

Characteristics and Mechanism of Surface Diffusion in Reversed-Phase Liquid Chromatography Using Various Alkyl Ligand Bonded Silica Gels

Kanji Miyabe

Faculty of Education, Toyama University, 3190, Gofuku, Toyama 930-8555, Japan

Kinetic and thermodynamic parameters concerning surface diffusion were derived in reversed-phase liquid chromatography (RPLC) systems using a series of silica gel packing materials bonded with C₁, C₄, C₈, and C₁₈ alkyl ligands. In this paper, a more detailed study on some characteristics and the mechanism of surface diffusion in the RPLC systems using the different alkyl ligand bonded silica gels was made from a thermodynamic point of view by analyzing the surface diffusion data with consideration of the correlation between the parameters concerning surface diffusion and those relating to the retention equilibrium. The mechanism of surface diffusion seems to be the same irrespective of the length of the alkyl ligands because of the presence of the extrathermodynamic relationships, i.e., the enthalpy–entropy compensation and the linear free energy relationship. It was indicated that the surface diffusion coefficient (D_s) of weakly retained compounds was of the same order of magnitude with corresponding molecular diffusivity and that D_s decreased with increasing retention. The activation energy of surface diffusion (E_s) was formulated as a linear function of the isosteric heat of adsorption (Q_{st}). A modified Arrhenius equation, which is derived by taking into account the linear correlation between the two thermodynamic parameters E_s and Q_{st} , appropriately explains the intrinsic characteristics and mechanism of surface diffusion.

Many types of separation media have been developed as the stationary phases for reversed-phase liquid chromatography (RPLC). There are a wide variety of chemical properties and physical structures of the packing materials. Separation-efficiency of the stationary phases depends on their retention behavior and mass transfer characteristics inside the porous packing materials.^{1–3} The abundance of the RPLC stationary phases having similar but quantitatively different chemical and physical properties is the essential reason RPLC is one of the most effective separation techniques for both analytical and preparative applications.^{1,4} Still,

however, alkyl ligand bonded silica gels are the most popular packing materials for RPLC.^{4,5} Many studies have been published discussing the effects of changing the length of the alkyl ligands on retention behavior and on column efficiency.^{7–14}

Most of the fundamental studies relating to the separation mechanism in RPLC have been made from the viewpoint of the retention equilibrium.⁶ The influence of the alkyl chain length on the separation behavior in RPLC has been studied using the retention factor (k') and the separation factor (α_s) as the indices.^{7–13} A few studies have also been published on the influence of alkyl chain length on column efficiency or on mass-transfer rate in RPLC.^{10,14} However, the references show contradictory conclusions concerning the influence of the length of the alkyl ligands on the separation behavior in RPLC; that is, (1) both k' and α_s tended toward constant values with increasing length of the alkyl chains,⁷ and (2) on the contrary, the values of k' or α_s linearly or monotonically increase with increasing alkyl chain length.^{9–12} It was also reported that the limited value of k' was observed for smaller sample compounds at high ligand densities and that the curvature of the correlation between k' and the carbon content of the stationary phases was more remarkable for smaller sample compounds than for larger sample compounds. The value of k' does not reach limited levels for sample molecules large enough. A similar conclusion was reported for the correlation between the logarithm of α_s and the length of the bonded alkyl ligands.⁸

Contradictory conclusions were also reported for the influence of the alkyl chain length on the column efficiency and on the mass transfer rate in RPLC. It was reported that the mass transfer rate was faster for RPLC packing materials chemically modified with n -alkyl ligands than for the bare silica gel and that it increased with decreasing length of the alkyl chain.¹⁴ On the other hand, it was also reported that the column efficiency was independent of the alkyl chain length.¹⁰

(4) Krstulović, A. M.; Brown, P. R. *Reversed-Phase High-Performance Liquid Chromatography*; John Wiley & Sons: New York, 1982.

(5) Sander, L. C.; Wise, S. A. *CRC Crit. Rev. Anal. Chem.* **1987**, *18*, 299.

(6) Carr, P. W.; Martire, D. E.; Snyder, L. R. Eds., *J. Chromatogr., A* **1993**, *656*, 1.

(7) Berendsen, G. E.; de Galan, L. *J. Chromatogr.* **1980**, *196*, 21.

