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Peak resolution in linear chromatography

Effects of intraparticle convection

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ABSTRACT

The quantitative relationship between separation performance and intraparticle convection in large-pore, permeable supports for chromatography is examined. A model for linear chromatography is used in the analysis for particles that contain both throughpores where diffusive and convective transport occur and purely diffusive micropores. The key concept is that of a convection-augmented intraparticle diffusivity, which depends only on the intraparticle Peclet number, λ. The separation performance is expressed in terms of both resolution and peak profiles at the column outlet. It is shown that, for given operating conditions, the separation enhancement obtained for intraparticle convection is dependent on the relative importance of throughpore and micropore diffusion rates. In the absence of micropore resistances, the resolution is always increased by intraparticle convection. The latter, however, is shown to have no effect on the separation performance when micropore diffusional resistances are dominant. Relationships necessary to assess the importance of these effects for linear chromatography conditions are provided.

INTRODUCTION

Permeable, large-pore materials are currently used as catalysts, adsorbents, supports for cell growth, membranes and HPLC packings [1]. Intraparticle transport of solutes in these materials is enhanced by pressure-driven intraparticle convection. As has been recognized since 1982, such an enhancement may be expressed in terms of a convection-augmented intraparticle diffusivity, $\tilde{D}_e$, defined as [2]

$$\tilde{D}_e = \frac{D_e}{f(\lambda)} = \frac{D_e}{\frac{3}{\lambda}\left(\frac{1}{\tanh \lambda} - \frac{1}{\lambda}\right)} \qquad (1)$$

where D_e is the intraparticle effective diffusion coefficient. The function $1/f(\lambda)$ represents the enhancement of intraparticle transport resulting from convection. It depends on the intraparticle Peclet number, which is defined as $\lambda = v_0 l / D_e$ for a slab-shaped pellet, where λ is the ratio of the characteristic times for diffusion of a solute, l^2/D_e, and for convection, l/v_0, in the pellet.

When the pellets are packed in a fixed bed, the intraparticle convective velocity, v_0, appearing in these equations may be estimated from Darcy's law, by equating the pressure drop per particle, $\Delta p/2l$ to the pressure drop per unit length of bed, $\Delta P/L$ [2,3]. The expression $v_0 = (B_p/\mu)(\Delta p/2l)$ is obtained for slab-shaped particles of thickness $2l$ and permeability B_p.

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Applications of such large-pore materials in chromatography have recently been introduced by Afeyan and co-workers [4,5] for the separation of macromolecules. They showed experimentally that, for such materials, the curve relating the height equivalent to a theoretical plate (HETP) (H) to the mobile phase velocity, u_0, approaches a plateau at sufficiently high values of u_0. They also provided a semi-theoretical explanation of the enhanced chromatographic performance seen with these materials, by assuming that diffusion and convection provide additive contributions to the rate of intraparticle transport of solutes. A more rigorous theoretical treatment later led Rodrigues et al. [1] to the definition of an extended Van Deemter equation that incorporates intraparticle convection effects in terms of the convection-augmented diffusivity concept. For a slab-shaped particle, their result reduces to

