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Comparison of the relative merits of port-location rearrangement and partial-feeding as the strategy for improving the performances of a three-zone simulated moving chromatography for separation of succinic acid and lactic acid

Sungyong Mun*

Department of Chemical Engineering, Hanyang University, Seoul 133-791, South Korea

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ABSTRACT

The three-zone simulated moving bed (SMB) chromatographic process for separation of succinic acid and lactic acid, which has been developed previously, was based on a classical port-location arrangement (desorbent → extract → feed → raffinate) and a classical feeding mode (full-feeding). To improve the performance of the three-zone SMB process, it is worth utilizing the strategy of either a port-location rearrangement (desorbent → feed → raffinate → extract) or a partial-feeding. To investigate which of the two strategies is more effective, the three-zone SMBs based on the port-location rearrangement (PR) and the partial-feeding (PF) were optimized each under equal conditions and then the two strategies were compared in terms of product purities or throughput. The result showed that the PR strategy led to higher purities or higher throughput than the PF strategy in regard to the previously reported three-zone SMB system. To check whether such trend is still valid in other separation systems, the above optimization works were repeated while varying only the selectivity between two feed components. It was confirmed that the PR strategy is definitely superior to the PF strategy. However, such superiority of the PR over the PF strategy is lessened as the selectivity becomes lower. If the selectivity is significantly low, the PR strategy is rather outperformed by the PF strategy.

1. Introduction

Succinic acid and lactic acid have been highly useful in many industries and they were reported to have a wide range of industrial applications [1–3]. One of the recent researches related to the production of such two organic acids was to utilize a series of fermentation and nanofiltration processes [3]. Since the outgrowth of these processes was a mixture of succinic acid and lactic acid, the task of separating the organic-acid mixture with high purity and high throughput became a matter of grave concern. Such a separation task has recently been attempted in a continuous mode by using a three-zone simulated moving bed (SMB) chromatographic process [4], which was based on a classical structure and a classical operation mode as shown in Fig. 1a.

To ensure the economic feasibility of the aforementioned organic-acid production, it is essential to maintain high performances of the three-zone SMB process in Fig. 1a, which is in charge of the separation between succinic acid and lactic acid. To address this issue, a proper strategy needs to be applied to the aforementioned organic-acid separation process (Fig. 1a). In regard to such strategy, it is worth mentioning that either a port-location rearrangement (PR) [5] or a partial-feeding (PF) [6,7] has proved to be effective in improving the performance of a three-zone SMB in the literature. It will thus be a task of great significance to investigate which of the two strategies is better suited for the previously reported three-zone SMB process for separation of succinic acid and lactic acid (Fig. 1a). To the best of our knowledge, there have been no previous studies on the comparison of the advantages of PR and PF strategies regarding a three-zone SMB chromatography for binary separation.

The goal of this study is to accomplish the aforementioned task. For this purpose, the three-zone SMB processes based on the PR and PF strategies will be optimized each under equal conditions and then the two strategies will be compared in terms of purity

* Correspondence to: Department of Chemical Engineering, Hanyang University, Haengdang-dong, Seongdong-gu, Seoul 133-791, South Korea. Tel.: +82 2 2220 0483; fax: +82 2 2298 4101.
E-mail address: munsy@hanyang.ac.kr

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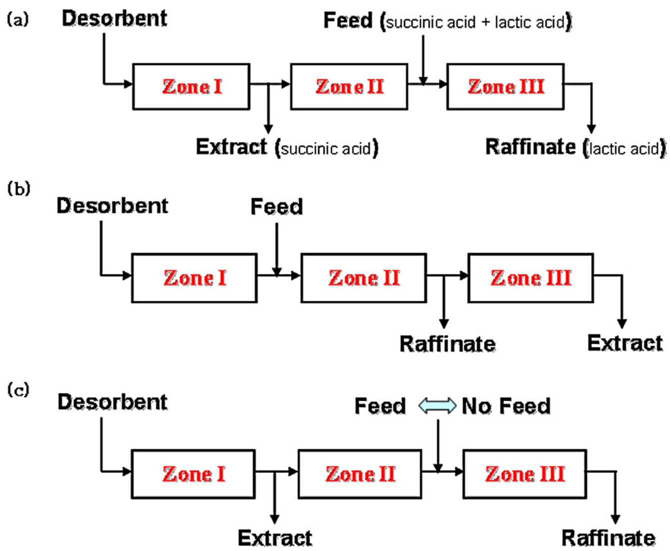

Fig. 1. Schematic diagrams of (a) the previously reported chromatography for separation of succinic acid and lactic acid (classical three-zone SMB), (b) a three-zone SMB based on the port-location rearrangement (PR) strategy, and (c) a three-zone SMB based on the partial-feeding (PF) strategy. Switching of ports in the SMB is not shown.

under a fixed throughput or in terms of throughput under a given purity requirement. This work will be accompanied by comprehensive optimizations of the three-zone SMBs based on the PR and PF strategies, which will be conducted by using a highly efficient adaptation of genetic algorithm, NSGA-II-JG (elitist nondominated sorting genetic algorithm with jumping genes) [8,9]. Finally, the effect of selectivity on the relative merits of PR and PF strategies will be examined.

