



# Partial port-closing strategy for obtaining high throughput or high purities in a four-zone simulated moving bed chromatography for binary separation

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## ABSTRACT

The “partial port-closing” operation strategy for a four-zone simulated moving bed (SMB) chromatographic process for binary separation was developed to improve the SMB performance. This strategy included the partial extract-closing (PEC) and the partial raffinate-closing (PRC) operations. In case of the PEC operation, the extract port is made to be closed during the first-half stage of a switching period. During the latter-half stage, the extract port is made to be open. In case of the PRC operation, the raffinate port is made to be open during the first-half stage of a switching period. During the latter-half stage, the raffinate port is made to be closed. If the operating conditions are chosen properly in each operation using a highly efficient optimization tool, the product stream can be collected during only the period that the product is almost separated from impurity. During the other period that the product is contaminated with impurity, the collection of the product stream can be stopped by closing the product port. The uncollected product stream is then allowed to keep migrating through the adjacent zone within the SMB process. Such a partial port-closing operation including PEC and PRC was found to surpass a conventional SMB operation remarkably in throughput and product purity.

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## 1. Introduction

Simulated moving bed (SMB) has been recognized as a highly efficient chromatographic process that was capable of continuous separation on a preparative or an industrial scale [1–4]. It has thus been of noteworthy applications in petrochemical, biochemical, and pharmaceutical industries [2,5–7]. Fig. 1 shows a schematic diagram of SMB chromatographic process for binary separation. It consists of multiple chromatographic columns that are packed with the same adsorbent particles. The packed columns are connected in series, creating a circular flow path as shown in Fig. 1. The circle is divided into four zones by two inlet ports (feed and desorbent) and two outlet ports (extract and raffinate). These four ports are moved periodically in the direction of the liquid-phase flow, which produces the effect of “simulated” counter-current movement of the adsorbent (solid phase) relative to the liquid phase. Such operation allows efficient use of the adsorbent and continuous processing of a feed mixture, leading to better performance than batch chromatographic processes [1–4].

In general, the performance of SMB process is evaluated by throughput or product purity. Since these two performance criteria are of conflicting nature, the evaluation of throughput is usually carried out under a given purity requirement and the evaluation of

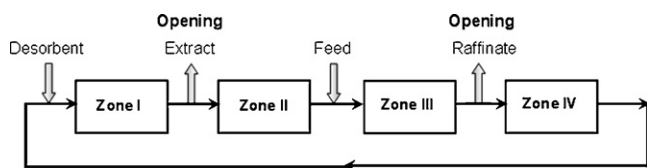
product purity is carried out under a fixed throughput. To ensure high economical efficiency and meet the increasingly strengthened needs of product quality, it is important to operate the SMB process in such a way that higher throughput and higher purity can be achieved [4].

Until now, several strategies for enhancing the SMB performance have been reported in the literature [8–17]. Among them, the partial-discard strategy [15] was known to be highly effective in improving product purity in a four-zone SMB for binary separation. The major concept of this strategy was to discard the stream exiting through extract or raffinate port during the period that each product stream was highly susceptible to contamination. Such a discarding approach led to much higher purity than a conventional SMB operation. But the purity improvement was always accompanied by a significant reduction of yield (or recovery) because some portion of product stream was to be discarded in every switching period [15]. If highly valuable feed materials are to be loaded or highly valuable product is to be obtained, such a significant loss of yield will be an obstacle to application of the partial-discard strategy.

As a potential alternative to addressing the aforementioned issue, this study proposed another concept, the “partial port-closing” strategy for a four-zone SMB for binary separation. In this strategy, the way of closing extract or raffinate port during the first-half or the latter-half stage of a switching period was employed as a major means to prevent both a possible contamination of product stream and a significant loss of yield. To maximize the effect of

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**Fig. 1.** Schematic diagram of the four-zone SMB process based on a conventional operation.

such measures on process performances, all the relevant operating parameters and the port-closing period were optimized simultaneously using a highly robust optimization tool.

Similar strategies were reported in the literature. One of them is the outlet streams swing (OSS) strategy [18], which is based on the idea of introducing dynamic collection fronts into a true moving bed model and reflecting the derived results into design of the equivalent SMB system. In the SMB designed according to the OSS strategy, the collection fronts in zones I and IV are controlled to be expanded or contracted by altering the flow rates in zones I and IV within a switching period [18], which in turn causes the extract and raffinate ports to be closed alternately.

The proposed “partial port-closing” strategy is similar to the aforementioned OSS strategy in that the product port is allowed to alternate its opening and closing during each switching period. On the other hand, the former differs from the latter in that the operating conditions of the proposed strategy are determined without regard to expansion and contraction of the collection fronts in zones I and IV. Instead, the proposed strategy optimizes all the relevant operating parameters including the port-closing period in such a way that the utilization of adsorbent bed can be maximized, thus leading to high throughput or high product purities. In addition, two different types of operations (partial extract-closing and partial raffinate-closing operations) are practicable individually in the scope of the proposed strategy depending on which product port is chosen to undergo a partial closing.

The proposed strategy is also similar to the Varicol process [8] in that the port has a non-uniform behavior during each switching period. However, the former is quite different from the latter due to the following reason. In the Varicol process, the location of the port undergoes a change within a switching period while the port is always kept open. By contrast, in the proposed strategy, the port is partially closed while its location remains unchanged during each switching period.

To verify the effectiveness of the partial port-closing strategy proposed, the SMB processes based on the partial port-closing operation and a conventional operation will be optimized each under equal conditions and then the two operations will be compared in terms of throughput under a given purity requirement or in terms of purity under a fixed throughput. The physical basis for the improvement of SMB performance, which will result from the application of the partial port-closing operation, will also be explained in detail. Furthermore, it will be investigated how the SMB performance is affected by the length of the port-closing period. Overall, this paper will report how much the partial port-closing operation will outperform a conventional SMB operation from various angles.

## 2. The partial port-closing strategy

In this study, a partial port-closing strategy was proposed to make a substantial improvement in the performances (throughput and product purities) of a four-zone SMB chromatographic process for binary separation. The proposed strategy was applied to the four-zone SMB process with one column per zone.

In a conventional SMB operation, two product ports such as extract and raffinate ports are kept open all the time throughout

the SMB operation (Fig. 1). Thus, both extract and raffinate products are collected during an entire switching period, which is the time interval between consecutive port switches ( $t_{sw}$ ). Such a conventional operation, however, was reported to be ineffective in addressing the following two issues [15]: (1) a possible contamination of extract product that can usually occur at the initial stage of a switching period and (2) a possible contamination of raffinate product that can usually occur at the last stage of a switching period.

In the partial port-closing strategy proposed, the product port is made to be open during only a part of the switching time. During the rest of the switching time, the product port is made to be closed. Accordingly, the product is partially collected during only the period that the product port is open. During the other period of closing the port, the product stream is not allowed to leave the SMB process via the product port but it is made to keep migrating through the adjacent zone within the SMB process.