(8) Löchmüller, C. H.; Wilder, D. R. *J. Chromatogr. Sci.* **1979**, *17*, 574.

(9) Roumeliotis, P.; Unger, K. K. *J. Chromatogr.* **1978**, *149*, 211.

(10) Karch, K.; Sebastian, I.; Halasz, I. *J. Chromatogr.* **1976**, *122*, 3.

(11) Karch, K.; Sebastian, I.; Halasz, I.; Engelhardt, H. *J. Chromatogr.* **1976**, *122*, 171.

(12) Majors, R. E.; Hopper, M. J. *J. Chromatogr. Sci.* **1974**, *12*, 767.

(13) Sander, L. C.; Wise, S. A. *Anal. Chem.* **1987**, *59*, 2309.

(14) Knox, J. H.; Pryde, A. *J. Chromatogr.* **1975**, *122*, 171.

(1) Guiochon, G.; Golshan-Shirazi, S.; Katti, A. M. *Fundamentals of Preparative and Nonlinear Chromatography*; Academic Press: Boston, 1994.

(2) Giddings, J. C. *Dynamics of Chromatography, Part I, Principles and Theory*; Marcel Dekker: New York, 1965.

(3) Ruthven, D. M. *Principles of Adsorption & Adsorption Processes*; John Wiley and Sons: New York, 1984.

In previous papers,^{15–17} Miyabe and Guiochon studied the chromatographic behavior of RPLC packing materials chemically modified with alkyl ligands such as C₁, C₄, C₈, and C₁₈. We indicated that the adsorption equilibrium constant (K), the isosteric heat of adsorption ($-Q_{st}$), and the activation energy of surface diffusion (E_s) increased with increasing length of the alkyl ligands while the surface diffusion coefficient (D_s) decreased. The value of K is defined as the ratio of the concentration of sample molecules in the stationary phase to that in the mobile phase. The value of Q_{st} is the enthalpy change due to the adsorption of sample molecules from the mobile phase to the stationary phase. Surface diffusion is the diffusive migration process of sample molecules along the surface of the stationary phase in a potential field of adsorption. The value of D_s indicates the mobility of sample molecules by surface diffusion in the adsorbed state in the vicinity of the stationary-phase surface. Surface diffusion is usually assumed to be an activated process. When sample molecules migrate in the manner of surface diffusion, it should be necessary for the molecules to gain E_s to overcome the energy barrier between two adsorption sites. However, the rate of change in these four parameters decreased in the range of carbon numbers larger than ~ 8 . Almost the same values of these four parameters were observed for C₈- and C₁₈-silica gel. From these results, it was concluded that only parts of the long alkyl ligands contributed to the retention behavior and the mass-transfer mechanism in RPLC.

As described above, a number of studies were carried out in order to clarify the fundamental aspects of the separation mechanism in RPLC. In most of them, however, experimental data were analyzed from the viewpoint of mainly the retention equilibrium. On the other hand, some kinetic studies were carried out by using an overall efficiency parameter such as the number of theoretical plates or the height equivalent to a theoretical plate. It would be effective for toward understanding the influence of the alkyl chain length on chromatographic behavior in RPLC to measure intrinsic mass-transfer kinetics and thermodynamics properties beyond the retention equilibrium. The kinetic study must be made from the following two points of view. At first, the band-broadening phenomena should be analyzed by dividing the contributions of each mass-transfer process, for instance, axial dispersion, fluid-to-particle mass transfer, intraparticle diffusion, and adsorption/desorption kinetics at actual adsorption sites, in the column, not using the overall efficiency parameters. Second, the characteristics and mechanisms of the mass-transfer processes in the column should be analyzed by considering their correlations with the retention equilibrium and with the related thermodynamic properties, for instance, Q_{st} , the heat of vaporization, the activation energy of molecular diffusion, the activation energy of viscosity, and the activation energy of each mass-transfer process such as E_s .

This paper is concerned with detailed analysis of the characteristics and the mechanism of surface diffusion. In this study, surface diffusion is chosen as an informative kinetic process because it is the molecular migration under an adsorbed state. The manner of surface diffusion is always affected by the strength of the retention of sample molecules because surface diffusion takes place in a potential field of adsorption. Intrinsic characteristics of surface diffusion directly reflect the variation in the chemical and structural conditions of the stationary-phase surface.

