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Variation analysis of affinity-membrane model based on Freundlich adsorption

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Abstract

The variation analysis of membrane properties including membrane thickness and pore-size was carried out theoretically by using affinity-membrane model based upon the Freundlich adsorption equation. As the percentage variation of membrane thickness and distribution of pore-size increase, we find that (1) the time of total saturation is delayed; (2) the loading capacity at the point of breakthrough are decreased; (3) solute recovery efficiency and ligand utilization efficiency is decreased; (4) the thickness of unused membrane is increased. The results show that even small variations of thickness and distribution of pore size may severely degrade the membrane performance.

Keywords: Affinity-membrane; Freundlich adsorption; Breakthrough curve; Variation analysis

1. Introduction

Affinity chromatography has been an industrial standard method used to economically purify high-value biomolecules present at very low concentrations in complex biological fluids because of its simplicity and high degree of specificity [1]. Conventionally, affinity purification is carried out in columns packed with porous beads to which the affinity ligand is immobilized. However, the compressibility, slow mass transfer and adsorption kinetics of the traditional particle media for column chromatography have significantly limited their application in purification of bioproducts on a large scale [2]. In order to overcome these drawbacks, affinity-membrane chromatography, using porous structures with flat sheet and hollow fiber forms, introduces a different approach to exploit the biospecific interactions between a ligate and a ligand for biomedical applications. Affinity membranes are operated in convective mode, which can significantly reduce diffusion and pressure drop limitations commonly encountered in column chromatography [3,4]. In our previous work, polylysine-attached affinity membranes were prepared and were used to adsorb bilirubin from the bilirubin–phosphate solution and bilirubin–albumin solution [5–8]. The results showed that the polylysine-attached affinity membranes have a higher capacity for bilirubin. Currently, the affinity-membrane chromatography is well accepted as a powerful technology for separation and purification of biomolecules.

The optimization and scale-up of affinity-membrane operations in the recovery, separation and purification of biochemical components is of major industrial importance [9]. The development of mathematical models to describe affinity-membrane processes and the use of these models in computer programs to predict membrane performance are an engineering approach that can help to attain these bioprocess engineering tasks successfully [1,10]. However, in literature, very few models have been developed so far to describe the observed breakthrough behavior. The Thomas model [11], which involves Langmuir reaction kinetics as the rate-limiting step, has been used frequently to describe the process of affinity chromatography in a packed column. In membrane column affinity chromatography, the Thomas solution can be used when working with axial Peclet numbers greater than 40 and radial Peclet numbers smaller than 0.04, and good agreement is observed between experiments and theory, particularly in the early portion of the breakthrough

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curves. Tejeda-Mansir et al. [12] developed a method, which was based on the analytical solution of the Thomas model for frontal analysis in membrane column adsorption, for affinity-membrane column design. This method permits to find the operating conditions to reach 93.5% of the column capacity as operating capacity, using a sharpness restriction for the system breakthrough curve. Sridhar [13] proposed a model including convection, diffusion and rate kinetics, and used the model to analyze the design and operation of affinity-membrane bioseparations. The results obtained from model simulation showed that the breakthrough of the solute is significantly influenced by Peclet number, feed protein concentration, ligand number, Damkőhler number, membrane thickness and flow rate. Suen and Etzel [14] extended the affinity-membrane chromatography model to study extra-column effects in membrane systems. Their results showed that these effects are relevant for a proper description of performance in these types of separations. To evaluate nonlinear chromatographic performance, a multi-plate mathematical model for affinity-membrane was proposed through frontal analysis by Hao and Wang [15]. The main advantage of this model is that the parameters can be easily calculated from experimental data. Due to good correlation between it and the equilibrium-dispersive or Thomas models, this model can be used to obtain information about band-broadening effects such as dispersion and sorption effects.

