Self-Focusing in Gradient Liquid Adsorption Chromatography of Polymers

C. Degoulet,[†] R. Perrinaud,[†,‡] A. Ajdari,[*,§] J. Prost,[⊥] H. Benoit,[#] and M. Bourrel[†]

Groupement de Recherches de Lacq, TotalFina Elf−*Atofina, BP34, 64170 Lacq, France; Elf Atochem North America Inc., 900 First Avenue, P.O. Box 61536, King of Prussia, Pennsylvania 19406-0936; Laboratoire de Physico-Chimie Théorique, Esa CNRS 7083, ESPCI, 10 rue Vauquelin, F-75231 Paris Cedex 05, France; Physico-Chimie Curie, Institut Curie, 11 rue P. et M. Curie, 75005 Paris, France; and Institut Charles Sadron, 6 rue Boussingault, 67083 Strasbourg Cedex, France*

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ABSTRACT: We point out the specificities of the separation process at work during liquid chromatography of polymers in a gradient of composition of the eluent. The main feature is that, after a transient regime, the concentration profile tends to move as a front, i.e., without diffusive spreading in time. This results in relatively sharp peaks and the uselessness of long columns. We propose a simple analytical model for this self-focusing process that allows us to anticipate optimal conditions of operation. This analysis is supported by experimental tests.

I. Introduction

The characterization of macromolecules has largely improved in the past decades thanks to fast techniques for the measurement of average molecular weights and polydispersity. In particular, size exclusion chromatography (SEC)[1] is now intensively used to obtain rapidly the entire molecular size distribution in chemically homogeneous samples. Recent progress is mostly due to the use of new types of columns, of more efficient detection devices, and of course of faster personal computers for data acquisition and processing.[2]

However, there is still a great demand for fast and efficient techniques that could provide detailed information on the topology of the macromolecules (e.g., amount and dispersity of branching) or on the composition fluctuations for the case of copolymers. These are difficult to obtain by SEC, so other methods have been proposed. Temperature rising elution chromatography (TREF)[3] provides for example information on short chain branching for polyolefins. Gradient high performance liquid chromatography (HPLC) of polymers,[4,6] also called gradient polymer adsorption chromatography[7] or liquid adsorption chromatography (LAC),[8,9] has also been put forward and is the subject of intensive studies to explore its analytical potentialities.

In this paper, we explore the transport process at work in a certain regime of operation of this technique. We highlight its specific features in terms of separation possibilities. Using a simple model and a set of experimental results obtained recently in the "Groupement de Recherches de Lacq", we show that this technique has intrinsic advantages that have not yet been fully appreciated. Our analysis provides a definite guide to select the experimental conditions appropriate for efficient separation.

The structure of the paper is as follows: in the next section we detail the typical operation scheme that we will be considering and its demonstrated ability to achieve interesting separations. In the third section we propose a simple analytical model that we solve to obtain the concentration profile in the column as a function of time. This allows us to make predictions for the elution time, and for the peak width and shape, as a function of various operating parameters (solvent flux, gradient strength, etc.). In section IV we report experimental observations performed on polystyrene samples that agree with the predictions of section III. We conclude the paper with a brief discussion (section V).

II. Principles of the Separation Technique

A. Typical Experimental Setup. We describe now typical conditions of operation. A 20 cm long column is filled with particles of a porous material (the particle diameter on the order of 10 μm, with a pore size around 50 Å). The solvent pumped through the column during the experiment is a mixture of two miscible liquids: a nonsolvent (NS) for the polymer and a good solvent (GS) for the polymer. The composition of the injected solvent is changed over time, which results in spatial gradients of solvent composition within the column.

At the beginning of the experiment, the column is flushed with the pure nonsolvent. A few tens of microliters of a dilute solution of the polymer in the good solvent (less than 1% w/w) is then injected at the inlet of the column. As the good solvent mixes with the surrounding nonsolvent, the polymer precipitates and adsorbs on the column.

