Numerical modeling of the elution peak profiles of retained solutes in supercritical fluid chromatography

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In supercritical fluid chromatography (SFC), the significant expansion of the mobile phase along the column causes the formation of axial and radial gradients of temperature. Due to these gradients, the mobile phase density, its viscosity, its velocity, its diffusion coefficients, etc. are not constant throughout the column. This results in a nonuniform flow velocity distribution, itself causing a loss of column efficiency in certain cases, even at low flow rates, as they do in HPLC. At high flow rates, an important deformation of the elution profiles of the sample components may occur. The model previously used to account satisfactorily for the retention of an unsorbed solute in SFC is applied to the modeling of the elution peak profiles of retained compounds. The numerical solution of the combined heat and mass balance equations provides the temperature and the pressure profiles inside the column and values of the retention time and the band profiles of retained compounds that are in excellent agreement with independent experimental data for large value of mobile phase reduced density. At low reduced densities, the band profiles can strongly depend on the column axial distribution of porosity.

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1. Introduction

Supercritical fluid chromatography (SFC) is considered as a "green" alternative to classical liquid chromatography due to its use of a mobile phase based on high-density CO_2. Even though organic solvents must often be added to CO_2 as modifiers, their required concentrations are lower than in HPLC. Other advantages of SFC are the possibility of an easy adjustment of the solvent properties by changing the operating pressure and the temperature. The efficiency of a column in SFC, compared to that of a similar system used in classical HPLC, is generally higher, due to lower mass transfer resistances. For these reasons SFC often permits the achievement of faster and more efficient separations than HPLC.

The desire to decrease the separation times of mixtures leads to increases in the mobile phase flow rate. This means that the columns must be run with a high pressure gradient. A large pressure drop along a column is not desirable because the temperature of the mobile phase decreases when it expands. Then, the mobile phase tends to absorb heat from the air outside the column. As a result, axial and radial temperature gradients form inside the column.

These temperature gradients cause corresponding axial and radial gradients of all the physico-chemical parameters. The phenomena observed in the SFC column are similar to those encountered in ultra high pressure liquid chromatography (UHPLC). For large back pressures (e.g., 500 bar and more in UHPLC and several dozen bars in SFC) the deformations of the peak shapes are similar – compare the experimental peak profiles in [1,2]. The difference is that in UHPLC the heat is generated inside the column due to viscous friction whereas in SFC the heat is absorbed from the column surroundings. As a result, the gradients of physico-chemical parameters are in the opposite direction in both versions of chromatography [3,4]. The other important difference is that the axial and the radial mobile phase density gradients are much greater in the case of SFC. Because the density has a crucial impact on the adsorption isotherm in SFC, the density gradients can have a significant impact on retention and efficiency.

Most SFC separations are performed using outlet pressures around 150 bar. The peak deformations noted above, however, are generally important only when columns are operated at temperatures and pressures slightly above the critical conditions, at outlet pressures below about 130 bar, temperatures up to about 100 °C, and reduced densities close to 1.0. These conditions tend to be accompanied by excess efficiency losses and are typically avoided in general practice [5]. This is unfortunate because the mass transport properties of carbon dioxide under these conditions

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favor faster, more efficient separations. Attempts to model chromatographic behavior under these conditions have thus far been unsuccessful [6,7]. A model that is valid over the entire range of potentially useful conditions in SFC could be beneficial by providing a basis for exploiting these conditions. The work presented in this paper addresses this serious deficiency by presenting an accurate model that satisfactorily describes chromatographic behavior under these severe conditions.

Due to the similarity of the physical phenomena taking place in SFC, the method developed for modeling the UHPLC peak profiles can be used also for modeling those in SFC. We previously developed and validated a model combining the heat and the mass balance equations of UHPLC columns, an isotherm model for the solute, and the equation accounting for flow in porous media [8,9]. This model accurately predicts analyte retention factors, their elution band profiles, and the dependence of the column efficiency on the mobile phase velocity. On the basis of this model described in the first part of our earlier paper [4], a general SFC model coupling the heat and the mass balance equations with an appropriate equation of state was proposed. The numerical solution of the generalized ED model coupled with the calculated temperature and pressure distributions enabled excellent forecasts of the retention times and efficiency for the elution of an unsorbed solute [4].

The goal of this work was to adapt and validate this model for retained solutes. We restricted our investigation to analytical scale of SFC. A new version of this model which enables analyses of the impact of the axial porosities distributions on the temperature, the flow rate and the concentration band profiles is proposed. To validate this model, we first compared the temperature recorded along the column wall and the pressure drop along the column with those calculated with our model. The agreement is excellent. Afterwards we compare the simulated peaks profiles for several retained and unretained solutes, for average carbon dioxide reduced density (RD) equal to 1.5 and 1.0. In the first case a good agreement between the experimental results and the calculated ones was obtained. In the second case the agreement is good at very low and very high flow rates. However, at medium mobile phase flow rates, some discrepancies between theory and experiments are observed.