Table 1. Physicochemical Properties of RP Stationary Phases

	alkyl ligand			
	C ₁	C ₄	C ₈	C ₁₈
particle density, ρ_p (g cm ⁻³)	0.74	0.73	0.74	0.86
porosity, ϵ_p (-)	0.62	0.61	0.56	0.46
carbon content (%)	4.1	6.7	9.9	17.1
alkyl ligand density, ($\mu\text{mmol m}^{-2}$) ^a	13.4	3.7	3.3	3.2
distance between ligands (nm) ^a	0.40	0.76	0.80	0.81

^a Calculated from the carbon content and the BET surface area of the base silica gel (290 m² g⁻¹).

Chromatographic data were acquired using different alkyl ligand bonded silica gels (C₁, C₄, C₈, C₁₈) and analyzed on the basis of the method of moments.^{1,3,15} The goal of this study is to clarify the kinetic and thermodynamic characteristics of surface diffusion and to obtain information about the influence of change in the alkyl chain length on them. On the basis of the results, it was also tried to derive a formula that can appropriately interpret the characteristic features of surface diffusion in RPLC. In previous papers,^{15–17} we studied the influence of modification conditions of alkyl bonded ligands on the characteristics of the retention equilibrium and the mass-transfer phenomena including surface diffusion in RPLC. In this paper, some intrinsic characteristics and mechanism of surface diffusion were studied in more detail with consideration of the correlations between surface diffusion and the retention equilibrium, between surface diffusion and molecular diffusion, and between Q_{st} and E_s in the RPLC systems using the four different alkyl ligands bonded silica gels.

EXPERIMENTAL SECTION

Columns and Reagents. Table 1 lists information about the physicochemical properties of the four RP packing materials, which are silica gels bonded with alkyl ligands of different lengths. The columns packed with these separation media and most of the information were obtained from YMC (Kyoto, Japan). The packing materials are synthesized by chemically bonding *n*-alkyldimethylsilyl ligands onto the surface of a same base silica gel. No end-capping was made for the silica gels bonded with C₁, C₄, and C₈ ligands. Regarding the C₁₈-silica gel, no substantial increase in the carbon content was observed upon the end-capping treatment with trimethylsilyl ligand. The modification density of trimethylsilyl ligands is comparable to that of *n*-butyldimethylsilyl ligands. However, the density of C₁ ligands is larger than that of C₄ ligands by a factor of ~ 3 in Table 1 because three methyl groups are included in one trimethylsilyl ligand. The average particle diameter of the base silica gel is 45 μm . As described later, this coarse-particle material was used in order to allow the derivation of accurate values of D_s from the experimental chromatographic data. The mobile-phase solvent was methanol/water mixture (70/30, v/v). Alkylbenzenes were used as the sample compounds. Sample solutions were prepared by dissolving the sample compounds using the mobile-phase solvent. Uracil and sodium nitrate were used as the inert tracer.

Apparatus. A high-performance liquid chromatograph system (LC-6A, Shimadzu, Kyoto, Japan) was used. A small amount of the sample solution (~ 0.5 – 300 μL) was injected using a Rheodyne (Cotati, CA) valve injector (model 7125). The column

(15) Miyabe, K.; Guiochon, G. *Adv. Chromatogr.* **2000**, *40*, 1.

(16) Miyabe, K.; Guiochon, G. *J. Chromatogr., A* **2000**, *903*, 1.

(17) Miyabe, K.; Guiochon, G. *Anal. Sci.* In press.

temperature was kept at constant levels by circulating temperature-controlled water around the column. The concentration of the sample compound leaving from the column was monitored with an ultraviolet detector of the HPLC system.