The column is then fed with solvent at a constant rate, but the quality of the injected solvent (i.e., the proportion of good solvent in the mixture) is continuously and progressively increased. This is achieved using a programmed pump. When the solvent becomes good enough (to be discussed later), the adsorbed polymer tends to desorb and is carried away by the flowing solvent, so that eventually it exits at the end of the column.

Its actual elution may however be rather tricky to detect. Indeed, due to the continuously changing composition (and thus refractive index) of the solvent,

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[†] TotalFina Elf−Atofina.
[‡] Elf Atochem North America Inc.
[§] ESPCI.
[⊥] Institut Curie.
[#] Institut Charles Sadron.
[*] To whom correspondence should be addressed. E-mail armand@turner.pct.espci.fr.

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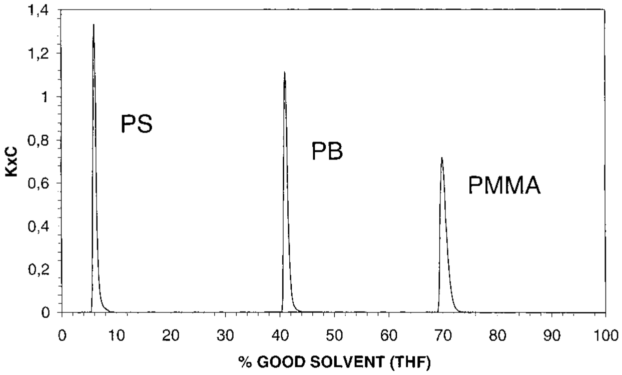

Figure 1. Liquid adsorption chromatography (LAC) of standards of PS, PB, and PMMA on a (20 cm long) grafted silica column, through a gradient hexane/THF. Flow rate = 3 mL min^{-1}; gradient parameter $a = 2.22\%$ min^{-1}. Injection volume = 50 μL at polymer concentration 1 g L^{-1}. Detection is performed with an evaporative light scattering detector, which provides a signal (denoted here and in Figure 5 *kxC*) proportional to the monomer concentration.

classical refractometric detectors cannot be used. A solution is (when possible) to use UV detection at a specific wavelength for which the polymer strongly absorbs while the solvent mixture is transparent, but the choice of the wavelength would have to be renewed for every new set of polymer/solvents system. We instead use an evaporative light scattering detector (ELSD) that analyzes the intensity scattered by an aerosol obtained by evaporating the polymer/solvent mixture. After careful calibration (see section IV.A) this provides quantitatively reproducible results.

A remarkable feature of the signal (chromatogram) obtained is that the peaks corresponding to the elution of the polymer are narrow. An example is provided in Figure 1, corresponding to the separation of a mixture of rather monodisperse samples of polystyrene (PS), polybutadiene (PB), and poly(methyl methacrylate) (PMMA), the nonsolvent being hexane and the good solvent tetrahydrofuran (THF). Although the discussion of these results is out of the scope of this paper, Figure 1 shows that satisfactory results can be obtained, even with a rather short column. On the chromatogram, the signal is plotted as a function of the composition in THF of the THF/hexane mixture exiting the column, rather than as a function of time. (In the most standard mode of operation, the solvent quality is increased linearly in time so the two scales can be easily converted into one another.)

B. Qualitative Picture. What determines the exit time (or solvent composition) of the polymer? Obviously, as long as the solvent quality is so poor that the polymer hardly desorbs, it essentially remains immobile on the surface. When the solvent quality increases to a level that induces its desorption in the now rather good solvent, the polymer is carried away with the solvent in a way reminiscent of SEC, i.e., avoiding the sterically inaccessible zones of the porous media. As a result, it moves on average faster than the solvent and thus catches up with domains of poorer solvent quality. This goes on until the solvent quality has dropped so much that readsorption is likely. The polymer then (re)adsorbs and is stuck, waiting for the subsequent increase of solvent quality that will dissolve it again. This picture, previously alluded to by Glockner[4] and Berek,[5] leads to an average drift due to a succession of “stick” and “fast motion” steps, with the polymer roughly remaining in solvent compositions close to the one triggering the equilibrium adsorption/desorption transition.

