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Analyses of simulated moving bed with internal temperature gradients for binary separation of ketoprofen enantiomers using multi-objective optimization: Linear equilibria

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ABSTRACT

Gradient operation of a simulated moving bed (SMB) can improve the separation and purification performance by adjusting adsorption strength in each individual zone according to its functional role. The feasibility of an internal temperature gradient (ITG) established by a difference between feed and desorbent temperatures for binary separation of ketoprofen enantiomers was investigated based on simultaneous optimization of purity and productivity of S-ketoprofen, the preferentially adsorbed species and desired product. ITG operation with a temperature difference of 20 K has a unit productivity higher than isothermal mode by about 20%. Due to the combined effects of temperature transition and downstream dilution, concentration profile may exhibit a remarkable peak and a pattern of two-step drop in the temperature descending and ascending areas, respectively. Both areas, if properly located under optimal conditions, are favorable for unit productivity, which cannot be predicted by the direct use of triangle theory and average Henry's constants. Modifications of the SMB operations to reduce solvent consumption were also discussed based on analyses of parametric sensitivity and internal concentration profiles.

1. Introduction

Simulated moving bed (SMB) technique provides an efficient alternative for chromatographic processes in that, compared with batch operations, it has the advantages of improved unit productivity, reduced solvent consumption, and complete separation for a binary system with low selectivity [1,2]. Its applications has been extended from large scale processes such as purification of *p*-xylene [3,4] and fructose/glucose separation [5] to productions of fine chemicals such as enantiomers and biological products [2,6]. As shown in Fig. 1, a typical SMB unit for binary separation has two outlet ports, one (extract) for the preferentially adsorbed species and the other one (raffinate) for the less retained species, and two inlet ports for feed and desorbent. During the operation, the ports are periodically switched along the fluid flow direction, resulting in a simulated counter-current movement of stationary and mobile phases, similar to the case of a true moving bed unit [1]. These ports divided the series-connected columns into four zones, each fulfilling a specific task: zone I and zone IV are for the regeneration of stationary and mobile phase, respectively; zone II is for the purging of less retained species; zone III is mainly for the adsorption of preferentially adsorbed species [7–10].

Conventional SMB units are operated under isothermal and isocratic conditions, featured by constant adsorption strength in all zones. However, according to the above described functional roles, low adsorption strength is favorable for zones I and II whereas high adsorption strength is favorable for zones III and IV. It is therefore desired to introduce a gradient of adsorption strength to improve SMB performance in terms of unit productivity and solvent consumption [11]. For liquid mobile phases, adsorption strength can be efficiently adjusted by either mobile phase composition or temperature. Implementation of solvent gradient in SMB processes has been extensively reported in the literature [12–15]. Several studies have been carried out to investigate the feasibility of enhancing SMB performance with energy-driven temperature gradient. Migliorini et al. developed the design criteria of non-isothermal SMB modes based on the assumption that temperatures of different zones can be independently adjusted [16]. Kim et al. [17] and Jin

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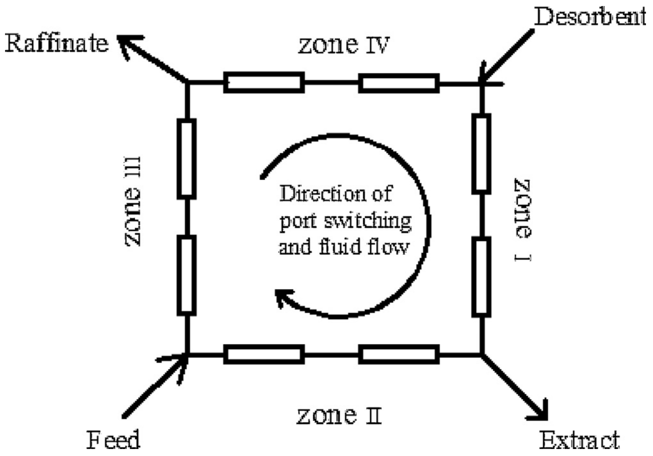

Fig. 1. Schematic diagram of a 4-zone SMB unit.

and Wankat [18] studied thermal four-zone SMBs for the separation of toluene-xylene using detailed simulations. They also developed a two-zone SMB concentrator with temperature gradient generated by inter-column heat exchangers [19]. Our recent study extended the non-isothermal operations to an SMB reactor where in-situ chromatographic separation of products and reactants is used to enhance the conversion of a reversible esterification reaction [20].

Temperature gradient can be introduced via direct or indirect mode [18]. The direct mode uses jackets to change the column temperature. Its large scale application is limited by radial heat transfer efficiency [16]. An indirect mode adjusts inlet temperature of each individual column by inter-column heat exchangers. In addition to the complicity that cannot be easily implemented in existing SMB units, mixing in extra dead volume of the exchangers is a major concern. Another indirect mode establishes a thermal gradient by the difference between feed and desorbent temperatures, similar to the two-step solvent gradient operation that was proven to be efficient [12,21]. This article is focused on the second indirect mode, which is hereafter referred to as internal temperature gradient simulated moving bed (ITG-SMB) for conciseness.

