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Enhancement of yield and productivity in the 3-zone nonlinear SMB for succinic-acid separation under overloaded conditions

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ABSTRACT

For a biotechnological process of succinic-acid (SA) production, one of the essential requirements for ensuring its economical feasibility is to establish an effective way for an economical separation of SA (target product) from other fermentation-sourced organic acids (by-products). For this purpose, we investigated the optimal design of a 3-zone simulated moving bed (SMB) process for the SA separation that could be operated under overloaded conditions. This work began by determining the intrinsic parameters of SA and other organic acids in a Langmuir-isotherm region, which were then used to clarify a proper set of feed concentration and port-arrangement mode that can be favorable for both SA yield and SA productivity.

Introduction

As for the production of useful organic acids, a biotechnological-pathway production method based on bacterial fermentation was recognized to have definite advantages over a chemical-pathway production method from an economical and environmental point of view [1–3]. One of the noteworthy organic-acids rooted in such a biotechnological-pathway production method is succinic acid (SA), which is widely useful in manufacturing valuable commodities in various industries. Such merit helped SA to be selected by the US Department of Energy as one of the top 12 building block chemicals that could be produced through a biotechnological route [4].

The aforementioned succinic-acid production process always generated two other kinds of organic acids, which included acetic acid (AA) and formic acid (FA) [3,5,6]. The composition of the resulting organic-acid mixture from such a succinic-acid production process based on the bacterial fermentation (i.e., the ratios of SA, AA, and FA in the fermentation output) was reported to depend largely on the fermentation conditions and the species of the bacteria used [1,3].

It has been a matter of interest to establish an effective way for the economical separation of SA (product of interest) from two other fermentation-sourced organic acids (by-products). Concerning this issue, it is worth referring to the recent literature, which reported that the use of well-designed adsorbent-based chromatographic process could be effective in the separation between different organic acids [7].

If an adsorbent-based chromatographic process is to be applied to the separation task under consideration, it will be a matter of grave concern to operate the process such that high productivity and high yield for SA can be guaranteed while maintaining a desired level of SA purity. To meet this requirement, a continuous-mode separation process needs to be adopted, and if possible, it should be operated under overloaded conditions [8]. As for a continuous-mode process, it is widely accepted that a simulated moving bed (SMB) is the most trustworthy process option in the field of chromatographic separations [8–11].

The structure of a standard four-zone SMB process for binary separation [8–10] is shown in Fig. 1. This process is characterized by the simultaneous use of a multitude of adsorbent columns and ports. The adsorbent columns are partitioned into four zones, which are specified by the locations of four ports in charge of feed loading, desorbent introduction, extract collection, and raffinate collection. The four ports are advanced periodically by one column in the same direction as that of the fluid flow. Under such circumstances, a proper design for SMB operating parameters (flow rates and port switching time) can enable an SMB process to implement both feed loading and product collection in a

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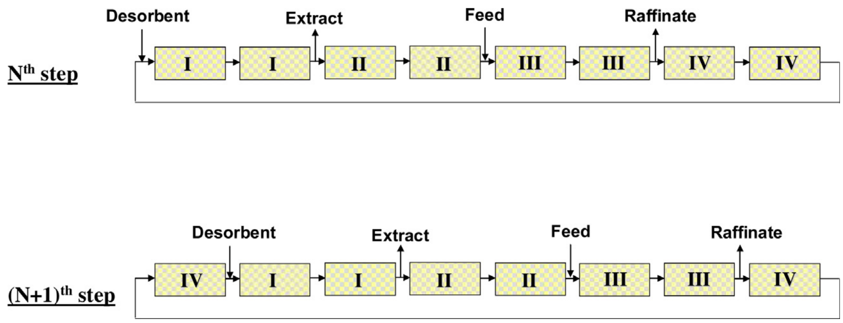

Fig. 1. Schematic diagram of a standard four-zone SMB process for binary separation.

continuous mode, thereby outperforming conventional batch separation processes in separation capability and process efficiency [8–12].

