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ScienceDirect
Journal of Chromatography A, 1166 (2007) 47–60
JOURNAL OF CHROMATOGRAPHY A
www.elsevier.com/locate/chroma

Consequences of the radial heterogeneity of the column temperature at high mobile phase velocity

Fabrice Gritti [a,b], Georges Guiochon [a,b,*]

[a] Department of Chemistry, University of Tennessee, Knoxville, TN 37996-1600, USA
[b] Division of Chemical Sciences, Oak Ridge National Laboratory, Oak Ridge, TN 37831-6120, USA

Received 4 April 2007; received in revised form 27 June 2007; accepted 29 June 2007

Abstract

When a high velocity stream of mobile phase percolates through a chromatographic column, the bed cannot remain isothermal. Due to the mobile phase decompression, heat is generated along the column. Longitudinal and radial temperature gradients take place along and across its bed. The various consequences of this thermal heterogeneity are calculated and their effects on the column efficiency investigated for a 0.46 cm × 25 cm stainless steel column packed with 5 μm particles. The maximum pressure drop applied was varied from 0.1 to 2 kbar. The amplitude of the longitudinal temperature gradient can be estimated on the basis of the integral heat balance equation applied to the whole column and of measurements of the eluent temperature at the column exit. Assuming that the radial gradient is parabolic and the longitudinal gradient linear, the amplitude of the radial gradient can be determined on the basis of the energy balance across the column and of direct measurements of the radial gradient at high inlet pressures. A radial temperature gradient causes a radial distribution of the eluent viscosity, hence of its local velocity. The result is that bands move faster in their center than along the wall, become warped, hence a radial concentration gradient, similar in origin to the one observed in open cylindrical tubes. Diffusion relaxes this gradient. If there is only a longitudinal temperature gradient, the column efficiency would be 30% smaller for a 2 kbar pressure drop than if there is no longitudinal temperature gradient. However, when both a longitudinal and a radial temperature gradient coexist, there is a large loss of efficiency. If the influence of the diffusive relaxation of the radial concentration gradient is neglected, the peak shape would be broad and exhibit a marked shoulder.

Keywords: Chromatographic column; Mobile phase friction; Heat effects; Longitudinal temperature gradients; Pressure drop; Radial temperature gradients; Column efficiency; C_{18}-bonded silica

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1. Introduction

The axial and radial temperature profiles in a conventional HPLC column (e.g., 150 mm × 4.6 mm) through which the mobile phase percolates at high velocity were recently measured experimentally and discussed [1]. This work was motivated by the high current interest of analysts for performing faster and/or more efficient separations. Due to the compressibility of liquids, an important amount of energy is stored into the mobile phase by the pump and conveyed into the column where it is dissipated into heat as the eluent decompresses. The chromatographic column is heated from its inside, which causes the formation of axial and radial temperature gradients, the axial gradient due to the progressive heating of the eluent, the radial gradient due to radial heat losses. The amplitude of these gradients increases rapidly with increasing inlet pressure. These effects and their consequences are negligible for inlet pressures less than *ca.* 100 bars. They increase rapidly with increasing inlet pressure.

The heat effects have little consequences with conventional column technology. During recent years, however, the industry needs for faster HPLC analysis have lead to important changes in column technology. This evolution is proceeding along three different directions. Two successive generations of monolithic columns which, for the same efficiency than packed columns, have a permeability that is several times higher, have already been developed [2]. New columns packed with fine particles, having diameters between 1 and 3 μm, are now available as well as the instruments needed to operate these columns at high mobile phase velocities, hence at pressures in excess of 1000 bar [3]. Finally, operating columns at temperatures higher than

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[*] Corresponding author. Fax: +1 865 974 2667.
E-mail address: guiochon@utk.edu (G. Guiochon).

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doi:10.1016/j.chroma.2007.06.067

ambient permits the achievement of faster analyses because the viscosity of the mobile phase decreases rapidly with increasing temperature, while the solute diffusivity and the optimum mobile phase velocity for maximum efficiency increase. Whether the mobile phase is pumped into the column under a high inlet pressure or at a high temperature, important stationary longitudinal and radial temperature gradients can be formed inside their beds. The only practical way to reduce the importance of these gradients and their consequences is to reduce the column diameter [4,5], but this introduces new, severe constraints on the extra-column volume of the instrument.

A radial temperature gradient causes a radial gradient of the mobile phase viscosity, hence a heterogeneous radial distribution of the mobile phase velocity, which reduces the column efficiency compared to what it would have been under isothermal conditions. On the other hand, a longitudinal temperature gradient is not directly harmful and may even be used to compensate to some extent for this efficiency loss. This would require an instrument design causing an inversion of the direction of the radial gradient somewhere along the column. Furthermore, the longitudinal pressure gradient may cause a significant reduction of the column efficiency for inlet pressures larger than 1 kbar, due to the decrease of the molecular diffusivity of analytes at these pressures. Thus, there are limits to the performance of unidimensional HPLC [6], which explain the new wave of interest for 2D-LC/LC, a combination that may improve the peak capacity achieved in liquid chromatography [7].