Procedure. Elution peaks were measured by means of the pulse response experiment (i.e., elution chromatography) under linear isotherm conditions while changing the column temperature (288–308 K) and the mobile-phase flow rate (1.0–2.0 mL min⁻¹). It is well known and accepted that adsorption isotherms are usually accounted for by the simple Langmuir model in most RPLC systems.¹ In this study, the pulse response experiments were made under the conditions that the adsorption isotherms of the sample compounds were linear because their amounts injected were small enough. The first absolute moment (μ_1) and the second central moment (μ_2') of the elution peaks were calculated on the basis of the moment analysis method. The information about the retention equilibrium and the mass-transfer kinetics in the column was derived from these moments.^{1,3,15} The procedure of data analysis is briefly described in the following. Further details on the moment analysis method can be found in other references.^{1,3,15}

The value of K was first calculated from the retention data. Then, the value of D_s was estimated from μ_2' by subtracting the contributions to the band broadening of axial dispersion, external mass transfer, and pore diffusion. The contribution of external mass transfer to band broadening was eliminated using the external mass-transfer coefficient, which was estimated by the Wilson–Geankoplis equation.¹⁸ The contribution of intraparticle diffusion was separated from that of axial dispersion by taking advantage of their different flow rate dependences. The value of D_s was derived from the intraparticle diffusivity (D_e) by correcting the contribution of pore diffusivity (D_p), which was estimated from the molecular diffusivity (D_m) of the sample molecule, the intraparticle porosity of the stationary-phase particles, and the tortuosity factor of the pores. It was assumed that intraparticle diffusion consisted of the contributions of pore diffusion and surface diffusion according to the parallel contribution model.³ The value of D_m was calculated by the Wilke–Chang equation.^{1,19–21} The tortuosity factor was determined from similar pulse response experiments using the inert tracer.

The contribution of the extracolumn volumes to μ_1 and μ_2' of the elution peaks was measured by performing the same measurements without the columns and was corrected to derive the values of K and D_s from μ_1 and μ_2' , respectively. The influence of peak distortion on the determination of μ_1 and μ_2' was also corrected. The occurrence of asymmetrical (tailing and fronting) peaks has been explained based on the several models.¹ In this study, the heterogeneity of the packing structure in the column in the radial direction was regarded as the only origin of peak skewness.^{22–24} Possible heterogeneous mass-transfer kinetics was not considered because the surface of the alkyl ligand bonded silica gels seemed to be energetically homogeneous. For instance,

when C₁₈-silica gels are used as the stationary phase, (1) the phase equilibrium isotherm can usually be accounted for by the simple Langmuir model^{1,15,25,26} and (2) both Q_{st} and E_s are nearly constant irrespective of the amount adsorbed.¹⁵ These experimental observations imply the apparent uniformity of the surface of C₁₈-silica gels. The influence of the injection volume of the sample solution on μ_1 and μ_2' of the elution peaks could be neglected because of the extremely small size of the sample solution injected. As described above, for instance, the injection volume of the sample solution of hexylbenzene was $\sim 300 \mu\text{L}$ because of the low solubility of the compound into the mobile-phase solvent. It is not so small in comparison with the conventional sample injection volume in LC. However, the retention volume of hexylbenzene is ~ 2 orders of magnitude or more larger than the sample injection volume, i.e., $\sim 300 \mu\text{L}$. The retention of hexylbenzene is so strong that the volume of the sample injection has very little influence on the moment analysis of the elution peaks. The corrections described above are responsible for the error made in the determination of D_s , which is estimated as 5–10%.¹⁵ In this study, the influence of these sources on peak broadening was minimized because the relatively large silica gel particles were used as the packing materials and consequently μ_2' was relatively large.

RESULTS AND DISCUSSION

Extrathermodynamic Relationships Concerning Surface Diffusion. The temperature dependence of D_s was analyzed on the basis of the Arrhenius equation.

$$D_s = D_{s0} \exp(-E_s/RT) \quad (1)$$

where D_{s0} and E_s are the frequency factor and the activation energy of surface diffusion, respectively, R is the gas constant, and T is the absolute temperature. Linear correlations were observed between the logarithm of D_s and the reciprocal of T . The correlation coefficient was more than 0.99 for the four different stationary phases and for the four different sample compounds.

Figure 1 shows the correlations between E_s and D_{s0} , which are respectively calculated from the slope and the intercept of the linear Arrhenius plots. The logarithm of D_{s0} is linearly correlated with E_s for each sample compound. The linear lines in Figure 1 are almost parallel irrespective of the sample compounds. The plots for the RP stationary phases having alkyl ligands of different lengths are linearly correlated by each single straight line. The linear correlations between $\ln D_{s0}$ and E_s suggest the establishment of an extrathermodynamic relationship, that is, the enthalpy–entropy compensation, concerning surface diffusion.^{15,16,27,28} It has been reported that detailed analyses of retention data in RPLC on the basis of the procedures proposed by Krug et al.^{29–31} suggest the existence of enthalpy–entropy compensation in the retention equilibrium.³² Detailed analyses of the surface diffusion data based on the procedures of Krug et al. are currently investigated.