In the next section, we propose a simple model for this process that will allow us to go beyond this qualitative picture and show the specific concentration profile (peaks) that results from this stochastic process. We can nevertheless point out immediately that a major ingredient is that this process is definitely non-Markovian: the probabilities of adsorption/desorption depend on the polymer position which in turn depends on its past history. As a result, one must abandon in the present case the classical phenomenology of the central limit theorem: the peak width does not increase as the square root of time, so that the separation power should not be measured in terms of equivalent number of plates, etc.

III. A Simple Theoretical Model

A. Description of the Model. We provide now a simple model to account for the qualitative picture described above. The two main ingredients that we will include are essentially (1) the fact that the adsorption and desorption rates of the polymer on/from the surface depend on the local composition (quality) of the solvent and (2) the fact that, when dissolved, the polymer can move on average faster than the solvent thanks to the size exclusion effect.

We limit ourselves to a one-dimensional picture, with z the direction of the axis of the column. The local quality of the solvent is described by the local amount of good solvent $X = X(z,t)$. The solvent (the mobile phase) drifts at a constant velocity V relative to the column. The polymer position is described by a local concentration $c_s(z,t)$ of polymer adsorbed on the surface and a local concentration $c_v(z,t)$ of polymer dissolved in the mobile phase. The conservation of the polymer is then classically described by

$$\partial_t c_v + \partial_z J_v = \omega_{vs} c_s - \omega_{sv} c_v \tag{1}$$

$$\partial_t c_s + \partial_z J_s = -\omega_{vs} c_s + \omega_{sv} c_v \tag{2}$$

where $J_v(z,t)$ and $J_s(z,t)$ are the flux of desorbed and adsorbed polymers in direction z, and ω_{sv} and ω_{vs} are the local adsorption and desorption rates of the polymer at location z and time t. (In principle, they are dependent on the local polymer concentrations c_s and c_v and on the solvent quality X.)

In the following, the flux J_s of adsorbed polymers is taken to be zero, which amounts to neglect diffusion or mobility of chains adsorbed on the stationary phase. This is reasonable since the surface mobility and diffusion constants are many orders of magnitude smaller than the one for desorbed chains.

The flux of mobile polymers J_v is classically the sum of a convective term and a dispersion term and can thus be expressed as $J_v = V_p c_v - D_p \partial_z c_v$. In the convective part, V_p is the velocity at which the polymer is dragged through the column by the solvent flowing at V. Because of the steric exclusion effect, V_p is larger than V, by an amount that depends on the actual polymer coils size and thus on the solvent quality.[10] Hence, one expects $V_p = V_p(X)$ (or actually more precisely $V_p/V = f(X)$ as long as the flow is weak enough so as not to deform appreciably the coils), with $V_p(X)/V$ an increasing function of X: as the solvent quality increases, the coils swell, and the steric exclusion effect is more pronounced.

In the dispersive contribution to J_v, D_p is the effective diffusion coefficient for dissolved polymers which in principle incorporates molecular diffusivity coupled to hydrodynamic dispersion.

To simplify the picture, we make two further approximations: (i) we neglect the dispersion term proportional to D_p in J_v, as we want to focus on the dispersion brought in by the statistics of the desorption/readsorption process (see below); (ii) we focus on a low concentration regime where ω_{vs} and ω_{sv} are independent of the concentrations and thus depend only on the local solvent quality X. This leads us to a set of simpler equations, *linear* in the concentrations:

$$\partial_t c_v + \partial_z(V_p(X)c_v) = \omega_{vs}(X)c_s - \omega_{sv}(X)c_v \tag{3}$$

$$\partial_t c_s + 0 = -\omega_{vs}(X)c_s + \omega_{sv}(X)c_v \tag{4}$$

Of course, although ω_{vs} and ω_{sv} are dynamical quantities, their ratio is related to the equilibrium adsorption isotherm of the polymer on the surface as a function of solvent quality. For example, in a column at rest with a homogeneous solvent of quality X, the proportion of desorbed polymers is $P_{\rm des}(X) = \omega_{vs}(X)/(\omega_{vs}(X) + \omega_{sv}(X))$, which goes from $P_{\rm des} = 0$ for low solvent qualities $X \simeq 0$ to $P_{\rm des} = 1$ for pure good solvent $X \simeq 1$.

