same PRI and the same pressure drop compared to the center-cut SMB cascade with one column per zone, but productivity is approximately 25% lower than that of the recycled center-cut SMB cascade with one column per zone.

DISCUSSION

Figure 11 for center-cut amino acid separation shows that the increase in the purity-recovery index is much steeper as particle diameter is decreased for recycled center-cut chromatography than for the two center-cut SMB systems. Since in chromatography processes the mass transfer zones exit

Table 7. Optimized switching times and flow rates (cm^3/min) for amino acid separations for $D_{total}/F = 2.0$ and productivity $= 4.07 \times 10^{-3}\ cm^3/cm^3 min$ ($C_A = C_B = C_C = 1.0$ g/l). SMB systems have one column per zone

	1st train					2nd train			
t_{sw} (min)	Q_{R1}	Q_{D1}	Q_{AB}	Q_{AC}	$t_{sw'}$ (min)	Q_{R2}	Q_{D2}	Q_A	Q_B
(a) Cascade with two four-zone SMBs for B purification (Fig. 2) ($Q_{feed} = 0.928\ cm^3/min$)									
44.50	0.666	0.928	0.928	0.928	9.38	2.234	0.928	0.928	0.928

	1st train					2nd train				
t_{sw} (min)	Q_{R1}	Q_{D1}	Q_{AB}	Q_{AC}	$t_{sw'}$ (min)	Q_{R2}	Q_{D2}	Q_A	$Q_{A\ recycle}$	Q_B
(b) Recycled cascade with two four-zone SMBs for B purification (Figure 3a) ($Q_{feed} = 0.928\ cm^3/min$)										
35.84	0.759	0.000	1.064	1.256	6.00	3.319	1.856	0.000	1.392	1.528

t_{sw} (min)	Q_{AC2}	Q_{D1}	Q_{AC1} (= Q_{D2})	Q_B (= Q_{D3})
(c) Center-cut two-zone SMB/chromatography system (Figure 4) ($Q_{feed} = 0.464\ cm^3/min$, $t_a = t_b = t_{sw}/2$)				
57.90	0.637	0.173	0.483	0.273

Q (cm^3/min)	t_{feed} (min)	t_1 (min)	t_2 (min)	t_3 (min)	$t_{recycle}$ (min)	t_{cycle} (min)
(d) Center-cut chromatography system with desorbent recycle (Figure 6)						
1.00	5.80	19.50	29.11	36.00	17.40	50.02

Table 8. Scaling amino acid separation systems for the same pressure drop of 1.0 bar and $D_{total}/F = 2.0$. SMB systems have one column per zone

	Center-cut SMB cascade (Fig. 2)	Recycled center-cut SMB cascade (Fig. 3)	Recycled center-cut chromatography (Fig. 6)
$d_{p,old}$ (μm)[a]	21.1	211.3	42.3
$\Delta P_{\max}$ (bar)[b] for $d_{p,old}$	13.0	0.20	0.30
$d_{p,new}/d_{p,old}$	1.900	0.701	0.741
Q_{new}/Q_{old}[c]	0.277	2.413	1.819
Purity_B (%) for $\Delta P^b_{\max} = 1.0$ bar	95.7	96.0	96.0
Recovery_B (%) for $\Delta P^b_{\max} = 1.0$ bar	94.5	94.6	94.1
PRI (%) for $\Delta P^b_{\max} = 1.0$ bar	95.1	95.3	95.1
Productivity ($\text{cm}^3/\text{cm}^3\text{min}$) for $\Delta P^b_{\max} = 1.0$ bar	1.13×10^{-3}	9.82×10^{-3}	7.41×10^{-3}

[a] Particle diameter for PRI ~ 95.0% in Fig. 11.

[b] Total pressure drop of train 2 for cascades with two four-zone SMBs.

[c] Operating conditions in Table 7.

the column while in SMB processes they are retained, we would expect the increase in mass transfer rates as particle diameter is decreased to have a larger effect on the purity of the chromatographic process. Below a particle diameter of approximately 50 μm the recycled center-cut chromatography shows better separation than the center-cut SMB cascade with one column per zone. Since large-scale HPLC columns packed with particles in the 20 μm range are readily available commercially, this range of particle sizes is quite reasonable for large-scale applications.

If we had continued the simulations below a particle diameter of 10 μm, which is not currently practical on a large-scale, the curves for recycled center-cut chromatography and recycled center-cut SMB cascade with one column per zone in Fig. 11 would probably cross. Then the order of preference of the processes would be the same as in the phenolic system. Since the phenolic system PRI values for the SMBs increased when there were 2 columns per zone, the amino acid separations are also expected to improve with multiple columns per zone. However, this makes the SMB systems more complex.

The sensitivity of $a_p k_{\text{eff}}$ on PRI was studied. For $d_p < 105.6$ μm, when $a_p k_{\text{eff}}$ values are varied within their accuracy in Table 6, PRI values do not change because the mass transfer rates for the particle sizes are fast enough.

The analysis in this paper was restricted to dilute systems with linear isotherms. Additional research is needed to study more concentrated systems with nonlinear isotherms.

The recycled center-cut chromatography system is considerably simpler and hence probably less expensive than the SMB systems. In addition, if the plant runs campaigns repacking one column is much easier than repacking eight or more columns.

NOTATION

D_{AB}	molecular diffusivity, cm^2/sec
D_{ax}	axial dispersion coefficient, cm^2/sec
D_p	intraparticle diffusion coefficient, cm^2/sec
D_{total}/F	ratio of total flow rate of desorbent to feed flow rate
d_p	particle diameter, cm
G_i	constant for determining the velocity of solute = $[1 + (1 - \varepsilon) \cdot K_i/\varepsilon]^{-1}$
K_i	linear equilibrium parameter = q_i/C_i
k_{eff}	lumped mass transfer coefficient, cm/sec
k_f	film mass transfer coefficient, cm/sec
Pe_{dp}	Peclet number based on particle diameter = $d_p\ v/D_{ax}$
PRI	purity-recovery index, eq (2)
Q	volumetric flow rate, cm^3/min
R	particle radius, cm
Re	Reynolds number = $\varepsilon d_p v \rho/\mu$
t_{sw}	switching time, sec
u	solute velocity, cm/sec
v	interstitial velocity, cm/sec

Greek Symbols

α	selectivity based on isotherms
α'	selectivity based on solute velocities
ΔP	pressure drop, bar
ε	total bed void fraction
ρ	fluid density, g/cm^3
μ	fluid viscosity, g/(cm sec)

Subscripts

i (A, B, C)	solute

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