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Optimal design and operation of a certain class of asynchronous simulated moving bed processes

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Abstract

A compact representation of the cyclic operation of simulated moving-bed chromatography is established from the governing equations for the analogous single-column model that reproduces the cyclic steady-state (CSS) behavior of the multi-column process. A broad class of physically realizable asynchronous processes is then derived by dropping the integrality condition on the number of columns per zone, which now represents the average over a cycle. The steady periodic solution of the multi-column unit is computed by solving the analogous single-column model using a full-discretization method. The nonlinear algebraic system resulting from the simultaneous discretization of both spatial and temporal coordinates is solved using the gPROMS software. This solution strategy leads to shorter computational times than those previously reported in the literature. Process optimization is handled using single objective functions, to avoid competing effects, which are explicitly constrained by product quality and maximum allowable internal flow rates. The process is optimized for maximum feed throughput, with a possible upper bound on eluent consumption or flow rate, or minimum eluent consumption for a given feed flow rate. The nonlinear programming problem is solved by an external solver while still carrying out the CSS calculations in gPROMS. The feasibility of the approach is demonstrated on the chromatographic separation of an enantiomeric mixture with nonlinear competitive isotherm. Emphasis is given to the benefits that can be gained by upgrading an existing system to asynchronous operation. It is shown that eluent consumption for optimized asynchronous configurations in the higher feed-throughput region can be significantly reduced by modulation of eluent flow rate and selective product withdrawal.

Keywords: Simulated moving bed chromatography; Asynchronous operation; Flow-rate modulation; Preparative chromatography; Optimization

1. Introduction

Simulated moving bed (SMB) chromatography has been increasingly applied for the separation of pure substances in the pharmaceutical, fine chemistry, and biotechnology industries, at all production scales, from laboratory to pilot to production scale [1]. The SMB has many advantages with respect to discontinuous batch chromatography [2], such as higher product purity, less solvent consumption, and higher productivity per unit stationary phase [3–5].

The SMB is a practical way of implementing a counter-current chromatographic process. The system consists of N identical chromatographic columns connected in series to build a closed loop. By moving the input and withdrawal ports one column ahead (i.e. in the direction of fluid flow) at fixed intervals, the counter-current contact between the adsorbent and liquid is simulated. A schematic diagram of a typical four-section SMB is shown in Fig. 1.

Thanks to recent developments in cyclic operation schemes, a number of possibilities for improving SMB performance have emerged through variation of parameters during a switching interval. These include, among others, the asynchronous shift of the inlet/outlet ports [6,7] and the cyclic modulation of feed flow [8–12] or feed concentration [13,14]. The potential of modulating solvent strength during the switching interval has not yet been realized, though the benefits of applying solvent-gradient operation to the SMB have already been demonstrated [15–19]. These advances are pushing the trend toward the use of units with a small number of columns, since less stationary phase is used, the setup is more economic, and the overall pressure drop can be reduced.

The optimal design and selection of optimal operating parameters are essential to realize the economic potential of nonstandard SMB operating modes and their successful implementation

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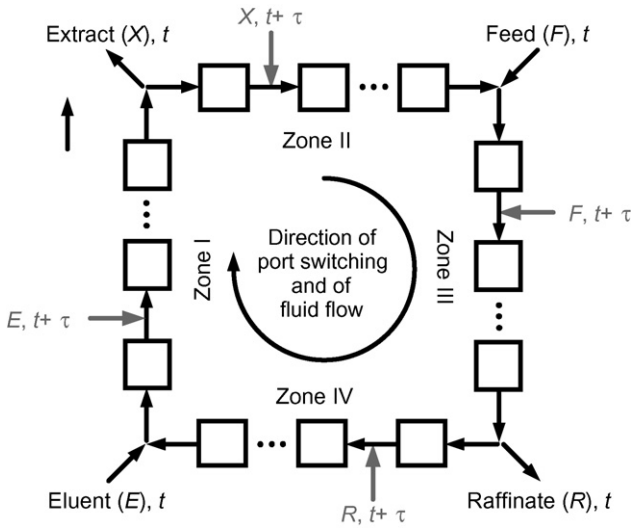

Fig. 1. Schematic diagram of a four-section SMB unit. Several chromatographic columns are interconnected circularly, the input and withdrawal ports are moved one column ahead every τ time units. The feed, eluent, extract, and raffinate streams are denoted by F, E, X, and R, respectively.

