Chromatographic Behavior of Alkyl Ligands Bonded Silica Gels

Kanji MIYABE¹ and Georges GUIOCHON²†

¹ Faculty of Education, Toyama University, 3190, Gofuku, Toyama 930-8555, Japan
²† Department of Chemistry, The University of Tennessee, Knoxville, Tennessee 37996-1600, and Division of Chemical and Analytical Sciences, Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831, U.S.A.

Several parameters characterizing the retention equilibrium, the mass transfer kinetics, and the thermodynamic properties in reversed-phase liquid chromatography (RPLC) were derived for alkylbenzene derivatives on silica gel packing materials bonded to alkyl ligands of various lengths and C₁₈ ligand densities. The adsorption equilibrium constant, the absolute value of the isosteric heat of adsorption, the intraparticle diffusivity, and the activation energy of surface diffusion increase while the surface diffusion coefficient decreases with increasing length of the alkyl chain and with increasing density of C₁₈ ligand. These results are consistent with increasing restriction of the mobility of an increasingly adsorbable molecule. On the basis of these results, a surface-restricted molecular diffusion model was proposed as a first approximation for the mechanism of surface diffusion, which plays a predominant role in intraparticle diffusion. An explanation based on the new model was provided to the contradictory thermodynamic results relating to the retention equilibrium and the surface diffusion in RPLC.

(Received on August 9, 2001, Accepted on October 6, 2001)

There are numerous types of stationary phases for reversed-phase liquid chromatography (RPLC). Alkyl chains and various functional ligands are bonded to the surface of different support materials such as silica gel particles, organic polymer beads, and so on. We can choose a suitable stationary phase according to the purpose of chromatographic separations. Still now, however, alkyl ligands bonded silica gels are the most popular packing materials for RPLC.

A great number of publications have discussed the effects of changing the length and/or the density of the alkyl ligands on the retention behavior and the related thermodynamic properties. In contrast to the extensive studies concerning the retention equilibrium in RPLC, there are few fundamental studies on the mass transfer kinetics in chromatographic columns, especially on the mass transfer phenomena taking place in RP packing materials. Mass transfer kinetics also influences the elution peak profiles as well as the phase equilibrium. Chromatographic behavior of the alkyl ligands bonded silica gels should be systematically studied from the viewpoints of the phase equilibrium, the mass transfer kinetics, and the thermodynamic properties.

The goal of this study is, based on experimental results, to clarify the influence of the nature and density of the alkyl bonded ligands on the characteristics of RPLC, on the mass transfer kinetics and the thermodynamics in this mode of chromatography, and to discuss the characteristics and the mechanism of surface diffusion, which plays an important contribution in intraparticle diffusion.

Experimental

Pulse response experiments (elution chromatography) were made using six RP columns packed with different packing materials, which are prepared from the same base silica gel (average particle diameter: 45 μm) bonded to alkyl chains of three different lengths (C₁, C₄, and C₁₈), and for C₁₈, with four different bonding densities between 0.59 and 3.2 μmol m⁻². A methanol/water (70/30, v/v) mixture was used as the mobile phase solvent. Alkylbenzene derivatives were used as the sample compounds. The column temperature was changed in the range between 288 and 308 K.

The information on the retention equilibrium and the mass transfer kinetics in the columns was derived from the first absolute moment (μ₁) and the second central moment (μ₂) of the elution peaks, respectively, measured under linear isotherm conditions at different mobile phase flow velocities. The thermodynamic properties relating to the retention equilibrium and the surface diffusion were estimated from the temperature dependence of the related equilibrium and kinetic parameters. More detailed information on the moment analysis is available in the literature.

Results and Discussion

Retention equilibrium

Figure 1 shows the correlation between the adsorption equilibrium constant (K) and the carbon content of the stationary phases. The value of K increases with increasing carbon content. However, the slope of the curves gradually decreases for carbon contents above around 10%. Almost the same values of K are observed at 13.7% and 17.1%. We should conclude that only part of the C₁₈ ligands contributes to the retention behavior in RPLC.

Mass transfer kinetics

Figure 2 shows the correlation between the intraparticle diffusivity (Dₑ) and the carbon content of the stationary phases. Similar to the previous result concerning K, the value of Dₑ decreases for carbon contents above around 10%.
increases with increasing carbon content. However, the curve profiles depend on the molecular size of the sample compounds.