Most of previous theoretical non-isothermal SMB studies were carried out based on the assumption of arbitrary temperature distribution among different zones, such that equilibrium theory [8–10], a robust tool for the design of SMB processes using adsorption equilibria, can be straightforwardly applied to determine the operating parameters in terms of dimensionless flowrate ratio, normally referred to as m_j, where j is the index of operation zone. However, in the ITG-SMB mode, adsorption strength varies with temperature along both temporal and spatial coordinates, limiting the use of equilibrium theory [12]. Jin and Wankat showed by a parametric sensitivity analysis based on detailed simulations that, compared with isothermal model, ITG-SMB mode operated at the same flowrates and switching time can have either significant or minor effects on purity and recovery of desired product [18]. However, it has been found that the complicated SMB operation parameters may have contradicting effects on product purity, productivity, recovery and solvent consumption [22]. Successful design of SMB processes requires multi-objective optimization [23]. Therefore, it is desired to evaluate efficiency of the application of temperature gradient at optimized conditions.

This study is aimed at comparing ITG-SMB mode with isothermal mode for binary separation operated under optimized conditions. For this purpose, chiral separation of ketoprofen enantiomers [24,25] on an SMB chromatography unit consisting of 8 preparative Chiralpak-AD columns (2 in each zone, fixed) is used as the model system. For simplicity, linear equilibria are first considered at the current stage of study. The article is organized as follows. After this brief introduction, the model, formulation of optimization problem, and numerical scheme will be describe. The model parameters are summarized in Section 3. Then the results are presented and discussed using concentration and temperature profiles calculated at optimized conditions. Finally, conclusions are given. While this study is essentially theoretical, fundamental experiments have been carried out to acquire some of the model parameters, which are omitted in the main article for conciseness and scrutinized in the first part of Supporting information.

2. Theories

2.1. Model description

The conventional equilibrium-dispersive chromatography model [1,7] was extended to account for the temperature effects on adsorption equilibrium [20] and coupled with an energy balance equation based on the assumptions of (i) linear adsorption with temperature-dependent Henry's constants, (ii) isobaric system, (iii) negligible effects of adsorption heat, (iv) negligible radius gradient [19], and (v) constant heat capacities independent of temperature and composition. As such, the model consists of the following equations.

Component mass balance:

$$(1+\varphi H_i)\frac{\partial c_{i,j}}{\partial t}+c_{i,j}\varphi\frac{dH_i}{dT}\frac{\partial T}{\partial t}+u_j\frac{\partial c_{i,j}}{\partial z}-D_{app,i}\frac{\partial^2 c_{i,j}}{\partial z^2}=0 \quad (1)$$

where φ is the phase ratio defined as $\left(1/\varepsilon_t-1\right)$ with ε_t being the total voidage, c is concentration in the mobile phase, i is index of component, j is index for column from 1 to 8 or operating zone from I to IV, T is temperature, u is the interstitial velocity ($u=\frac{4Q}{\pi d^2\varepsilon_t}$), Q is mobile phase flowrate, d is the internal column diameter, D_{app} is the apparent diffusivity, t is time, z is the axial coordinate, and H is Henry's constant. Compared with isothermal ED model, Eq. (1) has an additional term that accounts for temperature effects on local adsorption capacity. Temperature dependence of Henry's constants is described as

$$H_i=H_i^r\exp\left[\frac{\Delta H_i}{R}\left(\frac{1}{T^r}-\frac{1}{T}\right)\right] \quad (2)$$

where ΔH is adsorption enthalpy and T is temperature, r denotes the reference temperature.

Energy balance:

$$\frac{1}{\gamma}\frac{\partial T_j}{\partial t}+u_j\frac{\partial T_j}{\partial z}-D_{app,T}\frac{\partial^2 T_j}{\partial z^2}=0 \quad (3)$$

where γ is a dimensionless parameter related to heat capacities of fluid and solid,

$$\gamma=\frac{A_L\rho_L c_{pL}}{A_L\rho_L c_{pL}+A_S\rho_S c_{pS}+A_W\rho_W c_{pW}} \quad (4)$$

where A is cross-section area, footnotes L, S and W are for fluid, solid and column wall, respectively.

Eqs. (1) and (3) are both partial differential equations. The definite conditions will be discussed later in the numerical scheme section.

2.2. Formulation of optimization problem

Generally, the efficiency of a binary SMB separation can be evaluated by several objectives, such as product purity, recovery, productivity, and solvent consumption, which may be affected by operating parameters in a contradicting way [22]. Due to the inherent complicity of an SMB process, there could be a variety of formulations of the multi-objective optimization [26]. In the case of