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Modeling of closed-loop recycling liquid–liquid chromatography: Analytical solutions and model analysis

Artak E. Kostanyan*

Kurnakov Institute of General & Inorganic Chemistry, Russian Academy of Sciences, Leninsky Prospekt 31, Moscow 119991, Russia

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ABSTRACT

In closed-loop recycling (CLR) chromatography, the effluent from the outlet of a column is directly returned into the column through the sample feed line and continuously recycled until the required separation is reached. To select optimal operating conditions for the separation of a given feed mixture, an appropriate mathematical description of the process is required. This work is concerned with the analysis of models for the CLR separations. Due to the effect of counteracting mechanisms on separation of solutes, analytical solutions of the models could be helpful to understand and optimize chromatographic processes. The objective of this work was to develop analytical expressions to describe the CLR counter-current (liquid–liquid) chromatography (CCC). The equilibrium dispersion and cell models were used to describe the transport and separation of solutes inside a CLR CCC column. The Laplace transformation is applied to solve the model equations. Several possible CLR chromatography methods for the binary and complex mixture separations are simulated.

1. Introduction

The most simple way to improve separation efficiency of chromatograpic processes for a given two-phase solvent system, when compounds with close values of the partition coefficient are to be separated, is to increase the length of the column. In counter-current chromatography (CCC), this can be achieved by using multilayer coils connected in series [1,2]. However, the increasing of column length is sometimes limited by the increasing inlet pressure. The mobility of both phases in CCC allows the implementing of cyclic dual-mode counter-current processes, in which the CCC separation consists of a succession of two isocratic counter-current steps and is carried out in series alternating between normal phase and reversed phase operation, each phase eluting alternately through the opposite ends of the column [3–14]. The sample is fed at the beginning [8,10–14] or into the middle section [3–7] of a column and moves forward and back with the phases inside the column. This shuttle movement of the sample actually corresponds to an increase in length of the column, which requires no increase in the column inlet pressure. Another approach to simulate the lengthening of the column, which is not associated with an increase in inlet pressure, consists of recycling the sample several times over the column. The main advantages of the recycling chromatography are considerable solvent saving, since the separation takes place in the enclosed volume, and better peak resolution. The closed-loop recycling (CLR) gas chromatography has been known since 1959 [15]. Since then, various recycling chromatography methods have been suggested and investigated [16–23]. The first applications of the recycling principle in CCC were reported in [24,25]. The recycling CCC was successfully implemented for isolation of natural products [26–31]. In this paper, we will consider closed-loop isocratic recycling liquid–liquid chromatography.

For simulation and optimal design of CLR liquid–liquid chromatography, an appropriate theory is needed. The process can be described on the bases of continuous-diffusion or discrete (staged)-cell models. Simulations of chromatographic separations based on discrete and continuous models give identical results, supposed correct relationship between model parameters is used. Theoretical approaches for the CLR solid–liquid chromatography, based on the continuous equilibrium dispersion model, were proposed and analyzed by numerical calculations [16,19].

This paper is devoted to the further development of the theory of CLR liquid–liquid chromatography with a view to derive an analytical description of such processes of chromatographic separation.

2. Mathematical description of the closed-loop recycling counter-current chromatography

To describe the transport and separation of solutes inside a CLR liquid–liquid chromatographic column, we will first build on the

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* Tel.: +7 4959554834; fax: +7 4959554834.
E-mail address: kost@igic.ras.ru

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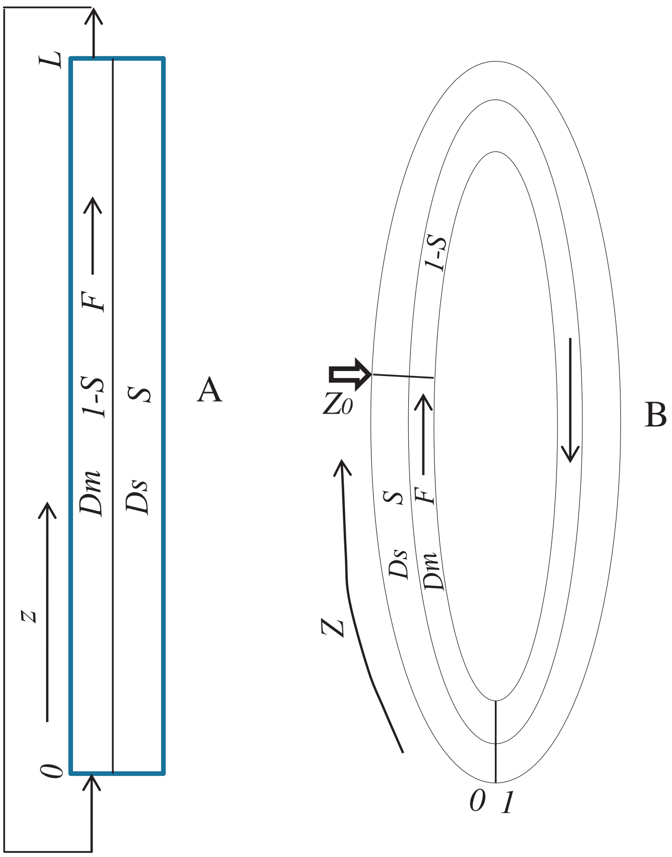

Fig. 1. Schematic diagram of the CLR CCC (A) and the applied mathematical model (B).

ideal recycling equilibrium-dispersive (IRED) model: the column outlet is connected to the column inlet; the effects caused by the pump and connecting lines are neglected [16,19]. This model was proposed to describe the CLR solid–liquid chromatography. It is also applicable to CLR liquid–liquid chromatography. Analytical solutions presented for the first time in this paper may also be useful in the analysis of CLR solid–liquid chromatography.