- (18) Wilson, E. J.; Geankoplis, C. J. *Ind. Eng. Chem. Fundam.* **1966**, *5*, 9.
 (19) Reid, R. C.; Prausnitz, J. M.; Poling, B. E. *The Properties of Gases and Liquids*; McGraw-Hill: New York, 1987.
 (20) Treybal, R. E. *Mass-Transfer Operations*; McGraw-Hill: New York, 1980.
 (21) Bird, R. B.; Stewart, W. E.; Lightfoot, E. N. *Transport Phenomena*; John Wiley & Sons: New York, 1960.
 (22) Miyabe, K.; Guiochon, G. *J. Chromatogr., A* **1999**, *830*, 263.
 (23) Miyabe, K.; Guiochon, G. *J. Chromatogr., A* **1999**, *830*, 29.
 (24) Miyabe, K.; Guiochon, G. *J. Chromatogr., A* **1999**, *857*, 69.

- (25) Miyabe, K.; Guiochon, G. *Anal. Chem.* **2000**, *72*, 5162.
 (26) Miyabe, K.; Guiochon, G. *J. Chromatogr., A* **2000**, *890*, 211.
 (27) Miyabe, K.; Guiochon, G. *J. Phys. Chem. B* **1999**, *103*, 11086.
 (28) Miyabe, K.; Guiochon, G. *Anal. Chem.* **2000**, *72*, 1475.
 (29) Krug, R. R.; Hunter, W. G.; Grieger, R. A. *J. Phys. Chem.* **1976**, *80*, 2335.
 (30) Krug, R. R.; Hunter, W. G.; Grieger, R. A. *J. Phys. Chem.* **1976**, *80*, 2341.
 (31) Krug, R. R. *Ind. Eng. Chem. Fundam.* **1980**, *19*, 50.
 (32) Tan, L. C.; Carr, P. W. *J. Chromatogr., A* **1993**, *656*, 521.

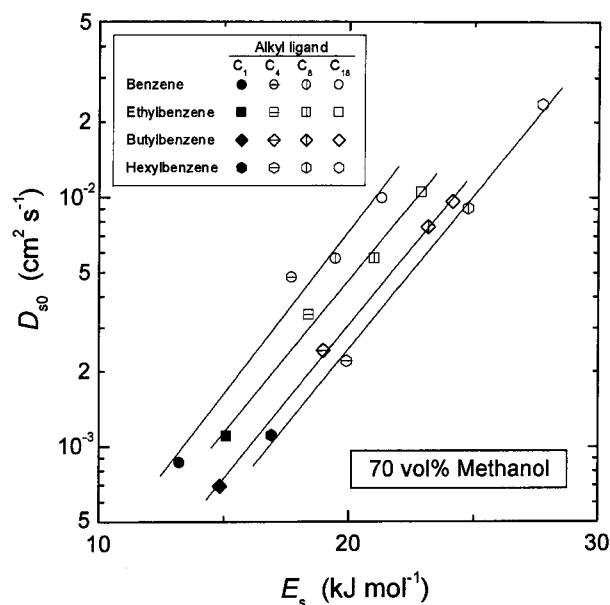


Figure 1. Correlation between frequency factor and activation energy of surface diffusion.