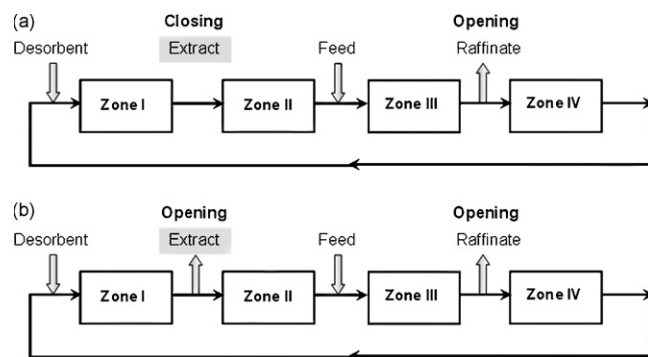
Compared to a conventional SMB operation, the partial port-closing operation is expected to give higher purities because the product port can be closed during the occurrence of product contamination. If such a process merit is actually realized, the partial port-closing operation will also be able to give higher throughput for a given purity requirement. In the course of obtaining these advantages, the partial port-closing operation will cause no problem of losing the feed materials through the product ports because the prevention of a possible product contamination can be fulfilled by closing the product port instead of discarding the contaminated product stream.

For a thorough comparison, the SMB processes based on the partial port-closing operation and a conventional operation will be comprehensively optimized each for the highest throughput under a given purity requirement or for the highest purities under a fixed throughput.

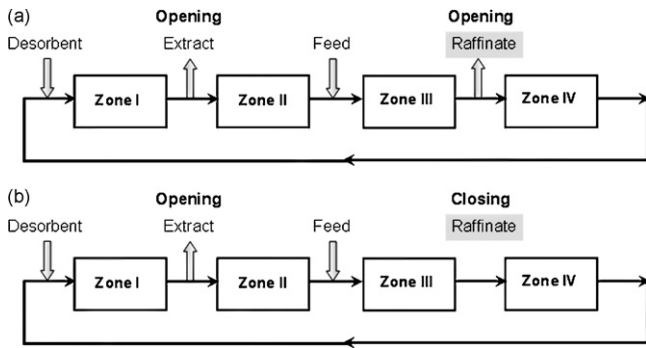
One additional variable is introduced into the SMB procedure via the partial port-closing operation. It is the port-closing length ( $\theta$ ), which is defined as a fraction of the port-closing period relative to an entire switching period. It is related to the duration of the partial port-closing approach performed within a switching period. Therefore, the value of  $\theta$  is zero in the case of a conventional operation.

The partial port-closing strategy can be applied to either the extract port at the initial stage of a switching period or the raffinate port at the last stage of a switching period as shown in Figs. 2 and 3. These two approaches will be called hereafter “partial extract-closing (PEC) strategy” and “partial raffinate-closing (PRC) strategy”, respectively.

The outline of the PEC strategy is demonstrated in Fig. 2. We see that the extract port is closed as soon as a new switching period begins. Such a port-closing state is maintained until the time of  $\theta t_{sw}$  elapses. During the span of time ( $\theta t_{sw}$ ), the zone I flow rate is



**Fig. 2.** Schematic diagram of the four-zone SMB process based on the partial extract-closing (PEC) operation: (a) step a (the first-half stage of a switching period) and (b) step b (the latter-half stage of a switching period).



**Fig. 3.** Schematic diagram of the four-zone SMB process based on the partial raffinate-closing (PRC) operation: (a) step a (the first-half stage of a switching period) and (b) step b (the latter-half stage of a switching period).

kept the same as the zone II flow rate, which is done by increasing the raffinate flow rate while keeping the desorbent flow rate unchanged. After then, the extract port is opened and the collection of the extract stream is started. Simultaneously, the zone I flow rate is increased by decreasing the raffinate flow rate while keeping the desorbent flow rate unchanged. This state lasts until the end of a switching period. All of these procedures are repeated again immediately when a subsequent port switching occurs.

In case of the PRC strategy (Fig. 3), the raffinate port is opened and the collection of the raffinate stream is started as soon as a new switching period begins. Such a port-opening state and the raffinate collection are continued until the time of  $(1 - \theta)t_{sw}$  elapses. During this period, the zone IV flow rate is maintained lower than in the previous step, which is fulfilled by adopting a lower extract flow rate while keeping the desorbent flow rate unchanged. After then, the raffinate port is closed and the zone IV flow rate is kept the same as the zone III flow rate, which is done by increasing the extract flow rate while keeping the desorbent flow rate unchanged. This state lasts until the end of a switching period. All of these procedures are repeated again immediately when a subsequent port switching occurs.

### 3. Simulation model

The simulation model consists of the mass-balance equation for liquid phase and the mass-transfer equation between liquid phase and solid surface. For the liquid phase within each zone, the single porosity model [13] was used for the mass balance of component  $i$  as follows:

$$\frac{\partial C_i}{\partial t} + \frac{(1 - \varepsilon)}{\varepsilon} \frac{\partial q_i}{\partial t} + u_0 \frac{\partial C_i}{\partial z} - E_{b,i} \frac{\partial^2 C_i}{\partial z^2} = 0 \quad (1)$$

where the subscript  $i$  stands for different solutes;  $C$  and  $q$  are the solute concentrations in liquid phase and solid phase, respectively;  $E_b$  is the axial dispersion coefficient;  $\varepsilon$  is the total porosity; and  $u_0$  is the liquid interstitial velocity. For the mass-transfer equation, a linear lumped resistance model [13] was used as follows:

$$\frac{\partial q_i}{\partial t} = k_m a_p (C_i - C_i^*) \quad (2)$$

where  $k_m$  is the mass-transfer coefficient;  $C_i^*$  is the equilibrium liquid-phase concentration corresponding to the solid-phase concentration; and  $a_p = 3/R_p$  for spherical particles; and  $R_p$  is the radius of solid particle.

The equilibrium relationship between  $q_i$  and  $C_i^*$  is limited to the region of a linear adsorption isotherm in this study. The relevant linear isotherm equation is as follows:

$$q_i = K_i C_i^* \quad (3)$$

where  $K_i$  is the linear isotherm parameter of component  $i$ .

To solve the aforementioned model equations, a biased upwind differencing scheme (BUDS) was employed in conjunction with Gear integration having a step size of 0.1. The number of nodes in each column was set at 60. All of these numerical computations were carried out in Aspen Chromatography simulator.

## 4. Formulation of the optimization problem

### 4.1. Operating parameters of the SMB processes based on the conventional operation and the partial port-closing operation

Prior to the formulation of the relevant optimization frame, it is necessary to figure out what kinds of operating parameters are involved in each operation. First, the conventional SMB operation (Fig. 1) involves the following nine operating parameters: four zone flow rates ( $Q_1, Q_2, Q_3, Q_4$ ), two inlet flow rates ( $Q_{feed}, Q_{des}$ ), two outlet flow rates ( $Q_{ext}, Q_{raf}$ ), and switching time ( $t_{sw}$ ). Among these operating parameters, each of the inlet and outlet flow rates comes from the difference between the flow rates in two neighboring zones, which can be understood from Fig. 1.

On the other hand, the partial port-closing operation (Figs. 2 and 3) involves a total of 12 operating parameters, which can be classified into the following two categories. The first category of operating parameters, which are configured to remain unchanged during an entire switching period, include  $Q_2, Q_3, Q_{feed}, Q_{des}, t_{sw}$ , and  $\theta$ . The second category of operating parameters, which are configured to undergo an immediate change every at the moment of port-closing or port-opening, include  $Q_1, Q_4, Q_{ext}$ , and  $Q_{raf}$ . These flow rates, if applied during the initial stage (from the beginning of a switching period to the moment of port-closing or port-opening), will be denoted as  $Q_{1a}, Q_{4a}, Q_{ext-a}$ , and  $Q_{raf-a}$ . By contrast, they will be denoted as  $Q_{1b}, Q_{4b}, Q_{ext-b}$ , and  $Q_{raf-b}$  if applied during the last stage (from the moment of port-closing or port-opening to the end of a switching period).