at industrial scale. These call for the use of advanced optimization procedures coupled with a detailed model of process dynamics. The complexity of the optimization problem is increased further by the intrinsic dynamic nature of the process, which approaches a cyclic steady state (CSS) after a sufficiently long period of time. For process design the initial transient behavior is of little interest, but only the fully established periodic state. In most cases, the latter has been computed by direct dynamic simulation of the whole process unit. Often, the hypothetical true moving-bed (TMB) process is used as a simplified model for the SMB. The TMB model is continuous and has a stationary state which can be computed easily. However, if a small number of columns is used, or the operating parameters are varied during the switching interval, the system behavior deviates significantly from the classical SMB process and precludes the application of the TMB analogy.

A detailed SMB process model is computationally expensive and becomes an issue for rigorous model-based optimization [20–25], especially when the number of optimization variables is increased by the extra degrees of freedom (d.f.) of the operating conditions of nonstandard SMB processes. Stochastic approaches, as well as gradient-based approaches, have been proposed to tackle the complex optimization problem of continuous chromatographic processes. Stochastic optimization methods, such as genetic algorithms [26], adaptive random search [27] and simulated annealing [28–30], are robust and less sensitive to non-convexities in both the objective function and constraints when compared to gradient-based methods. They have been recently applied with success for the optimization of the isocratic SMB process [31,32], Varicol [32–35], PowerFeed [35], and gradient SMB process [36]. Gradient-based methods additionally require the values of the partial derivatives (sensitivities) of the objective function and constraints with respect to the design variables. However, if a preliminary parameter study is performed in order to find initial values close to optimum before the optimization problem is solved, these methods require far less function evaluations to converge than stochastic methods [20–25].

In this work, we begin by establishing a compact representation of the cyclic operation of the SMB process from the governing conditions for the single-column model that reproduces the CSS behavior of the multi-column process. By relaxing the integrality condition on the number of columns per zone, we show that a broad class of physically realizable asynchronous processes is readily obtained from the same set of governing equations. We then briefly describe an optimization strategy that relies on simultaneous temporal and spatial discretization to directly compute the CSS solution at every step of the optimization procedure. This is shown to be very efficient for chromatography optimization. The feasibility of our approach is demonstrated on the separation of an enantiomeric mixture with nonlinear isotherm. Units with a small number of columns, between three and five, are considered, since they look more promising for future applications of SMB and related technologies. The results presented here, as well as those of other authors, show that significant performance improvements can be achieved by varying some of the operating parameters during the switching interval. It is further shown that eluent consumption for some of the optimized asynchronous configurations can be significantly reduced by modulation of eluent flow rate and partial product withdrawal.

2. Mathematical formulation

In the notation employed here the N columns are numbered sequentially in the direction of liquid flow. Because they are connected circularly, the column index is implicitly defined modulo N. Thus, $j = 0$ actually means column N, whereas $j = N + 1$ is the same as referring to column 1.

Fig. 2 shows the schematic of a generic node between two consecutive columns, say $j - 1$ and j. The notation employed is as follows: Q is the liquid flow rate, $c^{\text{out}}_{i,j-1}$ is the concentration of solute i at the outlet of column $j - 1$ and c^{in}_{ij} is the corresponding solute concentration at the inlet of column j. The solute concentration and flow rate of the external inlet/outlet lines are identified by scripts E (eluent), X (extract), F (feed), and R (raffinate).

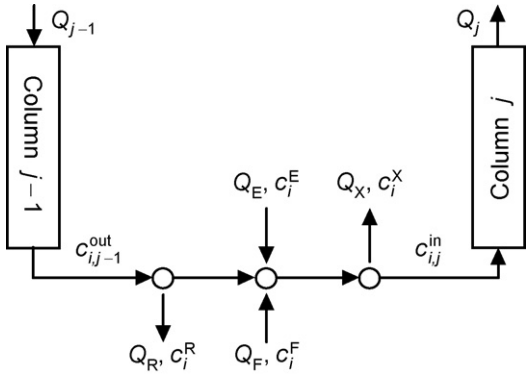

Fig. 2. Schematic of node connecting columns $j - 1$ and j of an SMB unit. The concentration of solute i in liquid phase is c_i and Q is the volumetric flow rate. Scripts E, X, F, and R denote eluent, extract, feed, and raffinate lines, respectively.