![Graph](image1)

**Fig. 1** Correlation between the adsorption equilibrium constant and the carbon content of the stationary phases. Lines and symbols refer to Figs. 6 and 7, respectively.

![Graph](image2)

**Fig. 2** Correlation between the intraparticle diffusivity and the carbon content of the stationary phases. Lines and symbols refer to Figs. 6 and 7, respectively.

Intraparticle diffusion is usually assumed to consist of two mechanisms, i.e., pore diffusion and surface diffusion. 

\[ D_s = D_p + \rho_p K D_s \]  

where \( D_p \) is the pore diffusivity, \( \rho_p \) the density of the stationary phase particles, and \( D_s \) the surface diffusion coefficient. In Figure 3, the contribution of pore diffusion to intraparticle diffusion is compared with that of surface diffusion. Obviously, surface diffusion plays an important role in the mass transfer within the intraparticle space. Surface diffusion is a migration process that takes place in the adsorbed state. Although adsorbate molecules are adsorbed on the surface of the stationary phase, they can migrate on this surface. So, the characteristics of surface diffusion should be studied in more detail for a better understanding of the mass transfer kinetics in RPLC because it has a large contribution.

Figure 4 shows the correlation between \( D_s \) and the carbon content of the stationary phases. According to eq.(1), the value of \( D_s \) was estimated from \( D_p \) by correcting the contribution of pore diffusion to intraparticle diffusion. By contrast to the results regarding \( K \) and \( D_e \), the value of \( D_s \) decreases with increasing carbon content. However, it seems that \( D_s \) tends toward a limit for high carbon contents. The results indicate that the migration of adsorbate molecules along the surface is restricted by their retention behavior.

![Graph](image3)

**Fig. 3** Comparison of the contributions of pore and surface diffusions to intraparticle diffusion.

![Graph](image4)

**Fig. 4** Correlation between the surface diffusion coefficient and the carbon content of the stationary phases. Lines and symbols refer to Figs. 6 and 7, respectively.

**Thermodynamic properties**

Figure 5 shows the correlation between the isosteric heat of adsorption (\( Q_a \)) and the carbon content of the stationary phases. The value of \( -Q_a \) was calculated from the temperature dependence of \( K \) according to the van’t Hoff equation. Similar to the results of \( K \) and \( D_e \), the value of \( -Q_a \) increases with increasing carbon content. Similar trends are observed between the activation energy of surface diffusion (\( E_s \)) and the carbon content in Fig. 6. Analysis of the temperature dependence of \( D_s \) based on the Arrhenius equation provides the value of \( E_s \).

\[ D_s = D_{s0} \exp \left( -\frac{E_s}{RT} \right) \]  

where \( D_{s0} \) is the frequency factor of surface diffusion, \( R \) the gas constant, and \( T \) the absolute temperature.

The curves in Figs. 1, 2, and 4-6 indicate that the adsorptive interaction between the sample compounds and the alkyl chains on the stationary phases increases with increasing length.
of the alkyl ligands and with increasing density of the C_{18} ligands. However, there is a critical level of the carbon content, above which the chromatographic properties plotted in Figs. 1, 2, and 4-6, that is, K, D_m, D_s, Q_{st}, and E_s, no longer significantly change with increasing carbon content. The critical level seems to depend on the molecular size of the sample compounds. Even when the density of C_{18} ligands is so high that the carbon content exceeds the critical level, there may be a limit to the contact area between the sample molecules and the C_{18} ligands. Additionally, the values of the parameters in Figs. 1, 2, and 4-6 for some stationary phases of the C_{13}-silica gels are smaller than predicted by an extrapolation based on the data for C_{1}- and C_{4}-silica gels, suggesting that the adsorptive interaction of the sample molecules with the C_{18} chains should be limited even if the length of the C_{18} ligand is long enough. The results in Figs. 1, 2, and 4-6 suggest a sterical hindrance for the interaction between the sample molecules and the longer alkyl ligands bonded on the stationary phases with relatively high densities.

![Fig. 5](image1)

**Fig. 5** Correlation between the isosteric heat of adsorption and the carbon content of the stationary phases. Lines and symbols refer to Figs. 6 and 7, respectively.

![Fig. 6](image2)

**Fig. 6** Correlation between the activation energy of surface diffusion and the carbon content of the stationary phases. Symbols refer to Fig. 7.