In case of the PEC operation, the aforementioned parameters are related to each other in the following manner

$$Q_{1a} = Q_2, \quad Q_{4a} = Q_{1a} - Q_{des}, \quad Q_{4b} = Q_{1b} - Q_{des} \quad (4a)$$

$$Q_{ext-a} = 0, \quad Q_{ext-b} = Q_{1b} - Q_2 \quad (4b)$$

$$Q_{raf-a} = Q_3 - Q_{4a}, \quad Q_{raf-b} = Q_3 - Q_{4b} \quad (4c)$$

where the subscripts "a" and "b" indicate the initial (or the first-half) and the last (or the latter-half) stages, respectively, and  $Q_{ext-a} = 0$  implies the state of closing the extract port. Similarly, the operating parameters involved in the PRC operation are related to each other as follows

$$Q_{4b} = Q_3, \quad Q_{1a} = Q_{4a} + Q_{des}, \quad Q_{1b} = Q_{4b} + Q_{des} \quad (5a)$$

$$Q_{ext-a} = Q_{1a} - Q_2, \quad Q_{ext-b} = Q_{1b} - Q_2 \quad (5b)$$

$$Q_{raf-a} = Q_3 - Q_{4a}, \quad Q_{raf-b} = 0 \quad (5c)$$

where  $Q_{raf-b} = 0$  implies the state of closing the raffinate port.

In both the PEC and PRC operations, the flow rates of feed and desorbent ( $Q_{feed}$  and  $Q_{des}$ ), which are directly associated with economical performances such as throughput and desorbent consumption, are related to the flow rates in the adjacent zones as follows.

$$Q_{feed} = Q_2 - Q_3 \quad (6a)$$

$$Q_{des} = Q_{1a} - Q_{4a} = Q_{1b} - Q_{4b} \quad (6b)$$

As shown in the above relationships, some of the operating parameters are dependent on others on the basis of simple material balances. Therefore, the number of operating parameters to be optimized in each operation will be less than that mentioned above.

## 4.2. Optimization problems under consideration

### 4.2.1. Case I: maximization of throughput under the constraints on product purities

Two different types of optimization problems were considered. In the first type of optimization problem (Case I), the SMB processes based on the conventional operation and the partial port-closing operation were optimized each for maximizing the throughput while the constraints on product purities were kept the same between the two operations. Thus, the objective function employed in the Case I optimization is the throughput, which is defined as follows:

$$\text{Throughput} = \frac{Q_{\text{feed}}}{BV} \quad (7)$$

where  $Q_{\text{feed}}$  and  $BV$  are the feed flow rate and the total bed volume, respectively. Since the total bed volume remained constant in this study, throughput and feed flow rate can be used interchangeably in the stage of evaluating the process performance.

During the Case I optimization, the purities of both extract and raffinate products were constrained to be higher than 98%. The other details in such an optimization task are presented in the following optimization frame. First, those for the conventional SMB operation are as follows

$$\text{Max } J = \text{Throughput} [Q_1, Q_2, Q_{\text{feed}}, t_s] \quad (8a)$$

$$\text{Subject to } \text{PurR} \geq 98\%, \text{ PurE} \geq 98\% \quad (8b)$$

$$\text{Fixed variable } Q_{\text{des}} = Q_{\text{des}}^* \quad (8c)$$

$$\text{Dependent variables } Q_3, Q_4, Q_{\text{ext}}, Q_{\text{raf}} \quad (8d)$$

where  $\text{PurR}$  and  $\text{PurE}$  are the purity of A in the raffinate stream and the purity of B in the extract stream, respectively. The letters A and B stand for a low-affinity component (i.e., raffinate product) and a high-affinity component (i.e., extract product), respectively.

Secondly, the optimization frame relevant to the PEC operation is given by

$$\text{Max } J = \text{Throughput} [Q_{1b}, Q_2, Q_{\text{feed}}, t_{\text{sw}}, \theta] \quad (9a)$$

$$\text{Subject to } \text{PurR} \geq 98\%, \text{ PurE} \geq 98\% \quad (9b)$$

$$\text{Fixed variables } Q_{\text{des}} = Q_{\text{des}}^*, Q_{\text{ext-a}} = 0 \quad (9c)$$

$$\text{Dependent variables } Q_{1a}, Q_3, Q_{4a}, Q_{4b}, Q_{\text{ext-b}}, Q_{\text{raf-a}}, Q_{\text{raf-b}} \quad (9d)$$

Similarly, the optimization frame corresponding to the PRC operation is expressed as follows

$$\text{Max } J = \text{Throughput} [Q_{4a}, Q_2, Q_{\text{feed}}, t_{\text{sw}}, \theta] \quad (10a)$$

$$\text{Subject to } \text{PurR} \geq 98\%, \text{ PurE} \geq 98\% \quad (10b)$$

$$\text{Fixed variables } Q_{\text{des}} = Q_{\text{des}}^*, Q_{\text{raf-b}} = 0 \quad (10c)$$

$$\text{Dependent variables } Q_{1a}, Q_{1b}, Q_3, Q_{4b}, Q_{\text{ext-a}}, Q_{\text{ext-b}}, Q_{\text{raf-a}} \quad (10d)$$

where the relationships between the dependent variables and the other variables that were introduced in this section have already been clarified in the previous section.

Since the desorbent flow rate has a direct effect on one of the economic performances (i.e., desorbent usage) while affecting the maximum feed flow rate attainable, the desorbent flow rate was kept the same in all the three optimization frames presented above (Eqs. (8)–(10)). This was to make a fair comparison of throughput among the conventional operation, the PEC operation, and the PRC operation.

### 4.2.2. Case II: maximization of purities for the extract and raffinate streams under a fixed throughput

In the second type of optimization (Case II), the purities of both extract and raffinate products were maximized under a fixed throughput (i.e., under a fixed feed flow rate). Since there are two objectives to be maximized in this case, the Case II optimization virtually belongs to the category of multi-objective optimization. The mathematical frame of such a multi-objective optimization problem for the conventional SMB operation is given by

$$\text{Max } J_1 = \text{PurR} [Q_1, Q_2, t_{\text{sw}}] \quad (11a)$$

$$\text{Max } J_2 = \text{PurE} [Q_1, Q_2, t_{\text{sw}}] \quad (11b)$$

$$\text{Subject to } \text{PurR} \geq 90\%, \text{ PurE} \geq 90\% \quad (11c)$$

$$\text{Fixed variables } Q_{\text{des}} = Q_{\text{des}}^*, Q_{\text{feed}} = Q_{\text{feed}}^* \quad (11d)$$

$$\text{Dependent variables } Q_3, Q_4, Q_{\text{ext}}, Q_{\text{raf}} \quad (11e)$$