The purpose of this study is to investigate the optimal design of an SMB process aimed at SA separation under overloaded conditions, where the feed concentration is set sufficiently high to make the considered system fall into a nonlinear isotherm region. Here, the objects of the optimal design include not only the SMB operating parameters but also the SMB port-arrangement mode and feed concentration. In regard to the column and zone configurations for the SMB of interest, they were selected in accordance with the following issues. First, the total column number should be as small as possible because it has a major effect on SMB equipment cost. Secondly, the operation mode should be based on the simple pattern of a full feeding, a full product-collection, and a constant flow rate in each zone, which is usually known to be more advantageous in a failure rate and a life span of the process mechanical parts than other sophisticated patterns of a partial feeding, a partial product-collection, or a partial change in flow rates during a switching interval [13]. In consideration of the two aforementioned issues, the targeted SMB in this study is set to follow a 3-zone open-loop configuration based on the allocation of one column in each zone (Fig. 2). Under such column and zone configurations, the SMB of interest will be designed to produce the highest yield of SA while maintaining its purity higher than 99%. During the SMB design, the effects of feed concentration and port-arrangement mode on the SA yield will be investigated. Furthermore, we will examine how the level of the resultant SA yield will affect the SA productivity. Finally, we will determine the feed concentration and the port-arrangement mode that will be favorable for both SA productivity and SA yield.

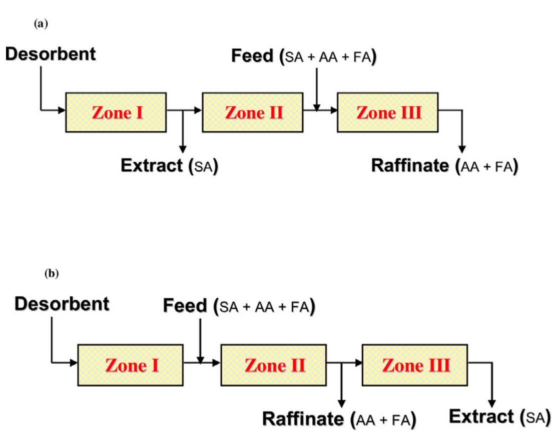

Fig. 2. Schematic diagrams of the P1-SMB and P2-SMB processes for separation of SA from AA and FA. (a) P1-SMB process (3-zone SMB based on the classical port-arrangement mode), (b) P2-SMB process (3-zone SMB based on the modified port-arrangement mode). Switching of ports in the SMB is not shown. SA: succinic acid, AA: acetic acid, FA: formic acid.

Theory

Column model for simulation of an SMB separation process

The optimal design of SMB is always accompanied by a simulation work, which is to numerically solve the mathematical governing equations for the transport phenomena of solutes through an adsorbent column. The governing equations that were developed for such purpose were referred to as column model in the literature [12–15]. One of the prevalent column models in previous studies is a lumped mass-transfer model, which is known to be sufficiently eligible for SMB simulation work [13–15]. This model was used as a major frame of the simulations and process design in the present study. Its relevant model equations can be found elsewhere [13–15]. The model equations were solved by using a biased upwind differencing scheme (BUDS) and Gear integration method, which was accomplished in Aspen Chromatography simulator.

SMB optimization tool

In this study, a robust optimization tool for multi-column processes was needed to perform the optimal design of an SMB process, which corresponded to the task of determining an optimal set of SMB operating parameters (switching time and flow rates). The SMB optimization tool of this study was organized by combining a well-known genetic algorithm with the aforementioned column model. There are several versions of genetic algorithms available in the literature. Among the genetic algorithms, NSGA-II-JG (non-dominated sorting genetic algorithm with elitism and jumping genes) [16,17] has been widely accepted as a highly robust and efficient algorithm in optimizing continuous multi-column processes like SMB [16,17]. It was thus adopted as the optimization algorithm of the SMB optimization tool in this work. Before the implementation of this algorithm, one should specify several key parameters that are related to the algorithm configuration. These are commonly called NSGA-II-JG parameters [16,17], which are presented in Table 1 for the case of the SMB optimization of this study.

Table 1
NSGA-II-JG parameters used in the optimization of the 3-zone SMB process of interest in this study.

Number of decision variables	2
Population size	50
Length of chromosome	26 bits
Crossover probability	0.9
Jumping gene probability	0.7
Mutation probability	1/(length of chromosome)