In isocratic conditions (with a constant solvent quality X) the above equations predict an elution at an average speed $\langle V\rangle = P_{\rm des}(X)V_{\rm p}(X)$, with a dispersion controlled by the desorption/adsorption process and quantified by an effective diffusion coefficient $\langle D\rangle = V_p^2\omega_{vs}\omega_{sv}/(\omega_{vs} + \omega_{sv})^3$.

B. Case of a Solvent Quality Increasing Linearly in Time. We now focus on the case where the solvent quality at the inlet is increased linearly in time at a rate a, so that, neglecting the effect of intersolvent diffusion, the solvent quality throughout the column can be approximated by

$$X = a(t - z/V) \tag{5}$$

This corresponds to a steady spatial gradient of solvent quality $\partial_z X = -a/V$, with the locus of a given X value drifting at velocity V.

Driven by the qualitative analysis that indicates that the polymer, through the succession of adsorption and fast forward moves, tends to remain in the vicinity of an X value where both desorption and adsorption are likely, we seek solutions of (3) and (4) that also drift at V:

$$c_v(z,t) = C_v(z - Vt) = C_v(u) \tag{6}$$

$$c_s(z,t) = C_s(z - Vt) = C_s(u) \tag{7}$$

where $u = z - Vt$ is a reduced spatial variable that describes position in the reference frame moving with the solvent quality (i.e., at V). Indeed, this spatial coordinate u and the solvent quality X are simply related by $X = -(a/V)u$. Then, using $\partial_z = {\rm d}/{\rm d}u$ and $\partial_t = -V\,{\rm d}/{\rm d}u$, we obtain

$$\frac{{\rm d}[(V_p - V)C_v]}{{\rm d}u} = \omega_{vs}(X)C_s - \omega_{sv}(X)C_v \tag{8}$$

$$\frac{{\rm d}[-VC_s]}{{\rm d}u} = -\omega_{vs}(X)C_s + \omega_{sv}(X)C_v \tag{9}$$

so that $({\rm d}/{\rm d}u)[(V_p - V)C_v - VC_s] = 0$ and thus $(V_p - V)C_v = VC_s$ for a concentration field that goes to zero for very large and very small values of u. It is then a matter of algebra to describe the spatial variations of the total concentration profile $C(u) = C_v(u) + C_s(u)$:

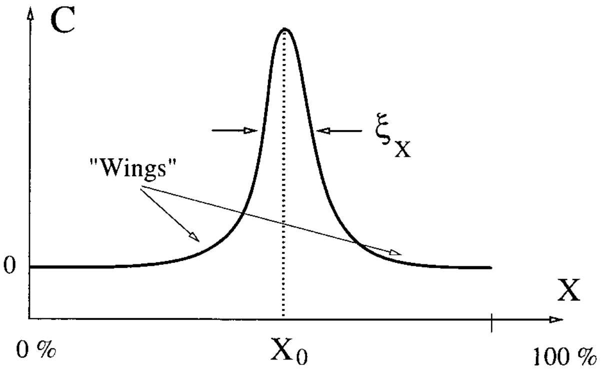

Figure 2. Schematic picture of a peak.

$$V(V_p - V)\frac{{\rm d}\ln C}{{\rm d}u} = \left[\omega_{vs}(V_p - V) - \omega_{sv}V + aV\frac{{\rm d}\ln V_p}{{\rm d}X}\right] \tag{10}$$

For large values of u (i.e., small values of $X = -(a/V)u$) the solvent is poor, and the adsorption term dominates, so that $C(u)$ is a decreasing function. For small values of u (i.e., large values of X) the desorption term dominates so that $C(u)$ is an increasing function. C thus displays a maximum at a position u_0 (Figure 2), which corresponds to a solvent quality $X_0 = -(a/V)u_0$ given by

$$\omega_{vs}(X_0)(V_p(X_0) - V) - \omega_{sv}(X_0)V + aV\frac{{\rm d}\ln V_p}{{\rm d}X}(X_0) = 0 \tag{11}$$