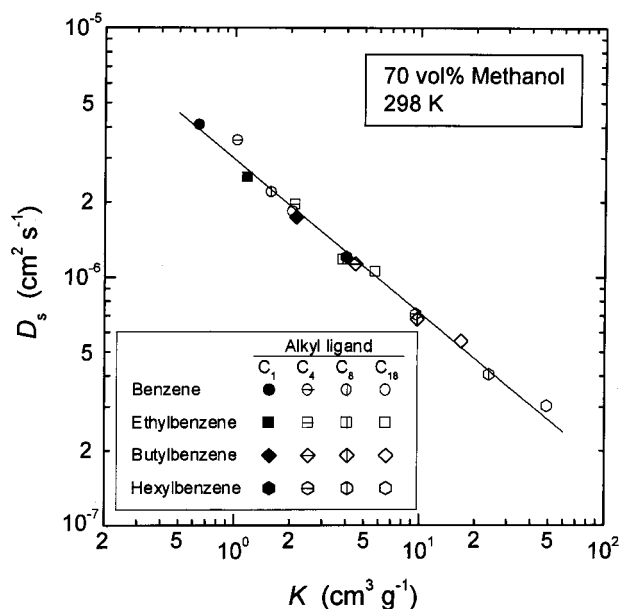


Figure 2. Full-logarithmic plot between surface diffusion coefficient and adsorption equilibrium constant.

Figure 2 shows the full logarithmic plots of D_s and K . All the experimental data at 298 K are plotted around a straight line, suggesting the presence of another extrathermodynamic relationship, that is, the linear free energy relationship.^{15,27,28} Other linear correlations are similarly observed between $\ln D_s$ and $\ln K$ at 288 and 308 K (not shown). The results in Figures 1 and 2 suggest that the mechanism of surface diffusion is probably the same irrespective of the sample compounds and the length of the alkyl ligands bonded to the base silica gel. If the mechanism of surface diffusion remains the same, it may be possible to consistently account for its characteristics and mechanism based on a comprehensive model. In the following, a model of surface diffusion is formulated on the basis of both the extrapolated surface diffusion data at nearly nonretained conditions and the

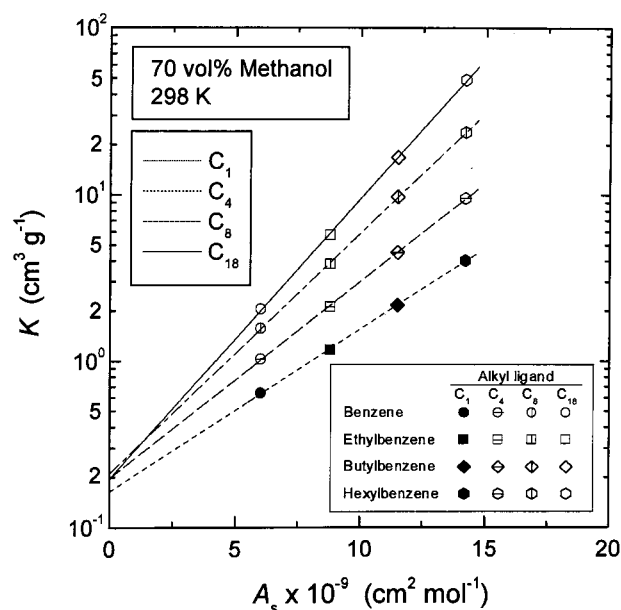


Figure 3. Logarithm of adsorption equilibrium constant as a linear function of hydrophobic surface area of sample compounds.

thermodynamic properties relating to the retention equilibrium and surface diffusion.

Surface Diffusion Coefficient at Nearly Nonretained Conditions. The negative slope of the linear line in Figure 2 indicates that the restriction of molecular migration in the manner of surface diffusion is amplified with an increase in retention. This result is reasonable because surface diffusion takes place in a potential field of adsorption, in which the sample molecules are influenced due to adsorptive interaction with the stationary-phase surface. The dependence of K on the molecular size of the sample compounds is analyzed at first because the retention affects the migration of the sample molecules by surface diffusion. Figure 3 shows the correlation between K and the surface area of the sample compounds (A_s). The logarithm of K is represented as a linear function of A_s .