$$h = \frac{H}{2l} = A + \frac{B}{u_0} + Cf(\lambda)u_0 \qquad (2)$$

where A, B and C are the constants in the classical Van Deemter equation [6] and $f(\lambda)$ is the same function used in eqn. 1. Fig. 1 shows the various effects of intraparticle convection that are predicted by this treatment. The function $1/f(\lambda)$, representing the ratio of the convection-augmented diffusivity and the effective molecular diffusivity, is shown in Fig. 1a. This function approaches unity at low values of λ, when intraparticle diffusion is dominant, and $\lambda/3$ at high values of λ, when intraparticle transport is dominated by convection. In this limit, the augmented diffusivity $\tilde{D}_e$ becomes equal to $v_0 l/3$ and depends only on the ratio of the particle and bed hydraulic permeabilities for given operating conditions. Fig. 1b shows qualitatively how intraparticle convection affects band broadening. For a given mobile phase flow-rate and particle size, a large-pore support gives a sharper band, as intraparticle transport limitations are reduced by the onset of intraparticle convection. Fig. 1c shows qualitatively the effect of the mobile phase velocity on the HETP for a conventional support containing only purely diffusive pores and for a support containing convective throughpores. We see that whereas with non-permeable supports
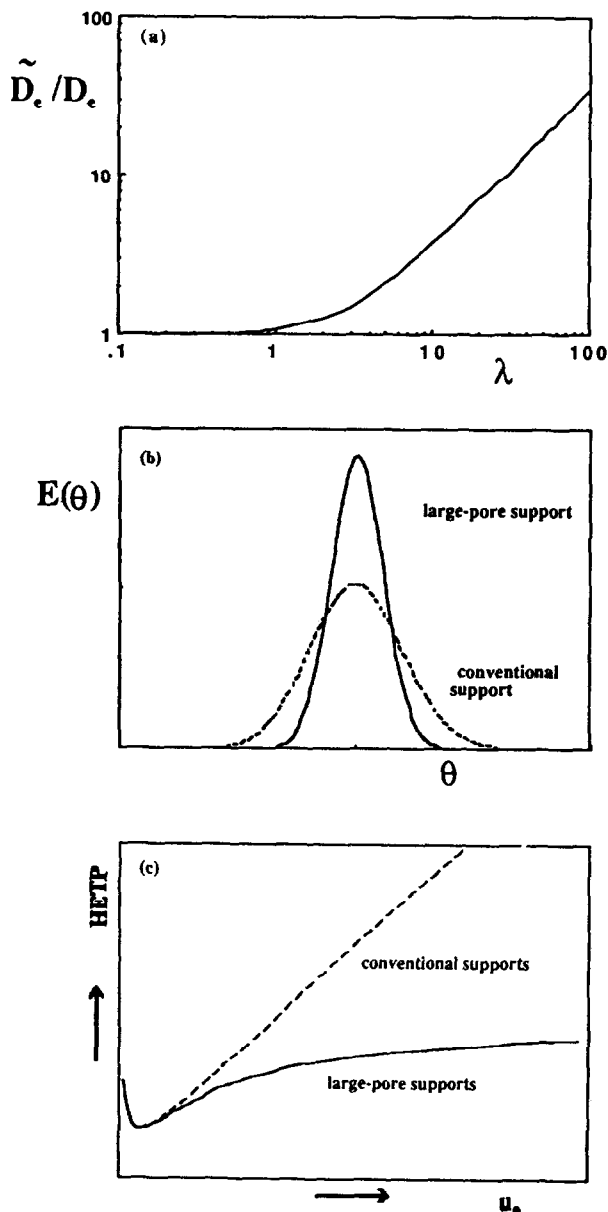

Fig. 1. Qualitative effects of intraparticle convection on (a) diffusivity, (b) peak sharpening and (c) HETP.

the HETP increases essentially linearly with increasing mobile phase velocity, a plateau is approached at high velocities with large-pore, permeable particles.

We should point out that intraparticle mass flux in permeable particles is the sum of diffusive and convective (viscous) fluxes, as both mass transport mechanisms act in parallel. This is in a

sense analogous to the coupling theory of Giddings [7] for the mobile phase contribution to the HETP. According to the coupling theory such contribution is $[(1/H_f) + (1/H_d)]^{-1}$ and comes from flow (H_f) and diffusional exchanges (H_d). At high flow-rates, diffusional exchanges are negligible and the contribution to the HETP is $H_f = 4\gamma R_p = A$ (eddy diffusivity term in the Van Deemter equation); at low velocities, flow exchanges become so slow that all velocity exchanges are caused by diffusion and the contribution to the HETP is $H_d = D_m/\omega R_p^2 u_0$. Therefore, one can say that convection and diffusion in the outer mobile phase also act in parallel to defeat concentration gradients outside particles; this was explained by Sie and Rijnders [8] in terms of the flow profile contribution for HETP. In the absence of intraparticle convection, eqn. 1 can be written as $H = (B/u_0) + A'u_0^n + Cu_0$ with $n = 1/3$ [9,10].

The analysis for slab-shaped particles of Rodrigues et al. [1] was extended to permeable spherical particles by Carta et al. [11]. These extensions, however, do not change the qualitative features predicted by the slab model, but only the magnitude of the effects. The effects of slow kinetics of adsorption and desorption and of diffusional limitations in non-convective micropores have also been addressed by Rodrigues et al. [12] and Carta and Rodrigues [13], respectively. Experimental evidence of these theoretically predicted effects has also been reported for different materials by Afeyan et al. [4], Lloyd and Warner [14], Frey et al. [15] and Carta et al. [11,16].

The objective of this paper is to explore through quantitative calculations the effects of intraparticle convection on peak resolution in linear chromatography. Models for particles containing both throughpores and purely diffusive micropores are considered in order to assess the relative importance of transport processes within the chromatographic particles.

THEORY

Models describing diffusive transport in adsorbent particles have been reviewed, e.g., by Ruthven [17]. Applications of such models to chromatography have recently been discussed by Golshan-Shirazi and Guiochon [18]. A model that is sufficiently general to describe diffusion within most porous particles is the "bidispersed pore model". In this model, the adsorbent particles are assumed to comprise an array of porous microparticles of radius r_c. These microparticles are, in turn, connected by a network of pores.