The total concentration profile is formally given by

$$C(u) = C(u_0)\exp\left(\int_{u_0}^{u}{\rm d}u'\,f(u')\right) \tag{12}$$

with

$$f(u') = \frac{\omega_{vs}(u')(V_p(u') - V) - \omega_{sv}(u')V + aV\frac{{\rm d}\ln V_p}{{\rm d}X}(u')}{V(V_p(u') - V)} \tag{13}$$

Let us here pause to emphasize the main characteristic of the above concentration profile: we have found a solution to eqs 3−5 of the form (6, 7) $c_v = C_v(u)$ and $c_s = C_s(u)$, with $u = z - Vt$. This solution corresponds to a polymer concentration profile $c = c_s + c_v$ translating as a front at velocity V, "stuck" on the solvent quality X_0, *without spreading*! Although this formal solution will not match exactly the boundary conditions imposed by the initial conditions, the finite length of the column, and the finite time of the experiment, the existence of such a localized front moving at a constant speed (solitary solution) is preserved if the typical front width is much shorter than the column length. So if two different species are to be separated (and characterized by e.g. $X_0^{(1)}$ and $X_0^{(2)}$), the two corresponding peaks, after a transient, remain at the same distance without widening. This is clearly at odds with classical Markovian methods in which the distance between peaks grows linearly in time whereas their width increases as the square root of time (e.g., in isocratic situations the same equations (3, 4) lead to such a broadening characterized by $\langle D\rangle$; see section III.A). In the present case there is in particular no necessity to use long columns.

C. Characteristics of the Peak. To get more information on the profile, the fraction in the integrand can be approximated for u' close to u_0 by

$$f(u') \simeq -(u' - u_0)/\xi^2 \tag{14}$$

with

$$\xi^2 = \frac{V^2(V_p - V)}{a\left[\frac{d\omega_{vs}}{dX}(V_p - V) - \frac{d\omega_{sv}}{dX}V + \omega_{vs}\frac{dV_p}{dX} + aV\frac{d^2 \ln V_p}{dX^2}\right]_{u=u_0}} \tag{15}$$

This gives the shape of the concentration profile in the vicinity of the peak position u_0:

$$C(u) \simeq C(u_0) \exp\left(-\frac{(u - u_0)^2}{2\xi^2}\right) \tag{16}$$

This can of course be rewritten in terms of solvent quality rather than spatial coordinate u:

$$C(X) \simeq C(X_0) \exp\left(-\frac{(X - X_0)^2}{2{\xi_X}^2}\right) \tag{17}$$

with

$$\xi_X = (a/V)\xi \tag{18}$$

To gain further insight, it is convenient to focus on the case where V_p varies only slowly with solvent quality which allows to neglect the term $aV(\mathrm{d}\ln V_p/\mathrm{d}X)$ in the above formulas and retain only those which explicitly describe adsorption and desorption. This will allow us to make predictions as to the influence of the control parameters a and V on the separation capabilities.

Position of the Peak. In particular, the position X_0 of the peak is in that case well approximated by $X_0 \simeq X^*$ where X^* is given by

$$V = V_p(X^*)\frac{\omega_{vs}(X^*)}{\omega_{vs}(X^*) + \omega_{sv}(X^*)} = V_p P_{\mathrm{des}}(X^*) \tag{19}$$

The value X^* has a clear interpretation: it corresponds to a solvent quality such that on average the polymer moves at the solvent velocity V. Indeed, it spends a proportion P_{des} of the time desorbed during which it moves at V_p, whereas it is immobile the rest of the time (when adsorbed), so that its average speed is V. This solvent quality X^* exactly corresponds to the solvent quality used in critical adsorption chromatography which is performed in isocratic conditions (no gradient of solvent quality).