On the other hand, the multi-objective optimization for the PEC operation is performed on the basis of the following mathematical frame

$$\text{Max } J_1 = \text{PurR} [Q_{1b}, Q_2, t_{\text{sw}}, \theta] \quad (12a)$$

$$\text{Max } J_2 = \text{PurE} [Q_{1b}, Q_2, t_{\text{sw}}, \theta] \quad (12b)$$

$$\text{Subject to } \text{PurR} \geq 90\%, \text{ PurE} \geq 90\% \quad (12c)$$

$$\text{Fixed variables } Q_{\text{des}} = Q_{\text{des}}^*, Q_{\text{feed}} = Q_{\text{feed}}^*, Q_{\text{ext-a}} = 0 \quad (12d)$$

$$\text{Dependent variables } Q_{1a}, Q_3, Q_{4a}, Q_{4b}, Q_{\text{ext-b}}, Q_{\text{raf-a}}, Q_{\text{raf-b}} \quad (12e)$$

Likewise, the mathematical frame of the multi-objective optimization for the PRC operation is expressed as follows

$$\text{Max } J_1 = \text{PurR} [Q_{4a}, Q_2, t_{\text{sw}}, \theta] \quad (13a)$$

$$\text{Max } J_2 = \text{PurE} [Q_{4a}, Q_2, t_{\text{sw}}, \theta] \quad (13b)$$

$$\text{Subject to } \text{PurR} \geq 90\%, \text{ PurE} \geq 90\% \quad (13c)$$

$$\text{Fixed variables } Q_{\text{des}} = Q_{\text{des}}^*, Q_{\text{feed}} = Q_{\text{feed}}^*, Q_{\text{raf-b}} = 0 \quad (13d)$$

$$\text{Dependent variables } Q_{1a}, Q_{1b}, Q_3, Q_{4b}, Q_{\text{ext-a}}, Q_{\text{ext-b}}, Q_{\text{raf-a}} \quad (13e)$$

### 4.2.3. Optimization tool

All the aforementioned optimization problems were handled using a highly efficient adaptation of genetic algorithm, NSGA-II-JG (elitist nondominated sorting genetic algorithm with jumping genes) [4,19]. The relevant computer-program codes for implementation of the NSGA-II-JG were prepared using Visual Basic Application (VBA) in Excel software. Since the NSGA-II-JG optimization requires a huge number of detailed rate-model simulations, the VBA codes were prepared to include the function of calling Aspen Chromatography simulator as well as the function of implementing the NSGA algorithm.

## 5. Results and discussion

For the purpose of investigating the effects of the partial port-closing strategy, the mixture of dextran T6 and fructose [13] was chosen as a model separation system. The relevant system parameters are listed in Table 1, which shows that dextran T6 has the low adsorption-affinity while fructose has the high adsorption-affinity. Therefore, in SMB process, dextran T6 and fructose will become a raffinate product (A) and an extract product (B), respectively.

In the following optimizations, the column configuration of the SMB process was fixed at 1–1–1–1 and the adsorption pattern of each component in the binary mixture was assumed to follow a linear isotherm relation in the concentration range examined.

**Table 1**  
System parameters of the model separation system.\*

	Dextran T6 (A)	Fructose (B)
Linear isotherm parameter, $K$ (L/L S.V.)	0.23	0.69
Mass-transfer coefficient, $k_m$ (cm/min)	$1.041 \times 10^{-3}$	$2.024 \times 10^{-3}$
Axial dispersion coefficient, $E_b$ (cm <sup>2</sup> /min)	Chung and Wen correlation [20]	
Column diameter, $d_c$ (cm)	2.0	
Single column length, $L_c$ (cm)	15.0	
Diameter of adsorbent particle, $d_p$ ( $\mu$ m)	50.0	
Total porosity, $\epsilon$	0.45	
Feed concentration, $C_{\text{feed}}$ (g/L)	5.0 (for each component)	

\* Data for adsorption isotherm, total porosity, mass-transfer, and feed concentration are from Ref. [13].

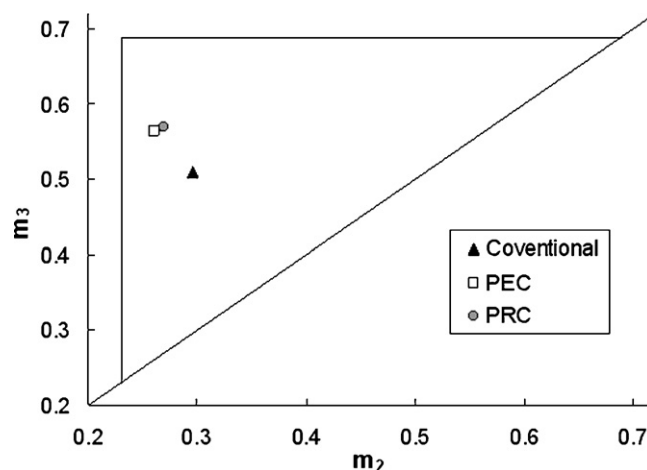
### 5.1. Case I optimization

Based on the system parameters in Table 1 and the relevant optimization frames (Eqs. (8)–(10)), the Case I optimization was performed for the conventional operation and the partial port-closing (PEC and PRC) operation while fixing the desorbent flow rate at 5 mL/min. The results from such a series of optimizations, which include the optimal operating parameters and the optimized throughput, are reported in Table 2. It is worth noting that both the PEC and PRC operations are definitely superior to the conventional operation in terms of the objective function, i.e. throughput. As can be seen in Table 2, the throughputs of the PEC and PRC operations are both about 85% higher than the throughput of the conventional operation.

To figure out the optimization results reported above more systematically, the operating parameters in Table 2 were depicted on the plane of ( $m_2$ – $m_3$ ) in Fig. 4, where  $m_j$  are the dimensionless flow-rate-ratio parameters based on the equilibrium theory [21]. The  $m_j$  value generally indicates the ratio of liquid (or mobile-phase) flow rate in zone  $j$  to the solid flow rate associated with periodic port movement. One noteworthy observation in Fig. 4 is that the operating point ( $m_2$ ,  $m_3$ ) corresponding to the partial port-closing (PEC and PRC) operation is located much farther away from the diagonal line, compared to the operating point corresponding to the conventional operation. This phenomenon is in agreement with the results