The bidispersed pore model was introduced by Carta and Rodrigues [13] for the analysis of intraparticle transport in permeable chromatographic media. In their analysis, intraparticle convection was assumed to occur only in the network of throughpores connecting the microparticles, while only diffusion was assumed to occur in the microparticle pores. The model equations are given in Table I for both spherical and slab-shaped pellets. The equations assume equilibrium between the fluid in the throughpores and the surface of the microparticles at each point in the pellet. The solution is obtained by means of the Laplace transform and the corresponding expressions for the transfer function of the chromatographic column, $G(s)$, the first moment, μ_i, and variance, σ_i^2, of the response peak for a pulse injection are given in Table II. It should be noted that, although the spherical geometry is in most instances a more accurate representation of commercial media, the model for slab-shaped pellets is much simpler. The results of this model, in fact, can be rendered analogous to those of the model for spherical particles in most instances with appropriate numerical factors [11,13].

The model parameters for slab-shaped pellets are as follows:

(a) Adsorption equilibrium parameter:

$$b_i = 1 + \frac{1 - \varepsilon_p}{\varepsilon_p} m_i$$

(b) Mobile phase Peclet number:

$$P_e = \frac{Lu_0}{\varepsilon_b D_{ax}}$$

(c) Intraparticle Peclet number:

$$\lambda_i = \frac{v_0 l}{D_{ei}}$$

TABLE I

MODEL EQUATIONS FOR SPHERICAL AND SLAB-SHAPED PELLETS WITH BIDISPERSE POROUS STRUCTURE

Structure	Spherical pellet	Slab-shaped pellet
Micropores	$D_c\left(\dfrac{\partial^2 q_i}{\partial r^2} + \dfrac{2}{r}\cdot\dfrac{\partial q_i}{\partial r}\right) = \dfrac{\partial q_i}{\partial t}$ $q_i(0, r) = 0$ $\dfrac{\partial q_i}{\partial r}(t, 0) = 0$ $q_i(t, r_c) = m_i c_i'$	Same as for spherical pellet
Throughpores	$D_e\left\{\dfrac{1}{R^2}\cdot\dfrac{\partial}{\partial R}\left(R^2\cdot\dfrac{\partial c_i'}{\partial R}\right) + \dfrac{1}{R^2}\cdot\dfrac{\partial}{\partial \mu}\left[(1-\mu^2)\dfrac{\partial c_i'}{\partial \mu}\right]\right\}$ $\quad - v_0\left[\mu\cdot\dfrac{\partial c_i'}{\partial R} + \dfrac{1-\mu^2}{R}\cdot\dfrac{\partial c_i'}{\partial \mu}\right]$ $\quad = \varepsilon_p\cdot\dfrac{\partial c_i'}{\partial t} + (1-\varepsilon_p)\dfrac{\partial\langle q_i\rangle}{\partial t}$ $c_i'(0, R) = 0$ $c_i'(t, 0) = \text{finite}$ $c_i'(t, R_p) = c_i$ $\langle q_i\rangle = \dfrac{3}{r_c^3}\displaystyle\int_0^{r_c} q_i r^2\, dr$	$D_e\cdot\dfrac{\partial^2 c_i'}{\partial z'^2} - v_0\cdot\dfrac{\partial c_i'}{\partial z'} = \varepsilon_p\cdot\dfrac{\partial c_i'}{\partial t} + (1-\varepsilon_p)\dfrac{\partial\langle q_i\rangle}{\partial t}$ $c_i'(0, z') = 0$ $c_i'(t, 0) = c_i$ $c_i'(t, 2l) = c_i$ $\langle q_i\rangle = \dfrac{3}{r_c^3}\displaystyle\int_0^{r_c} q_i r^2\, dr$
Bed fluid	$\varepsilon_b D_{ax}\cdot\dfrac{\partial^2 c_i}{\partial z^2} - u_0\cdot\dfrac{\partial c_i}{\partial z} = \varepsilon_b\cdot\dfrac{\partial c_i}{\partial t} + (1-\varepsilon_b)\dfrac{\partial\langle\!\langle q_i\rangle\!\rangle}{\partial t}$ $c_i(0, z) = 0$ $c_i(t, 0) = M\delta(t)$ $c_i(t, \infty) = \text{finite}$ $\langle\!\langle q_i\rangle\!\rangle = \dfrac{3}{2R_p^3}\displaystyle\int_{-1}^{1}\int_0^{R_p} R^2[\varepsilon_p c_i' + (1-\varepsilon_p)\langle q_i\rangle]\, dR\, d\mu$	Same as for spherical pellet with $\langle\!\langle q_i\rangle\!\rangle = \dfrac{1}{2l}\displaystyle\int_0^{2l} [\varepsilon_p c_i' + (1-\varepsilon_p)\langle q_i\rangle]\, dz$