For weak but nonzero values of a and $\mathrm{d}\ln V_p/\mathrm{d}X$, the peak position can be more precisely described by

$$X_0 \simeq X^* - aV\frac{\left(\frac{d \ln V_p}{dX}\right)_{X=X^*}}{\frac{d}{dX}(\omega_{vs}(V_p - V) - \omega_{sv}V)_{X=X^*}} \tag{20}$$

The order a correction being negative, one expects X_0 slightly smaller than X^* (polymer exits before X^*), and this all the more as a is increased. As mentioned above, V_p/V (rather than V_p) is expected to be a quantity that depends on the solvent quality X. Thus, X_0 in this regime is expected not to depend on V.

Vicinity of the Peak. By the same token, from formula 15, the length ξ describing the curvature of the concentration profile around the maxima depends on the control parameters as $\xi^2 \simeq V^2/a$. In terms of solvent quality (eq 17), this corresponds to a width $\xi_X \simeq a^{1/2}$, independent of V and increasing with a.

Wings of the Concentration Profile. Going further away from the maximum, the variation of $C(X)$ is given (see eq 10) by $\mathrm{d}\ln C/\mathrm{d}X \simeq \omega_{sv}V/[a(V_p - V)]$ on the poor solvent side and $\mathrm{d}\ln C/\mathrm{d}X \simeq -\omega_{vs}/a$ on the good solvent one. As $\omega_{sv}(X)$ and $\omega_{vs}(X)$ are respectively decreasing and increasing functions of X, it is clear that the concentration decays at least exponentially far from the peak, and over lengths (in terms of X) that scale linearly in a, and are roughly independent of V (Figure 2). This analysis also indicates that the asymmetry of the peak depends on the way the ωs vary with solvent quality X and is thus connected to the adsorption/desorption dynamics (and not only the thermodynamics which imposes conditions on the ratio of the ωs but none on each of them separately).

Eventually, we recall here that we have neglected thermal and hydrodynamic dispersion for desorbed chains as described by D_p (although we have accounted for potential dispersion due to desorption/readsorption). Taking them into account is expected to modify the picture at low velocities, where lengths such as D_p/V should characterize the width of the peak. The focusing mechanism is however robust to the incorporation of these dispersion terms as it relies on the fact that whatever lags behind catches back when desorbed and whatever is ahead is slowed down by adsorption.

D. Main Predictions of the Model. Let us summarize here the main predictions arising from our model.

(i) The main one is clearly that the polymer is eluted at a given solvent composition (X_0) given by eq 11 or in approximate form by eq 20. This value is almost independent of the solvent flux V and weakly decreasing when the rate of change of the solvent quality a is increased.

(ii) Then we predict that the concentration peak around this value does not broaden as time goes on but rather reaches asymptotically a fixed shape in the reference frame moving with the solvent at speed V. The width of this peak can be appreciated by looking either at the radius of curvature around the maximum ξ_X or at the lateral extent of the wings of the profile. Both, measured in terms of solvent quality, suggest a width δ_X independent of V and increasing with a.

(iii) As a consequence, the correct way to estimate the feasibility of a separation is the following. Two species 1 and 2, which are eluted at $X_0^{(1)}$ and $X_0^{(2)}$, respectively, can be separated if $|X_0^{(1)} - X_0^{(2)}| \geq \delta_X$. This is favored by a weak value of a, but is indifferent to the value of V, to the length of the column or duration of the experiment (provided time is left for the species to be eluted, of course). These points make this mode of operation original, as only few techniques (e.g., isoelectric focusing[11]) take advantage of the same kind of the "self-focusing" effect.

IV. Experimental Tests

We have run a series of experiment on polystyrene samples in mixtures of THF and hexane to test the predictions of the model.