2. Mathematical models

The mathematical model of SFC applied in this paper is very similar to that used in the first part of our earlier work [4]. The SFC model combines three separate models: (1) a model of heat transfer; (2) a model of mass transfer; and (3) a model of mobile phase velocity distribution. The heat transfer model is exactly the same as in previous paper [4] and will not being discussed here. The second model accounts for the propagation of a solute band along a column in which there are gradients of temperature, viscosity, velocity, density. It also includes other parameters, ignored previously, which can change along the column or in the radial direction, namely the packing heterogeneity. We apply our mass balance model on columns in which there is a gradient of packing density or in other words a gradient of external porosity. The existence of axial packing density gradients was mentioned by Wong et al. [10]. These authors found that the external porosity decreases along the column. The existence of a radial packing heterogeneity follows from experiments that point out a radial distribution of the flow rate obtained at low mobile phase velocity [11], that is for flow rates for which viscous friction heat effects could be neglected.

The mass transfer model was coupled with an isotherm model, the equilibrium constants of which depend on the local temperature and the mobile phase density.

The assumption of a bed heterogeneity forces modifications of the third model previously used, which accounts for the

distribution of the mobile phase velocity. In this work, we assumed that the flow rate depends on the local temperature, the pressure, the viscosity and the density of the mobile phase as well as on the bed porosity.

2.1. The mass balance equation

In writing the mass balance for an analyte, we assumed that the contributions to band broadening due to the finite mass transfer resistances and to the axial dispersion can be lumped into an apparent dispersion coefficient. We assumed that this coefficient can be evaluated using formulae developed in [9,12] and used in [4], in spite of the fact that the porosity is a function of the position inside the column. It should be also remembered that axial dispersion, radial dispersion and the velocity are functions of the position inside the column. Under this assumption, the mass balance equation is an extension of the equilibrium-dispersive (ED) model [4,13].

The mass balance equation of the generalized ED model is written as follows:

$$\frac{\partial C_A}{\partial t} + F\frac{\partial q_A}{\partial t} + \frac{1}{\varepsilon_t}\frac{\partial(uC_A)}{\partial z} = -\frac{\partial}{\partial z}(J_z) - \frac{1}{r}\frac{\partial}{\partial r}(rJ_r) \qquad (1)$$

where the axial and the radial components of the mass flux are

$$J_z = -D_{z,a}\frac{\partial C_A}{\partial z} \qquad (2)$$

$$J_r = -D_{r,a}\frac{\partial C_A}{\partial r} \qquad (3)$$

The C_A and q_A are the analyte concentrations in the mobile and stationary phases at equilibrium (g/L), respectively, t is the time, z is the axial coordinate, u is the axial superficial mobile phase velocity, $D_{z,a}$ and $D_{r,a}$ are the local axial and radial apparent dispersion coefficients (m²/s), respectively, $F = (1 - \varepsilon_t)/\varepsilon_t$ is the phase ratio and ε_t is the total porosity of the column, which can be a function of the axial and the radial positions. In the model, the convective mass transfer in the radial direction was neglected – the numerical experiments proved that it has no influence on the concentration band profiles.

The dispersion terms in Eqs. (2) and (3) follow from Fick's first law, namely the diffusion flux in Fick's law as depicted by the expression:

$$J = -D_m\nabla C_A \qquad (4)$$

It would be more theoretically justified to express the diffusion flux by the mass fraction [14]:

$$J = -D_m\rho\nabla\left(\frac{C_A}{\rho}\right) \qquad (5)$$

where D_m is the molecular diffusion coefficient and ρ is the fluid density. However, the differences between the peak profiles calculated with the first and the second equations were marginal in our case, so in the following, we refer the dispersion terms to the concentration C_A.

The apparent axial dispersion coefficient was calculated from the following equation [4]:

$$D_{z,a} = \frac{D_L\varepsilon_e}{\varepsilon_t} + \left(\frac{k_1}{1+k_1}\right)^2\frac{u^2 d_p}{\varepsilon_t\varepsilon_e F_e 6}\left[\frac{d_p}{10D_{\text{eff}}} + \frac{1}{k_{\text{ext}}}\right] \qquad (6)$$

where

$$k_1 = F_e\left(\varepsilon_p + (1-\varepsilon_p)\frac{\delta q_A}{\delta C_A}\right); \quad F_e = \frac{1-\varepsilon_e}{\varepsilon_e}; \quad D_{\text{eff}} = \frac{D_m\varepsilon_p}{\tau} \qquad (7)$$

and D_L is the axial dispersion coefficient, d_p is adsorbent diameter, D_{eff} is effective particle diffusivity, ε_e is the external porosity, which can depend on the position inside column, ε_p is the particle