It is important to understand the effects of the combination of a high pressure gradient, a radial and an axial thermal gradient in an HPLC column. At high mobile phase velocities, the column efficiency is essentially controlled by the flow pattern (eddy dispersion) and by the mass transfer to and through the stationary phase. The effects of axial diffusion become negligible [8]. Thus, the effect of an axial thermal gradient on the column efficiency is rather small. Diffusion coefficients increase with increasing temperature and the mass transfer kinetics of analytes through the particles accelerate. On the other hand, due to the pressure gradient, the molecular diffusivities of analytes, which decrease with increasing pressure [9], are low at the column inlet and this slows down mass transfer kinetics at the column inlet. This balance between temperature and pressure effects was recently discussed by Neue and Kele [10]. The formation of temperature gradients due to frictional heating in ultra-high-pressure liquid chromatography and its consequences have recently been investigated in the case of 2.1 mm I.D. columns [11].

The goal of this work is to calculate the consequences of the coexistence of a longitudinal pressure gradient, a longitudinal and a radial temperature gradients on the column efficiency under high inlet pressures (2 kbar maximum). We assume a simple, yet realistic model of the stationary profiles of temperature, a linear longitudinal temperature gradient and a parabolic radial temperature gradient. This assumption is based on the results of recent measurements performed with a 4.6 mm × 250 mm column, packed with 5 μm particles [1], operated with an inlet pressure of only 350 bar. The experimental temperature profiles constitute the constraints of the thermal problem. Based on the energy balance in the column, the outlet temperature of the eluent can be expressed as a function of the column pressure drop. Knowing the flow rate applied, the variations of the specific volume and the viscosity of the eluent as a function of its temperature and pressure, the integration of Darcy's law along the column gives the column pressure drop, hence the temperature increase between the column inlet and outlet. Integration of the local HETP over the column length and the column inner diameter permits the calculation of the apparent Van Deemter curve for a strong thermal heterogeneity of the packed bed.

2. Theory

2.1. General expression of the local sample bandwidth under fast elution chromatography

Fast elution chromatography is characterized by the use of a high inlet pressure in order to generate a high velocity stream of mobile phase. According to the classical theory of band broadening in chromatographic columns, the contribution of axial diffusion to the band width is negligible because the elution time is short. In contrast, the contribution of eddy dispersion, due to the heterogeneity of the flow pattern in the anastomosed interparticle channels is independent of the linear velocity because the number of diffusion steps is zero and the packed bed structure is stable and not affected by the high-pressure applied. Band broadening at high mobile phase velocity depends essentially on the kinetics of mass transfer between the liquid phase percolating along the bed and the stagnant liquid phase inside the packed particles and of mass transfer across particles. The film mass transfer resistance through the stagnant film of liquid surrounding the particles can be neglected because its influence is consistently weak on the overall mass transfer kinetics [12,13].

According to the general rate model of chromatography, the infinitesimal increment of the band second central moment, $\mathrm{d}\sigma_z^2$ (in length unit), associated with the migration of the solute by an infinitesimal length $\mathrm{d}z$ along the column is given by [14]:

$$\frac{\mathrm{d}\sigma_z^2}{\mathrm{d}z} = \frac{1}{6}\frac{\epsilon_\mathrm{e}}{1-\epsilon_\mathrm{e}}\left(\frac{\delta_0(T,P)}{1+\delta_0(T,P)}\right)^2 \frac{d_\mathrm{p}^2}{\Omega(T,P)D_\mathrm{m}(T,P)}u(T,P) \qquad (1)$$

where ϵ_e ($\simeq$0.40) is the local external porosity and d_p is the particle size. These parameters will be considered as independent of the temperature and the pressure. In contrast, δ_0 is a parameter related to the adsorption strength of the analyte [14]. It is a function of the temperature and the pressure given by

$$\delta_0(T,P) = \left(\frac{1-\epsilon_\mathrm{e}}{\epsilon_\mathrm{e}}\right)[\epsilon_\mathrm{p} + (1-\epsilon_\mathrm{p})K(T,P)] \qquad (2)$$

where ϵ_p (although $\epsilon_\mathrm{p} \simeq 0.40$ for many packing materials, it can vary rather broadly) is the particle or internal porosity (independent of both the temperature and the pressure) and $K(T,P)$ is the Henry's constant, which is generally a function of both the temperature and the pressure.

In Eq. (1), the parameter Ω is related to the diffusion rate of the sample inside the particles. It depends on two parallel diffusion processes, pore and surface diffusion. The general expression of