A. Experiments. *Equipment.* We used a classical apparatus only briefly described here. The chromatograph includes a quaternary gradient pump model 600, an automatic sampler model WISP 717+ (WATERS, Millford, MA), a grafted silica column (Spherisorb S5 × 10 × 250 mm, from WATERS-PHASE SEP, St Quentin en Yvelines, France) placed in an oven, and two detectors. The first one is a UV spectrometer model UV490 (WATERS, Millford, MA). The second one is an evaporative light scattering detector model DDL21 (EUROSEP, Cergy St Christophe, France). Data acquisition and treatment are achieved with a multimeter coupled to a scanner model 199 (KEITHLEY, Palaiseau, France) and a personal computer. Data storage and interpretation are performed with a software developed by J. Lesec (ESPCI, Paris, France). The calibration of the evaporative detector is performed regularly by injecting a given volume of a standard solution (PS sample for example) at different concentrations. This allows to correlate the signal to the monomer concentration, which yields a linear law with a concentration-dependent correction factor. In practice, this correction is significant only at very low concentrations.

Chromatographic Conditions. Solvents are tetrahydrofuran stabilized with 0.025−0.045% di-*tert*-butyl-2,6-methyl-4-phenol ("Special" quality, SDS, Peypin, France), and hexane ("HPLC" 99% pure, SDS, Peypin, France). These solvents are filtered before use on FH 0.5 μm type filters (MILLIPORE, St Quentin en Yvelines, France). The column oven temperature is 30 °C. The wavelength for UV detection is 254 nm. Polymer solutions in THF are prepared at concentrations ranging from 0.5 to 10 g L^{-1}. The results presented here were checked for independence on the initial concentration. The solutions obtained were then filtered on 0.5 μm Acrodisc CR PTFE filters (Gelman, Champs sur Marne, France), and generally samples of 50 μL were injected.

Samples. For the study presented here we used samples of polystyrene of narrow distribution ($M_w = 96$ kg/mol, $I = 1.07$, ref 20133 from Polymer Laboratories, Church Stretton, UK).

Operating Conditions. To check for the dependence in parameters V and a predicted by the above model, we ran gradient separation at various solvent flow rates and rates of increase of the quality. Namely, we used flow rates of 0.5, 1, 3, and 5 mL/min (corresponding to four different values of V) and three rates of increase of the solvent quality $a = 0.57\%\ \mathrm{min}^{-1}$ (ultraslow gradient), $a = 1.15\ \%\ \mathrm{min}^{-1}$ (slow gradient), and $a = 2.22\%\ \mathrm{min}^{-1}$ ("classic" gradient).

B. Results. The main results are summarized in Figures 3 and 4 where the peak position (peak width) are plotted as functions of the flux (i.e., as functions of V) for the three different values of a. Both peak position and width are reported in ordinate in terms of solvent quality, not in spatial coordinates.

Figure 3 qualitatively supports our prediction that the polymer is eluted essentially at a given solvent quality (here ≃41%) and not for example after a given time. A deviation toward lower values is perceivable for the "classic gradient": although such a decrease with increasing a is accounted for by the model, the dependence on V is not.

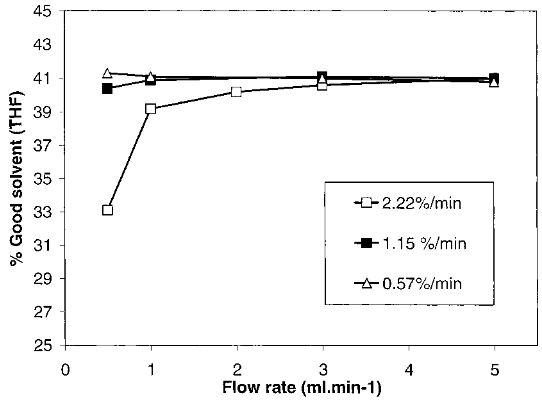

Figure 3. Position of the elution peak maximum as a function of the flow rate for various values of parameter a (i.e., various gradients of solvent quality): $a = 0.57\%\ \mathrm{min}^{-1}$, $a = 1.15\%\ \mathrm{min}^{-1}$, and $a = 2.22\%\ \mathrm{min}^{-1}$. Same chromatographic conditions as in Figure 1 but for a and flow rate.