**Table 2**  
Results from the Case I optimization.

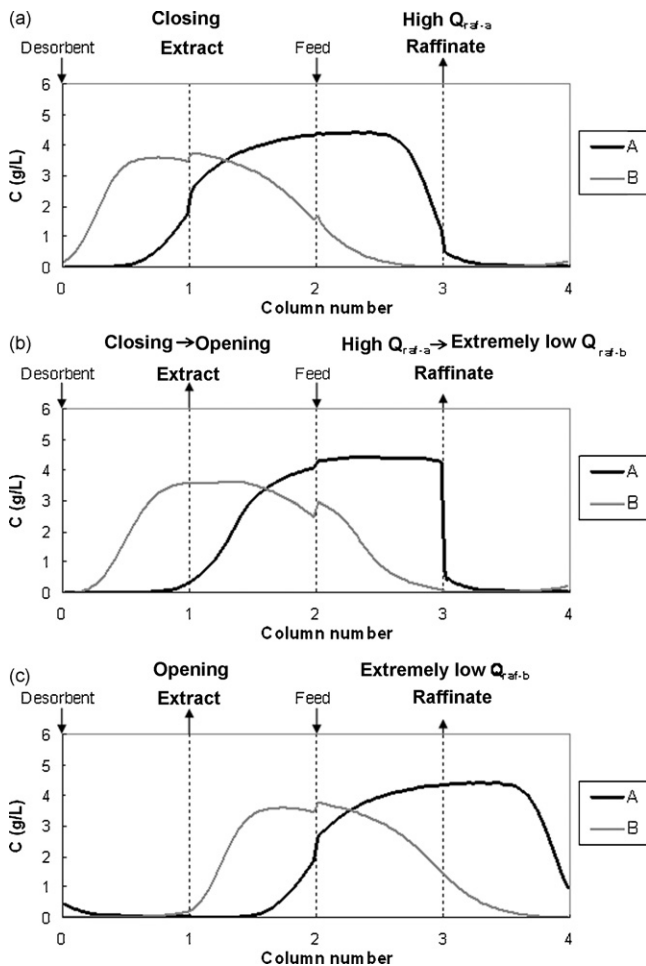
	Conventional operation	Partial port-closing operation	
		PEC operation	PRC operation
Throughput (L/h/100 L BV)	24.50	45.40	45.43
Product purities (%)	PurR = 98.0	PurR = 98.0	PurR = 98.0
	PurE = 98.0	PurE = 98.0	PurE = 98.0
Product yields (%)	Yield.A = 98.0	Yield.A = 98.0	Yield.A = 98.0
	Yield.B = 98.0	Yield.B = 98.0	Yield.B = 98.0
Optimal values of decision variables: $Q_j$ (mL/min), $t_{\text{sw}}$ (min)	$Q_1 = 8.4078$	$Q_{1b} = 11.4543$	$Q_{4a} = 0.2902$
	$Q_2 = 4.0296$	$Q_2 = 5.0659$	$Q_2 = 5.1979$
	$Q_{\text{feed}} = 0.7697$	$Q_{\text{feed}} = 1.4264$	$Q_{\text{feed}} = 1.4273$
	$t_{\text{sw}} = 7.1662$	$t_{\text{sw}} = 5.5176$	$t_{\text{sw}} = 5.4248$
			$\theta = 0.6458$
Optimal values of dependent variables (mL/min)	$Q_3 = 4.7993$	$Q_{1a} = 5.0659$	$Q_{1a} = 5.2902$
	$Q_4 = 3.4078$	$Q_3 = 6.4923$	$Q_{1b} = 11.6252$
	$Q_{\text{ext}} = 4.3782$	$Q_{4a} = 0.0659$	$Q_3 = 6.6252$
	$Q_{\text{raf}} = 1.3915$	$Q_{4b} = 6.4543$	$Q_{4b} = 6.6252$
		$Q_{\text{ext-b}} = 6.3884$	$Q_{\text{ext-a}} = 0.0923$
	$Q_{\text{raf-a}} = 6.4264$	$Q_{\text{ext-b}} = 6.4273$	
	$Q_{\text{raf-b}} = 0.0380$	$Q_{\text{raf-a}} = 6.3350$	
Values of fixed variables (mL/min)	$Q_{\text{des}} = 5$	$Q_{\text{des}} = 5$	$Q_{\text{des}} = 5$
		$Q_{\text{ext-a}} = 0$	$Q_{\text{raf-b}} = 0$
Product concentration (g/L)	$C_A = 2.71$	$C_A = 3.10$	$C_A = 3.12$
	$C_B = 0.86$	$C_B = 1.68$	$C_B = 1.67$



**Fig. 4.** Representation of the optimal operating points corresponding to the conventional, the PEC, and the PRC operations in the plane of ( $m_2$ – $m_3$ ) based on the equilibrium theory.

of the equilibrium theory that the distance from the diagonal line to the operating point is proportional to throughput.

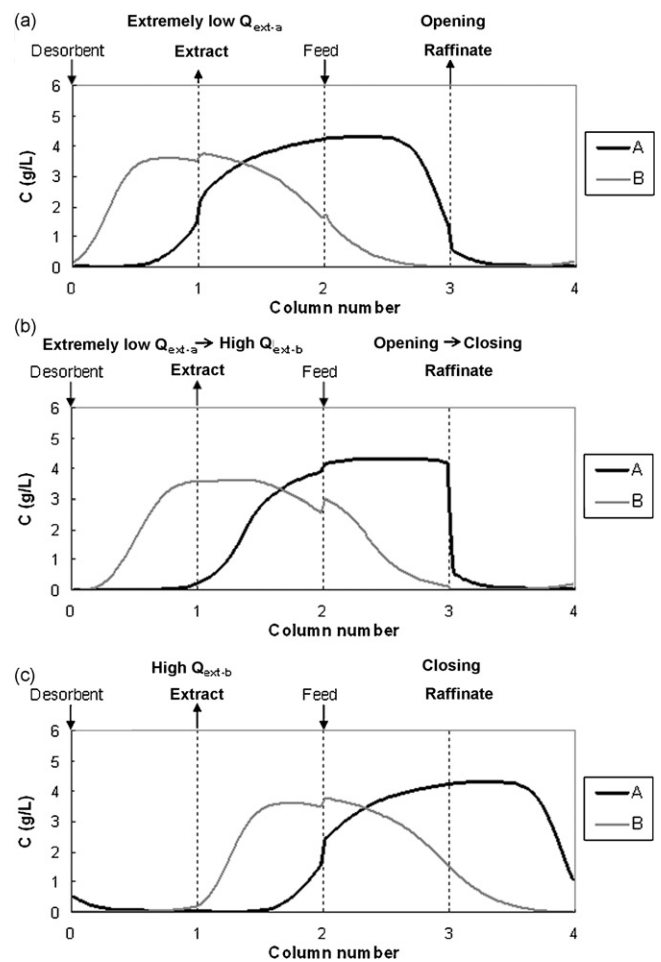
It is also evident in Fig. 4 that the attainment of higher throughput (i.e., larger distance from the diagonal line in Fig. 4) by the partial port-closing operation was mostly due to the fact that the  $m_2$  value was lower and the  $m_3$  value higher compared to the conventional operation. If such a shift in the positions of  $m_2$  and  $m_3$  values would occur in SMB without any measures, the extract and the raffinate products could suffer from significant contamination and eventually fail in meeting the purity requirement. However, in case of the PEC operation, the possible contamination of the extract stream due to a decrease in the  $m_2$  value could be overcome by closing the extract port during the optimized time period (Table 2) at the stage a (i.e., the first-half stage of a switching period). The effectiveness of such measures is well demonstrated in the column profiles (Fig. 5a and b) that were obtained from the simulations based on the operating parameters in Table 2 and the system parameters in Table 1.



**Fig. 5.** Column profiles for the PEC operation (Table 2) at cyclic steady state: (a) at the beginning of a switching period; (b) at the moment of opening the closed extract port; (c) at the end of a switching period.

On the other hand, it is not straightforward to understand how the PEC operation addresses the problem of possible raffinate contamination due to an increase in the  $m_3$  value. The clue to this issue can be obtained by examining closely the optimized flow rates in Table 2. We see that the raffinate flow rate during the latter-half stage ( $Q_{raf-b}$ ) is extremely low (i.e., almost close to zero). This means that the amount of the raffinate stream collected during the latter-half stage (b) is, in fact, negligible compared to that collected during the first-half stage (a). Hence, the purity of raffinate product, which is represented by the averaged purity over a switching period, is dominated by the purity of the raffinate stream collected during the first-half stage. Since the contamination of raffinate stream happens mostly during the latter-half stage (Fig. 5b and c), the aforementioned pattern of change in the raffinate flow rate (Table 2) is highly advantageous to attainment of the targeted raffinate purity (98%).