A comparison of -Q_{st} and E_s is shown in Table 1. A molecule releases Q_{st} when it is adsorbed from the bulk mobile phase to the stationary phase surface. On the other hand, E_s corresponds to the energy barrier between two equilibrium positions. It is necessary for the molecules adsorbed on the surface to overcome this energy barrier when they migrate by surface diffusion. The value of E_s should be smaller than -Q_{st} because surface diffusion is the mass transfer process under adsorbed state. However, the values of E_s are larger than those of -Q_{st} for all the sample compounds and for all the stationary phases. The results in Table 1 imply that surface diffusion would not be expected from a thermodynamic point of view.

Table 1  Thermodynamic properties in RPLC

<table>
<thead>
<tr>
<th>Stationary phases</th>
<th>Sample compounds</th>
<th>-Q_{st} (kJ mol^{-1})</th>
<th>E_s (kJ mol^{-1})</th>
</tr>
</thead>
<tbody>
<tr>
<td>C_{13} (C_{1.1%})</td>
<td>Benzene</td>
<td>7.6</td>
<td>13.2</td>
</tr>
<tr>
<td></td>
<td>Ethylbenzene</td>
<td>8.4</td>
<td>15.1</td>
</tr>
<tr>
<td></td>
<td>Butylbenzene</td>
<td>10.2</td>
<td>14.8</td>
</tr>
<tr>
<td></td>
<td>Hexylbenzene</td>
<td>12.5</td>
<td>16.9</td>
</tr>
<tr>
<td>C_{16} (C_{6.7%})</td>
<td>Benzene</td>
<td>8.6</td>
<td>17.7</td>
</tr>
<tr>
<td></td>
<td>Ethylbenzene</td>
<td>10.0</td>
<td>18.4</td>
</tr>
<tr>
<td></td>
<td>Butylbenzene</td>
<td>12.2</td>
<td>19.0</td>
</tr>
<tr>
<td></td>
<td>Hexylbenzene</td>
<td>15.3</td>
<td>19.9</td>
</tr>
<tr>
<td>C_{18} (C_{6.6%})</td>
<td>Benzene</td>
<td>7.8</td>
<td>16.5</td>
</tr>
<tr>
<td></td>
<td>Ethylbenzene</td>
<td>9.3</td>
<td>18.0</td>
</tr>
<tr>
<td></td>
<td>Butylbenzene</td>
<td>11.6</td>
<td>19.2</td>
</tr>
<tr>
<td></td>
<td>Hexylbenzene</td>
<td>15.1</td>
<td>21.7</td>
</tr>
<tr>
<td>C_{18} (C_{8.6%})</td>
<td>Benzene</td>
<td>7.5</td>
<td>20.6</td>
</tr>
<tr>
<td></td>
<td>Ethylbenzene</td>
<td>9.7</td>
<td>21.8</td>
</tr>
<tr>
<td></td>
<td>Butylbenzene</td>
<td>12.7</td>
<td>22.2</td>
</tr>
<tr>
<td></td>
<td>Hexylbenzene</td>
<td>16.2</td>
<td>23.1</td>
</tr>
<tr>
<td>C_{18} (C_{13.7%})</td>
<td>Benzene</td>
<td>7.8</td>
<td>21.3</td>
</tr>
<tr>
<td></td>
<td>Ethylbenzene</td>
<td>10.2</td>
<td>22.6</td>
</tr>
<tr>
<td></td>
<td>Butylbenzene</td>
<td>13.0</td>
<td>25.3</td>
</tr>
<tr>
<td></td>
<td>Hexylbenzene</td>
<td>17.0</td>
<td>27.1</td>
</tr>
<tr>
<td>C_{18} (C_{17.1%})</td>
<td>Benzene</td>
<td>6.8</td>
<td>21.3</td>
</tr>
<tr>
<td></td>
<td>Ethylbenzene</td>
<td>9.7</td>
<td>22.9</td>
</tr>
<tr>
<td></td>
<td>Butylbenzene</td>
<td>13.0</td>
<td>24.1</td>
</tr>
<tr>
<td></td>
<td>Hexylbenzene</td>
<td>17.5</td>
<td>27.7</td>
</tr>
</tbody>
</table>

Model for surface diffusion

A model should be developed for surface diffusion in order to provide an appropriate interpretation of the thermodynamic contradiction resulting from the values of E_s and Q_{st} listed in Table 1. Figure 7 shows the correlation between surface diffusion and the retention equilibrium constant.