(d) Number of transfer units for diffusion in the throughpores:

$$n_{ti} = \frac{\varepsilon_b L/u_0}{\varepsilon_p l^2/D_{ei}}$$

(e) Number of transfer units for diffusion in the microparticles:

$$n_{mi} = \frac{\varepsilon_b L/u_0}{r_c^2/D_{ci}}$$

The numbers of transfer units for diffusion are introduced in a manner analogous to that of Golshan-Shirazi and Guiochon [18]. The reciprocals of the two quantities n_t and n_m give the contributions to band broadening resulting from diffusion limitations in the throughpores and in the microparticles, respectively. Their ratio, $T = n_m/n_t$, is introduced to quantify the relative importance of the two contributions. The same parameters apply to the model for spherical

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TABLE II

TRANSFER FUNCTION AND MOMENTS OF THE RESPONSE PEAK

Parameter	Spherical pellet	Slab-shaped pellet
Bed transfer function	$G(s) = \exp\left\{\frac{Pe}{2}\left[1 - \sqrt{1 + 4 \cdot \frac{N(s)}{Pe}}\right]\right\}$	$G(s) = \exp\left\{\frac{Pe}{2}\left[1 - \sqrt{1 + 4 \cdot \frac{N(s)}{Pe}}\right]\right\}$
	$N(s) = s\left[1 + \frac{1 - \varepsilon_b}{\varepsilon_b} \cdot \varepsilon_p g_a(s)\right]$	$N(s) = s\left[1 + \frac{1 - \varepsilon_b}{\varepsilon_b} \cdot \varepsilon_p g_a(s)\right]$
	$g_a(s) = \frac{3\pi}{4\lambda s/n_t} \sum_{m=0}^{\infty} (-1)^m (2m+1) I_{m+1/2}(\lambda)$	$g_a(s) = \frac{r_1 - r_2}{2s/n_t} \cdot \frac{(1 - e^{2r_2})(e^{2r_1} - 1)}{e^{2r_1} - e^{2r_2}}$
	$\left[\beta \cdot \frac{I_{m+3/2}(\beta)}{I_{m+1/2}(\beta)} - \lambda \cdot \frac{I_{m+3/2}(\lambda)}{I_{m+1/2}(\lambda)}\right]$	$r_1, r_2 = \frac{\lambda}{2} \pm \sqrt{\frac{\lambda^2}{4} + s/n_t\left(1 + \frac{1 - \varepsilon_p}{\varepsilon_p} \cdot m_i f(\sqrt{s/n_m})\right)}$
	$\beta = \sqrt{\lambda^2 + s/n_t\left(1 + \frac{1 - \varepsilon_p}{\varepsilon_p} \cdot m_i f(\sqrt{s/n_m})\right)}$	$f(\sqrt{s/n_m}) = \frac{3}{\sqrt{s/n_m}}\left(\coth\sqrt{s/n_m} - \frac{1}{\sqrt{s/n_m}}\right)$
	$f(\sqrt{s/n_m}) = \frac{3}{\sqrt{s/n_m}}\left(\coth\sqrt{s/n_m} - \frac{1}{\sqrt{s/n_m}}\right)$	
First moment and variance of chromatographic peaks	$\mu_i = 1 + \frac{1 - \varepsilon_b}{\varepsilon_b} \cdot \varepsilon_p b_i$	$\mu_i = 1 + \frac{1 - \varepsilon_b}{\varepsilon_b} \cdot \varepsilon_p b_i$
	$\sigma_i^2 = \frac{2}{Pe} \cdot \mu_i^2 + \frac{2}{15} \cdot \varepsilon_p \cdot \frac{1 - \varepsilon_b}{\varepsilon_b} \cdot \frac{b_i^2}{n_t}\left[f(\lambda/3) + \frac{b_i - 1}{b_i^2 T}\right]$	$\sigma_i^2 = \frac{2}{Pe} \cdot \mu_i^2 + \frac{2}{3} \cdot \varepsilon_p \cdot \frac{1 - \varepsilon_b}{\varepsilon_b} \cdot \frac{b_i^2}{n_t}\left[f(\lambda) + \frac{b_i - 1}{5b_i^2 T}\right]$
	$f(\lambda) = \frac{3}{\lambda}\left(\frac{1}{\tanh\lambda} - \frac{1}{\lambda}\right)$	$f(\lambda) = \frac{3}{\lambda}\left(\frac{1}{\tanh\lambda} - \frac{1}{\lambda}\right)$

particles, simply by replacing the pellet half-thickness l with the pellet radius R_p.

When micropore diffusional resistance is negligible ($T = \infty$), the bidispersed model reduces to a simpler model where only throughpores are considered [1].

PEAK RESOLUTION AND BAND PROFILES

The resolution between the chromatographic peaks for two components 1 and 2 can be defined as [19]

$$R_s = \frac{\mu_2 - \mu_1}{2(\sigma_1 + \sigma_2)} \quad (14)$$

Following, for example, Giddings [19], unit resolution ($R_s = 1$) corresponds to an almost

complete separation and is adequate for most analytical purposes.