In a similar manner, the PRC operation could prevent the possible contamination of raffinate stream due to an increase in the  $m_3$  value by closing the raffinate port during the optimized time period (Table 2) at the stage b (i.e., the latter-half stage of a switching period). As demonstrated in the column profiles (Fig. 6a and b), the raffinate port is kept open only while the separated region in the solute band of the low-affinity component passes through the raffinate port (stage a). As soon as the front of the solute band of the high-affinity component reaches the raffinate port, the raffinate port is immediately closed and this state is maintained until the end of a switching period (stage b, Fig. 6b and c).



**Fig. 6.** Column profiles for the PRC operation (Table 2) at cyclic steady state: (a) at the beginning of a switching period; (b) at the moment of closing the opened raffinate port; (c) at the end of a switching period.

In addition, the possible reduction of extract purity, which may result from a decrease in the  $m_2$  value in the PRC operation, could be solved by placing a conspicuous difference between  $Q_{ext-a}$  and  $Q_{ext-b}$  as shown in Table 2 and Fig. 6. In an analogous manner to the aforementioned mode employed during the step b in the PEC operation, the extract flow rate in the PRC operation was maintained extremely low during the period of the step a that most of extract contamination was taking place (Fig. 6a and b). After such an extract contamination almost disappeared, the extract flow rate was maintained high. During this period (step b), the extract stream with high purity was collected (Fig. 6b and c). These two-step actions performed for the extract flow rate led to the attainment of the required extract purity (98%).

As a result of all the aforementioned behaviors in flow rates and wave migration, both the PEC and PRC operations can allow lower  $m_2$  value and higher  $m_3$  value at the same time, which enables the attainment of much higher throughput than the conventional operation. Besides such an improvement in throughput, the PEC and PRC operations can also obtain higher product concentration than the conventional operation, as listed in Table 2.

## 5.2. Effect of port-closing length on the product purities

For the optimized PEC and PRC operating conditions in Table 2, any variation in the port-closing length will have a significant effect on the product purities. To evaluate such an effect quantitatively, a series of simulations were carried out for the PEC and PRC opera-

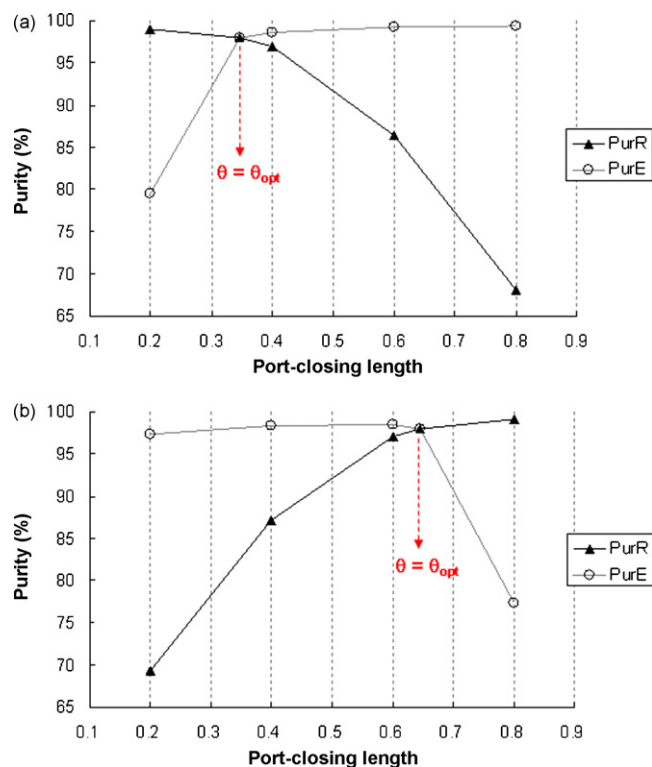


Fig. 7. Effect of port-closing length ( $\theta$ ) on the product purities: (a) PEC operation and (b) PRC operation.

tions while varying only the port-closing length ( $\theta$ ) and keeping all the other operating parameters the same as in Table 2.

The resultant extract and raffinate purities from the simulations were plotted as a function of  $\theta$  in Fig. 7. It should be mentioned that the overlap between the extract purity and the raffinate purity curves in Fig. 7 occurred at the optimal  $\theta$  value ( $\theta_{\text{opt}}$ ) resulting from the Case I optimization (Table 2), where the extract and raffinate purities were both maintained at the lowest acceptable limit, 98%.

In the first place, the relevant results for the PEC operation are discussed. Note in Fig. 7a that in the region of small  $\theta$  values, the extract purity increases sharply with increasing the  $\theta$  value. But if the  $\theta$  value is beyond  $\theta_{\text{opt}}$ , the extract purity increases very slightly and further becomes almost constant as the  $\theta$  value increases. This trend can be inferred from the column profiles in Fig. 5, which were obtained from the optimized PEC operation based on  $\theta = \theta_{\text{opt}}$ . In such column profiles, if the  $\theta$  value would be decreased below  $\theta_{\text{opt}}$ , a considerable portion of the trailing wave of the low-affinity solute could still be present in zone I even at the end of the step a. Such a portion of the low-affinity solute, in the subsequent step b, would contaminate the extract stream because it must pass through the extract port opened. Simultaneously, the advancing wave of the low-affinity solute would reach the end of zone IV quickly and then migrate into zone I within a switching period, thereby causing the contamination of the extract stream. Due to these two combining effects, a significant reduction in the extract purity occurred when the  $\theta$  value was decreased below  $\theta_{\text{opt}}$  (Fig. 7a). On the other hand, if the  $\theta$  value would be increased beyond  $\theta_{\text{opt}}$ , the trailing wave of the low affinity solute would be farther away from the extract port at the beginning of the step b, thereby making the extract stream less contaminated with the low-affinity solute. This may be of advantage to enhancing the extract purity, but such an advantageous effect is no longer enlarged if the  $\theta$  value is increased to such a degree that the trailing wave of the low-affinity solute leaves the extract port almost completely. This is why the increasing behavior of extract purity beyond  $\theta = \theta_{\text{opt}}$  follows the pattern in Fig. 7a.

Unlike the extract purity, the raffinate purity has a decreasing trend with increasing the  $\theta$  value, as shown in Fig. 7a. This phenomenon occurs due to the following two factors. First, as the  $\theta$  value is larger, the advancing wave of the high-affinity solute becomes closer to the raffinate port within the step a, during which the raffinate flow rate is maintained high. This will, of course, cause the reduction of raffinate purity. Secondly, a larger  $\theta$  value makes it more difficult to accomplish the desorption of the high-affinity solute from zone I within a switching period. In that case, some portion of the high-affinity solute could be moved back to zone IV after port switching, which also leads to the contamination of the raffinate stream. Such two combining factors will result in the decreasing pattern of raffinate purity that is demonstrated in Fig. 7a.