2. Theory

2.1. PR (port-location rearrangement) strategy

To improve the performance of a three-zone SMB process, its port locations can be rearranged in such a way that the load of adsorbent regeneration can be alleviated [5]. An efficient way for obtaining such advantage is to change the location of the extract port from its classical position (i.e., the position between zones I and II) to the zone III outlet while transferring the feed and raffinate ports backwards by one zone (Fig. 1b) [5]. This rearrangement causes the four ports to be located in the order of desorbent → feed → raffinate → extract as seen in Fig. 1b. Under such a rearranged port-location mode, the task of adsorbent-regeneration, which is to clear away high-affinity solute molecules from the adsorbent column for the purpose of its reuse in the next separation step, can be fulfilled by both zones I and III. This condition is obviously favorable for lightening the burden of adsorbent regeneration, compared to a classical three-zone SMB port arrangement where the adsorbent regeneration task should be handled only by zone I.

For the aforementioned reason, the three-zone SMB based on the port-location rearrangement (PR) strategy can make its adsorbent utilization more focused on the increase of throughput under given purity requirements or on the increase of product purities under a given throughput, compared to a classical three-zone SMB [5]. This is why the PR strategy can be regarded as one of the trustworthy ways for improving the performance of a three-zone SMB.

2.2. PF (partial-feeding) strategy

The partial-feeding (PF) strategy was reported to be effective in improving the performance of a three-zone SMB process [6,7]. The core of this strategy is to load a feed mixture during only a part of switching period, which is known to be of some help in widening the distance between the raffinate port and the leading edge of high-affinity solute band at the end of a switching period and also in widening the distance between the extract port and the trailing edge of low-affinity solute band at the beginning of a switching period [6,7]. Such effect can lead to an increase in product purities or throughput.

It is well known that the partial-feeding (PF) mode is governed by two controlling factors such as feed length and feed-loading time [6,7,10]. Since these two factors can be determined independently of each other, there will be a large number of options available in implementing the PF mode. In this study, only the three cases of PF applications will be taken into account. First, the feed length will be fixed at that corresponding to a third of the switching period ($1/3\ t_{sw}$) in time unit. Under such a feed length of $1/3\ t_{sw}$, we will consider only the following three feeding-sequences, which will be denoted by PF-1, PF-2, and PF-3 hereafter.

PF-1: feed-loading between $n\ t_{sw}$ and $(n+1/3)\ t_{sw}$.

PF-2: feed-loading between $(n+1/3)\ t_{sw}$ and $(n+2/3)\ t_{sw}$.

PF-3: feed-loading between $(n+2/3)\ t_{sw}$ and $(n+1)\ t_{sw}$.where n indicates the number of steps (or switchings). During the other time than the above feed-loading period, the feed flow rate is made to become zero by closing the feed port as depicted in Fig. 1c. Between the feed-loading and the feed-closing periods, only the flow rates of zone III and raffinate are changed to maintain mass balance while all the other operating parameters remain unchanged (Fig. 1c). Of course, the flow rates of zone III and raffinate are higher during the feed-loading period than during the feed-closing period (Fig. 1c).

In regard to the aforementioned PF modes, it is a matter of common knowledge that early feed loading favors extract purity whereas late feed loading favors raffinate purity [6]. If both extract and raffinate products are to be obtained with purities, it is usually recommended to load feed near the center of a switching period [6]. Hence, the PF applications in the first part of the following sections, where both extract and raffinate products are to be optimized simultaneously, will be based on only the PF-2 mode. In case of the other PF modes, they will be taken into considerations along with the PF-2 mode in the subsequent section, where the process throughput is to be optimized.

2.3. Simulation model

The simulation and optimization of a multiple chromatographic-column process like the three-zone SMB of interest require a detailed mathematical model (i.e., chromatographic column model) that can describe accurately the dynamic migration behaviors of solutes through a chromatographic column.

In this study, the lumped mass-transfer model [4,11–13] will be employed as the column model for the simulation of a three-zone SMB. This model considers convection, axial dispersion, and mass-transfer between the mobile phase and the solid phase (or adsorbent phase). The corresponding model equations for each chromatographic column are presented below [4,11–13].

$$\varepsilon_b \frac{\partial C_{b,i}}{\partial t} + (1-\varepsilon_b) K_{f,i}(C_{b,i} - C_i^*) + u_0 \varepsilon_b \frac{\partial C_{b,i}}{\partial z} - \varepsilon_b E_{b,i} \frac{\partial^2 C_{b,i}}{\partial z^2} = 0 \quad (1a)$$

$$\varepsilon_p \frac{\partial C_i^*}{\partial t} + (1-\varepsilon_p) \frac{\partial q_i}{\partial t} = K_{f,i}(C_{b,i} - C_i^*) \quad (1b)$$

where the subscript i stand for different solutes; $C_{b,i}$ is the mobile-phase concentration; C_i^* is the average pore-phase concentration;