The resolution is obtained directly from the expressions for the first moment and variance given in Table II for particles with a bidispersed pore structure. Calculated values of R_s are given in Fig. 2 as a function of the intraparticle Peclet number, λ, for different values of the parameter T. These calculations were carried out with a value of $n_t = 100$. Such a value is representative of conditions that might be encountered in the HPLC of proteins. For a protein with an effective throughpore diffusivity $D_e = 1 \cdot 10^{-7}$ cm^2/s, using bed and particle porosities $\varepsilon_b = 0.3$ and $\varepsilon_p = 0.5$, respectively, and 10-μm particles in a 20-cm long chromatographic bed, the value $n_t = 100$ corresponds to a mobile phase velocity of ca.
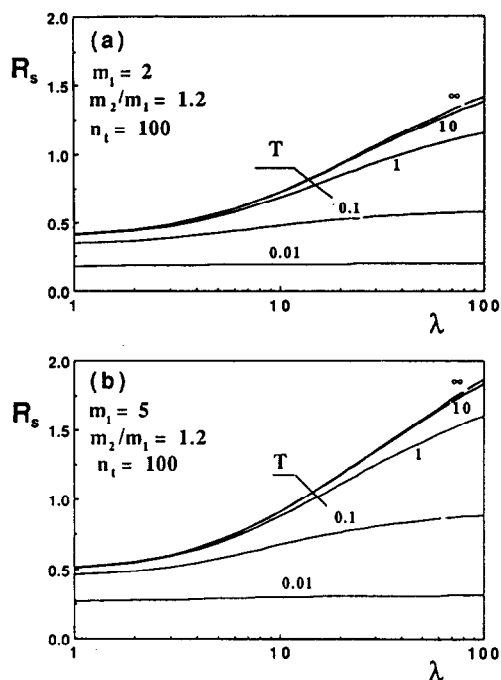
Fig. 2. Effect of the relative importance of micropore and throughpore diffusion rates, measured by T, on the R_s versus λ curves. (a) $m_1 = 2$, $m_2/m_1 = 1.2$, $n_t = 100$; (b) $m_1 = 5$, $m_2/m_1 = 1.2$, $n_t = 100$.

3 cm/min. The value of T depends on the relative size of the protein and of the micropores. For small pores, when restricted or hindered diffusion occurs, values of T much smaller than unity could be found. The selectivity value chosen for these calculations was $m_2/m_1 = 1.2$ while the distribution coefficient for the least retained species was $m_1 = 2$ in Fig. 2a and $m_1 = 5$ in Fig. 2b.

For simplicity, the calculations were carried out assuming that $\lambda_1 = \lambda_2 = \lambda$ and $n_{t1} = n_{t2} = n_t$. This is a reasonable assumption for the separation of two closely related species whose diffusivities are likely to be nearly the same. The values of the remaining model parameters were taken to be $Pe = 10\,000$, $\varepsilon_b = 0.3$ and $\varepsilon_p = 0.5$.

In both instances, when $T \leqslant 0.01$ the resolution is unaffected by the values of λ. In this instance, in fact, the separation performance is controlled by the micropore diffusional resistance. Conversely, for values of $T \geqslant 10$, the resistance to mass transfer in the micropores is unimportant, and the process is dominated by

transport in the throughpores. For these conditions, as seen previously, at low λ values diffusion in the throughpores is dominant, whereas at high λ values intraparticle convection becomes dominant. Hence R_s varies between two limits, one for low λ where throughpore diffusion controls and the other for high λ where intraparticle resistances are eliminated and equilibrium along with flow and geometric factors control the separation performance. When $T \rightarrow \infty$, in the limit of high λ values, R_s approaches a horizontal asymptote with a value given by

$$R_s = \sqrt{\frac{Pe}{2}} \cdot \frac{\dfrac{1 - \varepsilon_b}{\varepsilon_b} \cdot \varepsilon_p (b_2 - b_1)}{2 + \dfrac{1 - \varepsilon_b}{\varepsilon_b} \cdot \varepsilon_p (b_1 + b_2)}$$

A different asymptotic value is obtained, however, when T is finite. Qualitatively similar results would be obtained for spherical particles, as shown by Carta and Rodrigues [13].
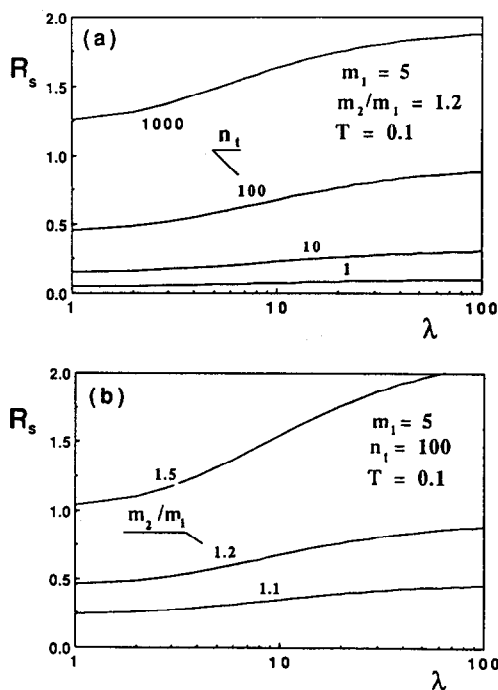
Fig. 3 shows the resolution as a function of λ