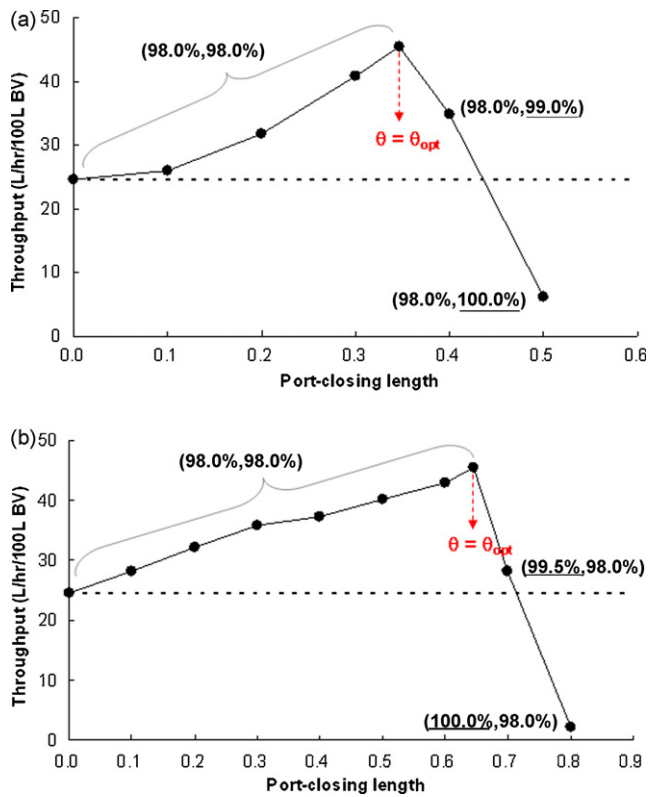
Following the PEC operation, the effect of port-closing length on the purities for the PRC operation is presented in Fig. 7b. One can see that the pattern of a change in the extract and raffinate purities for the PRC operation is apparently opposite to that for the PEC operation. The reasoning behind such a pattern for the PRC operation can also be made in an analogous manner to the previous inference regarding the PEC operation. In particular, it is worth noting that the raffinate purity has a decreasing trend as the  $\theta$  value becomes smaller than  $\theta_{\text{opt}}$  (Fig. 7b). This trend can be understood from the column profiles obtained from the optimized PRC operation based on  $\theta = \theta_{\text{opt}}$  (Fig. 6), in which the front of the advancing wave of the high-affinity solute is seen to touch the raffinate port at the end of the step a (Fig. 6b). In such column profiles, if the  $\theta$  value would be smaller than  $\theta_{\text{opt}}$  (i.e., the period of the step a would be lengthened), the amount of the high-affinity solute contaminating the opened raffinate-port would be increased, resulting in a decrease in the raffinate purity.

### 5.3. Effect of port-closing length on the optimum of throughput under the constraint on product purities

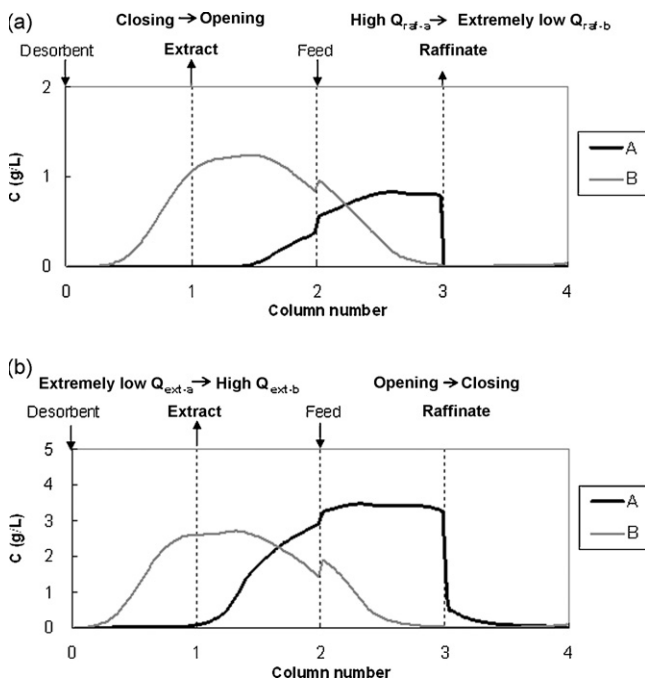
As the product purities were largely affected by the port-closing length ( $\theta$ ), so the throughput could be strongly dependent on the  $\theta$  value. To investigate such an issue, the Case I optimization for the PEC and PRC operations was performed again on condition that the port-closing length belonged to the category of fixed variables. Then, the optimization was repeated in series while varying the  $\theta$  value at the intervals of 0.1. The resultant throughputs from these optimizations and the throughputs reported in Table 2 were plotted as a function of the  $\theta$  value in Fig. 8, where the throughput of the conventional operation, indicated by the dotted line, was also included for comparison purpose.

One of the notable phenomena in Fig. 8a is that in the region of small  $\theta$  values, the throughput of the PEC operation increases with increasing the  $\theta$  value. Such a trend is continued until the  $\theta$  value reaches  $\theta_{\text{opt}}$ , beyond which the throughput decreases sharply with increasing the  $\theta$  value (Fig. 8a). The clue to a major reason for such a sharp decrease in throughput beyond  $\theta = \theta_{\text{opt}}$  can be found in the product purities reported together with the throughput in Fig. 8a. Note that the extract purities of the PEC operation with  $\theta > \theta_{\text{opt}}$  are far higher than the lowest acceptable limit (98%) (Fig. 8a), which indicates that the adsorbent bed in zone II was not fully utilized for maximization of throughput. This point can be confirmed from the relevant column profiles (Fig. 9a), which clearly reveals the presence of a large gap between the extract port and the trailing wave of the low-affinity solute at the moment of opening the extract port (i.e., at the beginning of the step b). As long as the  $\theta$  value larger than  $\theta_{\text{opt}}$  is used, the occurrence of such a gap region, which virtually corresponds to the under-utilized adsorbent bed, seems to be inevitable. This is why a sharp reduction in throughput happens in the region of  $\theta > \theta_{\text{opt}}$  in the PEC operation (Fig. 8a).

Similarly, the throughput of the PRC operation also had a sharp reduction if the  $\theta$  value was chosen to be larger than  $\theta_{\text{opt}}$  (Fig. 8b).



**Fig. 8.** Effect of port-closing length ( $\theta$ ) on the maximum throughput: (a) PEC operation and (b) PRC operation. The dotted line indicates the maximum throughput of the conventional operation. The two values inside the parenthesis indicate the raffinate purity and the extract purity, respectively.



**Fig. 9.** Column profiles obtained at the moment of opening the extract port (PEC) or at the moment of closing the raffinate port (PRC) in the partial port-closing operation, where the throughput was optimized under the fixed  $\theta$  value: (a) PEC operation ( $\theta = 0.5$ ) and (b) PRC operation ( $\theta = 0.7$ ).

This phenomenon is also related to the degree of the bed utilization in one of the separation zones. As shown in the relevant column profiles in Fig. 9b, a large gap exists between the raffinate port and the advancing wave of the high-affinity solute at the moment of closing the raffinate port (i.e., at the beginning of the step b), which leads to the occurrence of far higher raffinate purity than the lowest acceptable limit (98%). This phenomenon indicates that the adsorbent bed in zone III was not fully utilized, resulting in a severe reduction in throughput (Fig. 8b).