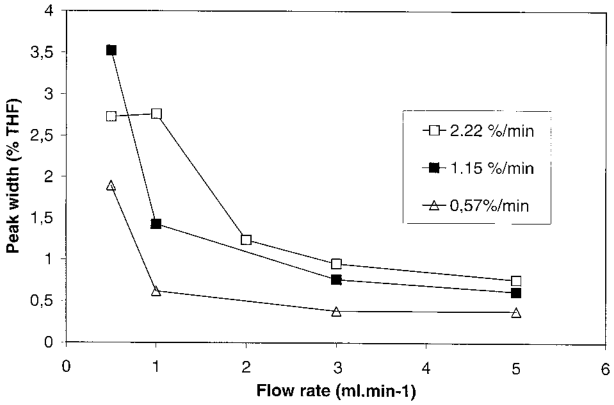

Figure 4. Peak width at midheight as a function of the flow rate for various values of parameter a (i.e., various gradients of solvent quality): $a = 0.57\%\ \mathrm{min}^{-1}$, $a = 1.15\%\ \mathrm{min}^{-1}$, and $a = 2.22\%\ \mathrm{min}^{-1}$. Same chromatographic conditions as in Figure 1 but for a and flow rate.

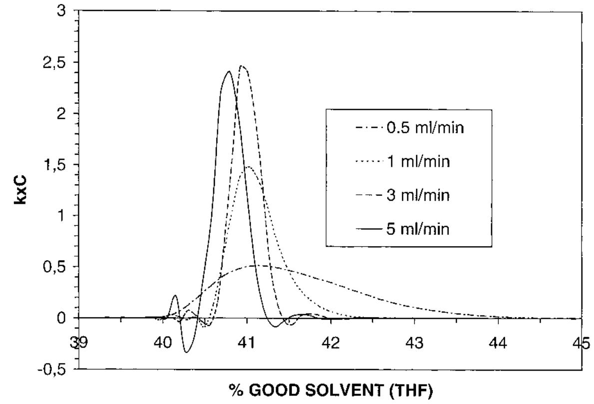

Figure 5. Peaks obtained for various flow rates and $a = 1.15\%\ \mathrm{min}^{-1}$. As in Figure 1, kxC denotes the signal proportional to monomer concentration from the evaporative detector. Note however that the scale in solvent quality (% THF) has been noticeably enlarged compared to Figure 1. A slight asymmetry of the peaks is visible.

Figure 4 supports our prediction that the width of the peak does not simply increase in time as in most separation methods. It is found, in agreement with our model, that the peaks are thinner (in terms of solvent quality) if a slow gradient is used (small value of a). The noticeable increase of the peak width for low values of the flux (see also Figure 5) is not described by our model in its present simplest form, where many dispersion effects have not been taken into account, including the hydrodynamic dispersion of the solvent quality and of polymer motion. This should indeed result in a broadening of the peak at weak solvent fluxes (weak values of V).

V. Conclusion

In conclusion, through a simple model we have shown that there is no peak broadening mechanism at work with this method, where thanks to the spatial heterogeneities of the solvent composition, a focusing mechanism maintains the polymer concentrated around a given solvent quality. This makes this method intrinsically different from most chromatographic methods, including the closely related critical adsorption chromatography,[12,13] where a mixture of solvents of a specific composition X_0 is used. Indeed in the latter case, the solvent is homogeneous, so that the process is Markovian and the peaks broaden as the square root of time.

We have shown that, by using slow gradients, one can in principle achieve very selective separations. This does not require long columns, but rather good ones to avoid dispersion effects. Of course, slow increases of solvent quality lead to slow methods with waste of much solvent. A way around could be a two-step analysis: a first fast screening with the solvent quality ramped from $X = 0\%$ up to $X = 100\%$ in a limited amount of time permits to roughly locate species to be separated, and then another run can be performed with solvent quality increased slowly only in the vicinity of interesting values of X.

Eventually, our model provides a guide to interpret the observed molecular weight dependence of the elution quality X_0. This, together with the application to molecules of varied topology and composition, will be reported elsewhere.

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