Fig. 3. Effect of (a) n_t, mass transfer units for diffusion in the throughpores (with $m_2/m_1 = 1.2$), and (b) m_2/m_1, the ratio of the adsorption equilibrium isotherm slopes of the two components (with $n_t = 100$), on the R_s versus λ curves. $m_1 = 5$, $T = 0.1$.

for an intermediate value of $T = 0.1$ with $m_1 = 5$. The effect of the number of transfer units for diffusion in the throughpores, n_t, is shown in Fig. 3a for $m_2/m_1 = 1.2$. It is seen that the enhancement of resolution by intraparticle convection is more significant when n_t is high. This happens because in these calculations $T = n_m/n_t$ has been kept constant. Thus, as n_t is reduced by a certain proportion, so is n_m in the same proportion. Lower values of n_m imply a greater contribution of the micropore diffusional resistance to the overall transport rate, thereby reduc-

ing the effects of convection in the throughpores. The effect of the equilibrium selectivity ratio, m_2/m_1, is shown in Fig. 3b for a constant value of $n_t = 100$. The resolution is increased as m_2/m_1 is increased. Similarly, R_s becomes larger as λ is increased, approaching a horizontal asymptote whose value is dependent on the ratio m_2/m_1 when λ is very large.

The effects of intraparticle convection on the peak profiles at the exit of a chromatographic column are shown in Figs. 4–6 for slab-shaped pellets with a bidispersed pore structure. The
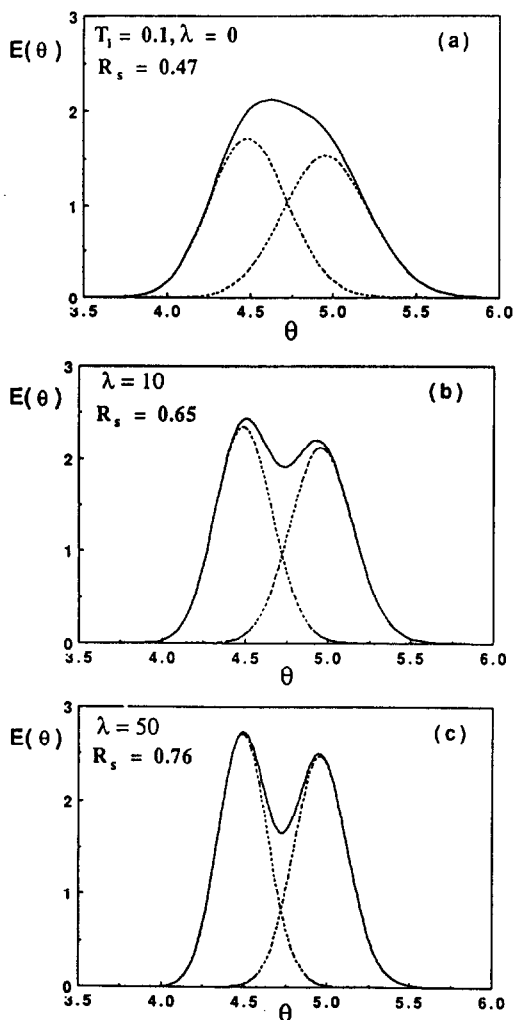