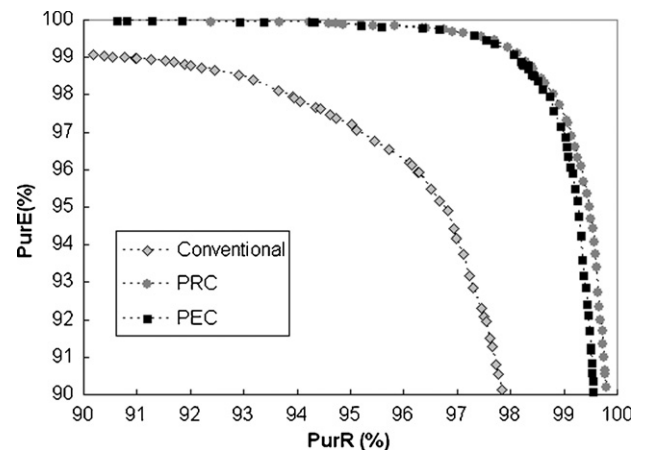
Fig. 8a and b also show that the throughputs of the PEC and PRC operations are superior to that of the conventional operation in a wide range of  $\theta$  value. But such an advantage of the PEC and PRC operations could no longer be effective if they would adopt too large  $\theta$  value.

#### 5.4. Case II optimization

The superiority of the partial port-closing operation over the conventional operation was verified in terms of throughput in the previous sections. To demonstrate such superiority from another angle, the Case II optimization (Eqs. (11)–(13)) was performed for each operation while fixing the flow rates of feed and desorbent at 1.3 mL/min and 5 mL/min, respectively. The goal of this optimization was the simultaneous maximization of both the extract and the raffinate purities under the fixed feed flow rate, i.e. under the fixed throughput.

The results from the Case II optimization are presented in Fig. 10, which shows multiple optimum solutions instead of a single solution for each operation. Such type of multiple solutions is known as Pareto optimal solutions or Pareto set [4, 18]. One of the interesting phenomena in the Pareto optimal solutions is that an increase in the extract purity leads to a decrease in the raffinate purity and vice versa. Such a trade-off phenomenon between the extract and the raffinate purities is typical of multi-objective optimization solutions, in which one objective improves while one other deteriorates along the set of optimal solutions (or Pareto solutions). Hence, any point along the Pareto curve is considered to possess an equal optimum status in terms of both the extract and the raffinate purities.

Comparing the Pareto optimal solutions of the partial port-closing operation and the conventional operation in Fig. 10, one can find that the former definitely outperforms the latter in terms of product purities under the fixed throughput. As for the Pareto solutions of the PEC and PRC operations belonging to the partial port-closing operation, both of them exhibit a similar behavior on



**Fig. 10.** Comparison of the Pareto optimal solutions (PurR versus PurE) resulting from the Case II optimization for the conventional operation, the PEC operation, and the PRC operation.



the whole (Fig. 10). But a little or slight difference between the PEC and PRC operations is observed in the two extreme regions, i.e. the lower right region and the upper left region in Fig. 10. In the former region, the PRC operation is seen to give a little higher raffinate purities than the PEC operation whereas in the latter region the PEC operation is seen to give slightly higher extract purities than the PRC operation. Such a trend indicates that if extremely high purity is demanded in only one of the product streams, it will be more effective to adopt the partial port-closing operation that controls the corresponding product port.

In light of the aforementioned results, the partial port-closing operation is highly expected to have far-reaching effects on the application of an SMB chromatography to drug separations because high product purity is typically an important requirement in drug manufacture.

## 6. Conclusions

The “partial port-closing” strategy was proposed to improve the performance (throughput and purity) of the four-zone SMB chromatographic process for binary separation. When the “partial port-closing” strategy was applied to the extract product, the extract port was closed at the first-half stage of a switching period (PEC strategy). On the other hand, when the “partial port-closing” strategy was applied to the raffinate product, the raffinate port was closed at the latter-half stage of a switching period (PRC strategy). While the extract or the raffinate port was kept closed, the product stream was not allowed to leave the SMB process but it was made to keep migrating through the adjacent zone within the SMB process. If the operating conditions and the port-closing length were optimized properly, such a partial port-closing operation led to much higher throughput or higher product purities than the conventional SMB operation based on the optimized conditions. In addition, the former operation gave higher product concentration than the latter operation.

Overall, it was concluded that the partial port-closing operation was definitely superior to the conventional SMB operation in every

respect. The strategy proposed in this study is therefore expected to provide a valuable engineering alternative for extending the application scope of a current four-zone SMB process toward the separation tasks demanding a marked improvement in throughput and purity.

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## References

- [1] Y. Xie, D.-J. Wu, Z. Ma, N.H.L. Wang, *Ind. Eng. Chem. Res.* 39 (2000) 1993.
- [2] K.B. Lee, C.Y. Chin, Y. Xie, G.B. Cox, N.H.L. Wang, *Ind. Eng. Chem. Res.* 44 (2005) 3249.
- [3] Y.-S. Bae, J.-H. Moon, C.-H. Lee, *Ind. Eng. Chem. Res.* 45 (2006) 777.
- [4] K.B. Lee, R.B. Kasat, G.B. Cox, N.H.L. Wang, *AIChE J.* 54 (2008) 2852.
- [5] Y. Xie, B. Hritzko, C.Y. Chin, N.H.L. Wang, *Ind. Eng. Chem. Res.* 42 (2003) 4055.
- [6] L.S. Pais, J.M. Loureiro, A.E. Rodrigues, *J. Chromatogr. A* 827 (1998) 215.
- [7] F. Wei, B. Shen, M.J. Chen, *Ind. Eng. Chem. Res.* 45 (2006) 1420.
- [8] O. Ludenmann-Hombourger, R.M. Nicoud, M. Bailly, *Sep. Sci. Technol.* 35 (2000) 1829.
- [9] Y. Zang, P.C. Wankat, *Ind. Eng. Chem. Res.* 41 (2002) 2504.
- [10] Z. Zhang, K. Hidajat, A.K. Ray, M. Morbidelli, *AIChE J.* 48 (2002) 2800.
- [11] H. Schramm, A. Kienle, M. Kaspereit, A. Seidel-Morgenstern, *Chem. Eng. Sci.* 58 (2003) 5217.
- [12] Z. Zhang, M. Mazzotti, M. Morbidelli, *AIChE J.* 50 (2004) 625.
- [13] J.S. Hur, P.C. Wankat, *Ind. Eng. Chem. Res.* 44 (2005) 1906.
- [14] J.S. Hur, P.C. Wankat, *Ind. Eng. Chem. Res.* 45 (2006) 8713.
- [15] Y.-S. Bae, C.-H. Lee, *J. Chromatogr. A* 1122 (2006) 161.
- [16] Y. Kawajiri, L.T. Biegler, *AIChE J.* 52 (2006) 1343.
- [17] Y. Kawajiri, L.T. Biegler, *Comput. Chem. Eng.* 32 (2008) 135.
- [18] P.S. Gomes, A.E. Rodrigues, *Sep. Sci. Technol.* 42 (2007) 223.
- [19] R.B. Kasat, S.K. Gupta, *Comput. Chem. Eng.* 27 (2003) 1785.
- [20] S.F. Chung, C.Y. Wen, *AIChE J.* 14 (1968) 857.
- [21] G. Storti, M. Mazzotti, S. Carra, M. Morbidelli, *Chem. Eng. Sci.* 44 (1989) 1329.