![Fig. 7](image3)

**Fig. 7** Ratio of the surface diffusion coefficient to the molecular diffusivity as a function of the adsorption equilibrium constant.

The ratio of D_s to the molecular diffusivity (D_m) increases with decreasing K. The extrapolated intercept is probably close to unity although extrapolation includes a certain error. It can be concluded that D_s for weakly retained compounds is almost equal to the corresponding D_m. There is an intimate correlation between surface and molecular diffusion.

Figure 8 also illustrates the influence of the retention strength on surface diffusion. Linear correlations are observed between D_s/D_m and Q_{st}/RT for all the stationary
phases. Although the slopes of these lines are almost the same, their intercepts depend on the nature and density of the alkyl ligands on the stationary phases. The intercepts decrease with increasing length of the alkyl ligands and with increasing density of the C18 chains. However, all the intercepts are near unity, if slightly different.

Figure 8 shows linear correlations between $E_m$ and $Q_s$ for the C18-silica gels. The intercepts of the linear lines are close to the value of $E_m$, which is calculated to be about 21 kJ mol$^{-1}$. The results in Fig. 9 seem to support the validity of eq.(5). The straight lines intersect the diagonal line (slope of unity) at $-Q_s = 25$ - $45$ kJ mol$^{-1}$, suggesting that $E_s$ would be smaller than $-Q_s$ when $-Q_s$ is larger than about 25 - 45 kJ mol$^{-1}$. However, the value of $-Q_s$ in RPLC is usually smaller than this critical value, as listed in Table 1.

**Fig. 8** Correlation between the ratio of the surface diffusion coefficient to the molecular diffusivity and the isosteric heat of adsorption. Symbols refer to Fig. 7.

This discrepancy probably arises from a difference between the physico-chemical properties of the mobile phase solvent near the surface of the stationary phases and in the bulk mobile phase. For instance, the mobile phase composition could be different because the organic modifier of the mobile phase solvent, i.e., methanol in this study, is preferentially attracted near the alkyl ligands compared with water. The presence of the alkyl ligands also influences the structure of the solvent molecules. It is known that short alkyl chains such as methyl and ethyl groups are structure-breaker. It would be easier for molecules to diffuse in a disordered mobile phase solvent. By contrast, longer alkyl chains are structure-maker. The mobile phase solvent near long alkyl ligands could be more structured by hydrophobic repulsion. Additionally, the presence of the alkyl ligands could physically obstruct molecules from diffusing in the vicinity of the stationary phase surface. The extent of this interference could increase with increasing alkyl chain length and density of C18 ligands. The order of the intercepts in Fig. 8 is probably explained by taking the influence of these factors on the diffusive migration of the sample molecules into account.

The results in Figs. 7 and 8 suggest that the mechanism of surface diffusion is originally similar to that of molecular diffusion. However, the migration of adsorbate molecules must be more restricted by the adsorptive interaction. From these observations, a surface-restricted molecular diffusion model was derived as a first approximation.

$$D_s = D_m \exp(-\beta(-Q_s)/RT)$$  \hspace{1cm} (3)$$

In this model, surface diffusion is regarded as molecular diffusion restricted by the adsorptive interaction, accounted for by $\beta(-Q_s)$. Equation (3) is modified as follows, because molecular diffusion is also considered as an activated process.

$$D_s = D_{m0} \exp(-E_m - \beta(-Q_s)/RT)$$  \hspace{1cm} (4)$$

where $D_{m0}$ and $E_m$ are the frequency factor and the activation energy of molecular diffusion, respectively. Comparing with eq.(2), eq.(4) suggests that $E_s$ is roughly of the same order of magnitude with the sum of $E_m$ and $\beta(-Q_s)$. Although $D_{m0}$ would not be completely equal to $D_s$.

$$E_s = E_m + \beta(-Q_s)$$  \hspace{1cm} (5)$$

**Fig. 9** Correlation between the activation energy of surface diffusion and the isosteric heat of adsorption. Symbols refer to Fig. 7.

**Acknowledgment**

This work was supported in part by a Grant-in-Aids for Scientific Research (No. 12640581) from the Japanese Ministry of Education, Science and Culture.

**References**