Fig. 4. Chromatographic response to a pulse input of two components. $Pe = 10\,000$; $m_1 = 2$; $m_2/m_1 = 1.2$; $n_t = 200$; bidisperse particles. Effect of intraparticle convection on peak resolution when micropore mass transfer resistances cannot be neglected ($T = 0.1$).
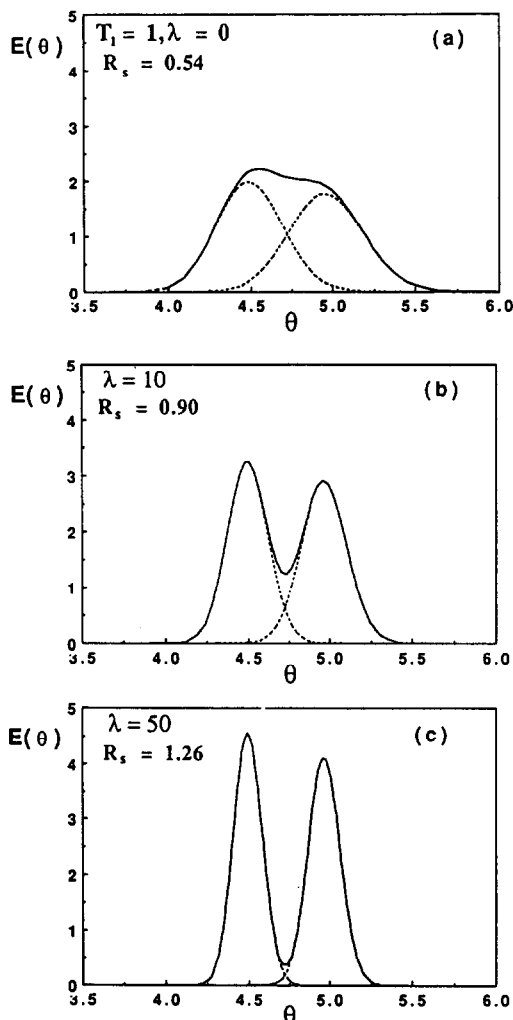
Fig. 5. Chromatographic response to a pulse input of two components. $Pe = 10\,000$; $m_1 = 2$; $m_2/m_1 = 1.2$; $n_t = 200$; bidisperse particles. Effect of intraparticle convection on peak resolution when micropore and throughpore resistances are comparable ($T = 1.0$).
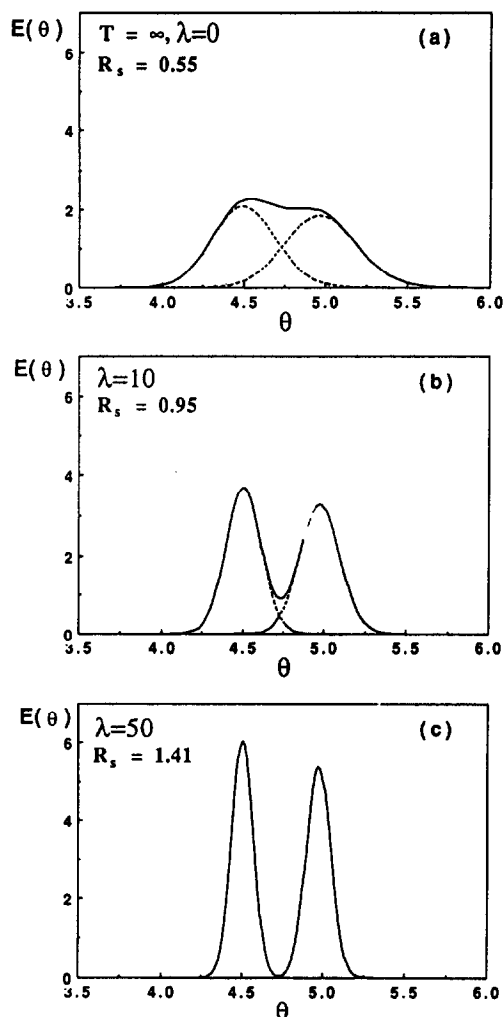
Fig. 6. Chromatographic response to a pulse input. $Pe = 10\,000$; $m_1 = 2$; $m_2/m_1 = 1.2$; $n_t = 200$; particles containing only throughpores $(T = \infty)$. Effects of intraparticle convection.

peak profiles are obtained from the numerical inversion of the transfer function for the bed given in Table II. The numerical inversion was obtained with a fast Fourier transform algorithm. For all three cases considered, the values $Pe = 10\,000$, $m_1 = 2$, $m_2/m_1 = 1.2$ and $n_t = 200$ were used as representative of the HPLC of macromolecules such as proteins. Different levels of micropore diffusional resistance are, however, considered.

Fig. 4 shows the effect of λ when $T = 0.1$, i.e., $n_m = 20$. For these conditions, the micropore resistance is significant and only a small improve-

ment in the resolution from $R_s = 0.47$ to 0.76 is obtained when λ is increased from 0 to 50. However, when T is increased to 1 ($n_m = 200$), as in Fig. 5, a much more pronounced effect of λ is seen. In this instance, the micropore diffusional resistance becomes unimportant and R_s increases from 0.54 to 1.26 when λ is changed from 0 to 50, when an almost complete separation is obtained.

For comparison, Fig. 6 shows the calculated profiles obtained for different λ values when micropore diffusion is neglected, i.e., $T \rightarrow \infty$. The profiles in this instance were computed from the solution of Rodrigues et al. [1] for a pellet containing only throughpores. A greater resolution is obtained for each value of λ and a baseline separation is realized when $\lambda = 50$.

CONCLUSIONS

Large-pore, permeable supports have been shown to be promising in many applications, because in these materials intraparticle convection can reduce the overall transport resistance. The quantitative relationship between intraparticle flow and resolution in linear chromatography with such particles was examined in this paper. Two models were used: in the first, it is assumed that the particles contain only throughpores in which diffusion and convection occur simultaneously $(T = \infty)$; in the second, the particles are assumed to compromise a bidispersed pore network with a microporous structure intercalated by throughpores. Only diffusion is assumed to occur in the micropores, while convection is accounted for in the throughpores.