It is known that the retention equilibrium in RPLC increases with increasing surface area or volume of hydrophobic parts of sample molecules. For instance, the increment in K due to the addition of one methylene unit to the sample molecules is called "methylene selectivity". In the solvophobic theory,^{15,33,34} it is assumed that retention of sample molecules on alkyl ligands is caused by the decrease in contact area between the polar mobile-phase solvent and the hydrophobic surfaces of both the sample molecules and the alkyl ligands. The reduction of the hydrophobic surface area (ΔA) is assumed to be proportional to A_s . The ratio of ΔA to A_s is estimated from the slope of the linear lines in Figure 3. The ratio $\Delta A/A_s$ depends on chromatographic conditions such as the type and concentration of organic modifiers in the mobile-phase solvent in RPLC.^{15,28} For instance, the value of the ratio $\Delta A/A_s$ has been reported as ~ 0.30 – 0.35 for methanol/water mixture (70/30, v/v) and ~ 0.18 for acetonitrile/water mixture (70/30, v/v).^{15,28} The slope of the linear lines in Figure 3 increases with increasing length of the alkyl ligands bonded to the base silica gel. This result arises from the difference in the manner of

(33) Horváth, C.; Melander, W.; Molnar, I. *J. Chromatogr.* **1976**, *125*, 129.

(34) Belfort, G.; Altshuler, G. L.; Thallam, K. K.; Feerick, C. P., Jr.; Woodfield, K. L. *AIChE J.* **1984**, *30*, 197.

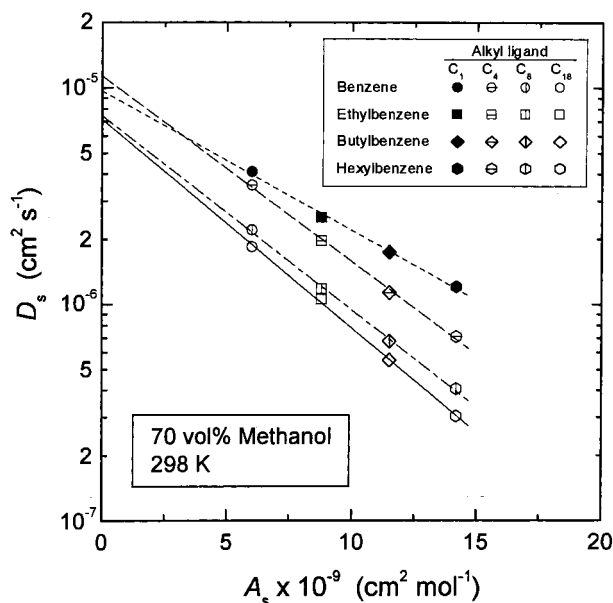


Figure 4. Logarithm of surface diffusion coefficient as a linear function of hydrophobic surface area of sample compounds. Lines refer to Figure 3.

steric interactions between the sample molecules and the alkyl ligands. It is possible that the sample molecules penetrate into a layer of long alkyl ligands,^{35,36} whereas only planar interactions would take place on the surface of the C₁-silica gel. The ratio $\Delta A/A_s$ is calculated from the slope of the linear lines in Figure 3 as 0.20 (C₁), 0.25 (C₄), 0.30 (C₈), and 0.35 (C₁₈).^{15,28}

On the other hand, the linear correlations for the four different stationary phases almost converge at about $K = 0.2 \text{ cm}^3 \text{ g}^{-1}$ on the ordinate irrespective of the length of the alkyl ligands. Because no retention should take place at $A_s = 0 \text{ cm}^2 \text{ mol}^{-1}$, the intercept of the straight lines suggests that a value of K smaller than $0.2 \text{ cm}^3 \text{ g}^{-1}$ has no physical meaning. In Figure 2, the linear correlation implies that the value of D_s would infinitely increase when K tends toward $0 \text{ cm}^3 \text{ g}^{-1}$. As described above, however, the experimentally meaningful minimum value of K should be $\sim 0.2 \text{ cm}^3 \text{ g}^{-1}$. According to the straight line in Figure 2, the value of D_s at $K = 0.2 \text{ cm}^3 \text{ g}^{-1}$ is estimated at $\sim 8 \times 10^{-6} \text{ cm}^2 \text{ s}^{-1}$. This value is in the range of D_m , suggesting that there is a kind of correlation between surface diffusion and molecular diffusion.¹⁵

On the basis of the results in Figures 2 and 3, it is predicted that the logarithm of D_s is also linearly correlated with A_s . Figure 4 shows the semilogarithmic plot between D_s and A_s . The value of D_s decreases with increasing molecular size of the sample compounds. It is well known that the diffusivity of a molecule is a function of its molar volume.^{1,19–21} Previously, it was reported that $\ln D_s$ is also linearly correlated with some parameters of sample molecules other than A_s , such as $V_b^{1/3}$.¹⁵ As described above, the retention of sample compounds should become weak as A_s approaches $0 \text{ cm}^2 \text{ mol}^{-1}$. In Figure 4, the values of D_s at $A_s = 0 \text{ cm}^2 \text{ mol}^{-1}$ range from 7×10^{-6} to $1.1 \times 10^{-5} \text{ cm}^2 \text{ s}^{-1}$, which are of the same order of magnitude with D_m in liquid-phase systems.