In classical chromatography, a solute is transported along the column only with the mobile phase and remains longitudinally motionless in the stationary phase. In CCC, both liquids undergo intense mixing, and the axial mixing in the stationary phase can considerably contribute to band broadening. The diffusion model under consideration takes into account the rate of axial mixing in both phases in terms of effective longitudinal diffusion coefficients (D_m – in the mobile phase, D_s – in stationary phase).

As applied to CCC, the following propositions of the IRED theory can be postulated (Fig. 1):

(1) The system is closed, the column outlet is connected with the column inlet, so that at both points the concentrations are identical.
(2) The concentrations in the mobile and stationary phases are in equilibrium at any cross section of the column.
(3) The retained volume of stationary phase is constant at any cross section of the column.
(4) The phenomena of axial mixing (D_m – in the mobile phase, D_s – in stationary phase) and interphase mass transfer that cause band broadening can be described by a single dispersion parameter.

Under these assumptions, and according to Fig. 1, the mass balance equation and boundary conditions are given as follows:

$$A_c(1-S)\frac{\partial x}{\partial \tau} + A_c S\frac{\partial y}{\partial \tau} = A_c(1-S)D_m\frac{\partial^2 x}{\partial z^2} + A_c S D_s\frac{\partial^2 y}{\partial z^2} - F\frac{\partial x}{\partial z} \qquad (1)$$

$$A_c(1-S)\int_0^L x(z,\tau)dz + A_c S\int_0^L y(z,\tau)dz = Q \qquad (2)$$

$$x(0,\tau) = x(L,\tau) \qquad (3)$$

where A_c is the column cross-section; F is the volumetric flow rate of the mobile phase; L is the length of the column; $S = \frac{V_s}{V_s+V_m} = \frac{V_s}{V_c}$ is the fractional volume of the stationary phase, V_m and V_s are the volumes of mobile and stationary phases in the column, respectively, and $V_c = V_s + V_m$ is the column volume; z is the coordinate along the perimeter of the circulating loop; $\boldsymbol{x}$ and $\boldsymbol{y}$ are solute concentrations in mobile and stationary phases, respectively; Q is the amount of the solute in the sample injected; τ is the time.

The boundary condition (3) corresponds to the assumption (1) and is identical to that considered in [16,19], while the condition (2) is new and represents the law of conservation of mass.

Taking into account the linear equilibrium relationship between the solute concentrations in the phases $y = K_D x$, Eqs. (1) and (2) can be rewritten as

$$A_c(1-S+SK_D)\frac{\partial x}{\partial \tau} = A_c\left[(1-S)D_m + SD_sK_D\right]\frac{\partial^2 x}{\partial z^2} - F\frac{\partial x}{\partial z} \qquad (4)$$

$$A_c(1-S+SK_D)\int_0^L x(z,\tau)dz = Q \qquad (5)$$

The initial conditions for the case, when the sample is impulsively injected at a cross-section $z = 0$ of the chromatographic loop, may be represented in the form [32]:

$$x(z,0) = \left|\begin{array}{ll} 0 & 0 \le z \le \Delta z \\ \dfrac{Q}{A_c\Delta z\left(1-S_f+S_fK_D\right)} & 0 \le z \le z_0+\Delta z \\ 0 & z > z_0+\Delta z \end{array}\right. \qquad (6)$$
$$\Delta z \to 0$$

Rendering the problem to be solved dimensionless, the model equations can be transformed to:

$$\frac{1}{a}\frac{\partial X}{\partial t} = \frac{1}{Pe}\frac{\partial^2 X}{\partial Z^2} - \frac{\partial X}{\partial Z} \qquad (7)$$

$$X(0,t) = X(1,t) \qquad (8)$$

$$\int_0^1 X(Z,t)dZ = a \qquad (9)$$

$$X(Z,0) = \left|\begin{array}{ll} 0 & 0 \le Z \le \Delta Z \\ \dfrac{a}{\Delta Z} & 0 \le Z \le Z_0+\Delta Z \\ 0 & Z > Z_0+\Delta Z \end{array}\right. \qquad (10)$$
$$\Delta Z \to 0$$

with

$$Pe = \frac{FL/A_c}{(1-S)D_m + K_DSD_s} \qquad (11)$$

$$a = \frac{1}{1-S+SK_D} = \frac{V_c}{V_R} = \frac{\tau_c}{\tau_R} \qquad (12)$$