When only the throughpores are considered, the onset of intraparticle convection improves the separation performance by enhancing the overall transport rate; accordingly, the resolution of two adjacent components is increased. For conditions which are representative of the HPLC of macromolecules, simulations carried out with this model show that starting with two non-separated peaks, for given equilibrium and flow characteristics, as the intraparticle convection is increased the separation is gradually improved and the two components become completely separated. This is also possible for conditions representative of gas chromatographic separa-

tions, but higher values of the intraparticle convection coefficient λ would be required.

When the bidispersed model is used to simulate the chromatographic behaviour, two limiting situations can occur. In the first, the mass transfer resistance is dominated by transport within the throughpores, whereas in the second the mass transfer resistance is dominated by the micropores. In the former instance, the onset of intraparticle convection leads to an improved resolution, as mass transfer resistances are reduced. In the latter instance, intraparticle convection has no effect on resolution, which is entirely determined by the diffusional resistance in the micropores. In other situations between these two limits, intraparticle convection can increase the resolution to an extent that depends upon the relative magnitude of the T ratio and the adsorption capacity.

The possibility of kinetic limitations resulting from a finite rate of adsorption at the microparticle surface should, of course, also be considered [12,20], especially when dealing with affinity chromatographic systems. However, when the rate of adsorption and desorption is not limiting, it is apparent that a key to the successful exploitation of intraparticle convection effects is that micropore transport resistances must be minimized. The equations given in this paper provide the quantitative relationship between chromatographic performance and intraparticle flow, and can be used in assessing the relative importance of diffusional resistances for the optimum design of permeable media for chromatography. Numerical inversion of the expressions provided for the bed transfer function in the Laplace domain can be used to obtain a prediction of peak histories for different values of the intraparticle convection velocity.

ACKNOWLEDGEMENTS

SYMBOLS

b_i parameter [$=1 + (1 - \varepsilon_p)m_i/\varepsilon_p$]

B_p particle permeability, cm^2

c_i species concentration in the bulk fluid phase, mol/cm^3

c'_i species concentration in the macropore fluid, mol/cm^3

D_{ax} axial dispersion coefficient, cm^2/s

D_{ei} effective diffusivity of species i in macropore, cm^2/s

D_{ci} effective diffusivity in micropore, cm^2/s

D_m molecular diffusivity, cm^2/s

$\tilde{D}_e$ "apparent" effective diffusivity in macropore, cm^2/s

$E(\theta)$ normalized response of the chromatographic column to a pulse input

H_d diffusion term in the mobile phase contribution to the HETP, cm

H_f flow term in the mobile phase contribution to the HETP, cm

H height equivalent to a theoretical plate (HETP), cm

l half-thickness of the slab, cm

L bed length, cm

M strength of the impulse, mol s/cm^3.

m_i slope of the adsorption isotherm of species i

n_m mass transfer units for diffusion in micropores $\left(\dfrac{D_c}{r_c^2} \cdot \dfrac{\varepsilon_b L}{u_0} \right)$

n_t mass transfer units for diffusion in throughpores $\left(\dfrac{D_e}{\varepsilon_p R_p^2} \cdot \dfrac{\varepsilon_b L}{u_0} \text{ or } \dfrac{D_e}{\varepsilon_p l^2} \cdot \dfrac{\varepsilon_b L}{u_0} \right)$

Pe bed Peclet number $\left(\dfrac{L u_0}{\varepsilon_b D_{ax}} \right)$

Δp pressure drop across the particle, Pa

ΔP pressure drop across the bed, Pa

q_i micropore concentration of species i

$\langle q_i \rangle$ average concentration in micropore of species i, mol/cm^3

$\langle\!\langle q_i \rangle\!\rangle$ average concentration inside the particle of species i, mol/cm^3

R radius coordinate for the particle, cm

R_p particle radius, cm

R_s resolution

r_c micropore radius, cm

s Laplace variable

T parameter (n_m/n_t)

t time, s

u_0 bed superficial velocity, cm/s

v_0 intraparticle convective velocity, cm/s

z axial coordinate for the bed, cm

z' axial coordinate for the particle, cm

Greek letters

ε_b	bed porosity
ε_p	intraparticle porosity
γ	constant in the A term of the Van Deemter equation
λ_i	intraparticle Peclet number ($v_0 R_p / D_{ei}$ or $v_0 l / D_{ei}$)
μ_i	first moment of the impulse response for species i
σ_i^2	variance for species i
τ	space time ($\varepsilon_b L / u_0$), s
θ	reduced time (t/τ)
ω	constant in the H_d contribution

Subscript

i	species

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