The equilibrium adsorption of a solute on an affinity matrix based on the above models is often described simply by the Langmuir equation, with the assumption that single site, homogeneous interaction occurs between the solute and the ligand, and that nonspecific interactions promoted by the support are absent [9,16]. However, homogeneity is seldom true in practical cases, which has been shown in some of the recent works on affinity adsorption, ion-exchange adsorption and adsorption to polymer surface [17]. Recently, we developed a new affinity-membrane model based upon Freundlich equation [18]. The model was simulated by the experimental data of bilirubin adsorbed on affinity-membrane. The experimental and modeling results are in good agreement. This model can be used to describe the affinity-membrane processes in which the adsorption mechanism between ligand and ligate is Freundlich adsorption.

The key performance criteria for affinity-membrane processes are breakthrough curve sharpness and residence time at the adsorption stage [1]. In fact, not only the feed solute concentration, ligand number, Peclet number, membrane thickness and flow rate but also the nonuniformites in membrane thickness [19,20] and pore-size [20] may have significant effects on the breakthrough curve sharpness and residence time. In this paper, variation analysis of the membrane thickness and pore size is proposed to predict the effects of nonuniformites on membrane performance by using our affinity-membrane model [18].

2. Theoretical background

The assumptions of the Langmuir model are that surface is homogeneous, and adsorption energy is constant over all sites. In fact, as the adsorbent surface is often heterogeneous and/or interaction among adsorbed molecules cannot be neglected, the heat of adsorption varies with the surface coverage.

When adsorption between ligand and ligate can be described by kinetics equation of Freundlich, we propose the following model to predict the breakthrough behavior of affinity-membrane [18].

A mass balance over a section of the membrane gives the following continuity equation:

$$\varepsilon\frac{\partial c}{\partial t} + \varepsilon v\frac{\partial c}{\partial z} = \varepsilon D\frac{\partial^2 c}{\partial z^2} - (1-\varepsilon)\frac{\partial c_s}{\partial t} \tag{1}$$

The kinetics equation of Freundlich is

$$\frac{\partial c_s}{\partial t} = k_{a0}c\left(\frac{c_s}{c_1}\right)^{-b_1} - k_{d0}\left(\frac{c_s}{c_1}\right)^{b_2} \tag{2}$$

where c_1 is the total adsorbed capacity, c and c_s the solute concentration in the fluid phase and concentration of solute–ligand complex in the solid phase, ε the void porosity, D the axial diffusion coefficient, v the flow velocity of the solute through the membrane, and k_{a0} and k_{d0} are association and dissociation rate constants of Freundlich adsorption equation, respectively.

Initial conditions:

$$c = 0 \quad \text{at} \quad z \geq 0, t = 0 \tag{3}$$

$$c_s = 0 \quad \text{at} \quad z \geq 0, t = 0 \tag{4}$$

Boundary conditions:

$$\varepsilon vc - \varepsilon D\frac{\partial c}{\partial z} = \varepsilon vc_0 \quad \text{at} \quad z = 0, t > 0 \tag{5}$$

$$\frac{\partial c}{\partial z} = 0 \quad \text{at} \quad z = L, t > 0 \tag{6}$$

For convenience, Eqs. (1)–(6) can be converted to dimensionless groups as follows:

$$\frac{\partial C}{\partial \tau} + \frac{\partial C}{\partial \zeta} = \frac{1}{Pe}\frac{\partial^2 C}{\partial \zeta^2} - m\frac{\partial C_s}{\partial \tau} \tag{7}$$

$$\frac{\partial C_s}{\partial \tau} = \frac{n}{m}CC_s^{-b_1} - \frac{n}{m(r-1)}C_s^{b_2} \tag{8}$$

Initial conditions:

$$C = 0 \quad \text{at} \quad \zeta \geq 0, \tau = 0 \tag{9}$$

$$C_s = 0 \quad \text{at} \quad \zeta \geq 0, \tau = 0 \tag{10}$$

Boundary conditions:

$$C - \frac{1}{Pe}\frac{\partial C}{\partial \zeta} = 1 \quad \text{at} \quad \zeta = 0, \tau > 0 \tag{11}$$

$$\frac{\partial C}{\partial \zeta} = 0 \quad \text{at} \quad \zeta = 1, \tau > 0 \tag{12}$$

The definitions and physical meanings of the dimensionless parameters in Eqs. (7) and (8) are summarized in Table 1.

We used the finite-difference method to solve the Eqs. (7)–(12) for the model of affinity-membrane performance.