Figure 5 shows the plot of $\ln D_s$ against the carbon content of the stationary phases. The value of D_s decreases with increasing

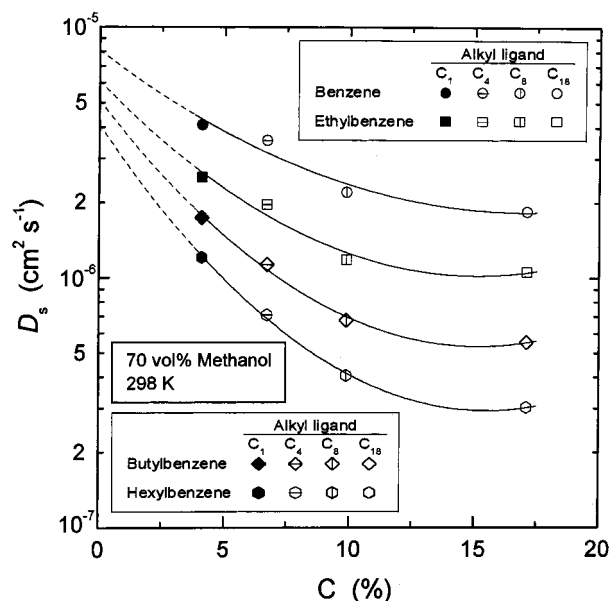


Figure 5. Semilogarithmic plot between surface diffusion coefficient and carbon content of stationary phases.

carbon content of the stationary phases. However, the curve profiles approach plateau levels for each sample compound in the range of high carbon contents. Almost the same values of D_s are observed for the C₈- and C₁₈-silica gel. Because the retention behavior of the sample molecules onto the stationary-phase surface is due to the hydrophobic interaction, no retention should take place under the conditions that the carbon content is equal to 0%. As indicated in Figure 5, the extrapolated values of D_s on the ordinate are estimated between 4×10^{-6} and $8 \times 10^{-6} \text{ cm}^2 \text{ s}^{-1}$. Again, these hypothetical values of D_s at nonretained conditions almost agree with the range of D_m .³⁷ This conclusion is consistent with those derived from the results shown in Figures 2 and 4.

Linear Correlation between E_s and Q_{st} . As shown in Figure 2, the linear correlation is observed in the full-logarithmic plot of D_s and K . Because the logarithm of D_s and that of K respectively correspond to E_s and Q_{st} according to the van't Hoff and the Arrhenius equations, the result in Figure 2 allows us to assume a linear correlation between the two thermodynamic parameters. The correlation between E_s and Q_{st} suggests that surface diffusion is affected due to the retention. This assumption seems to be reasonable because surface diffusion is the mass-transfer process under the adsorbed state. In this section, the meaning of the linear correlation between E_s and Q_{st} is considered.

Figure 6 shows the plot of E_s , which is estimated from the slope of the linear Arrhenius plots, against A_s . According to eq 1, the straight line between $\ln D_s$ and A_s in Figure 4 suggests that E_s should be linearly correlated with A_s . As predicted, there are linear correlations between E_s and A_s in Figure 6. The slope of the linear lines has a tendency to increase with increasing length of the alkyl ligands on the whole. The change in the slope of the linear lines would depend on the difference in the steric interactions between the sample molecules and the alkyl ligands. A quite limited surface area of the sample molecules interacts with C₁ ligands because only planar interactions probably take place on

(35) Tchaplal, A.; Colin, H.; Guiochon, G. *Anal. Chem.* **1984**, *56*, 621.

(36) Tchaplal, A.; Heron, S.; Colin, H.; Guiochon, G. *Anal. Chem.* **1988**, *60*, 1443.

(37) Miyabe, K.; Guiochon, G. *Anal. Chem.* **2001**, *73*, 3096.

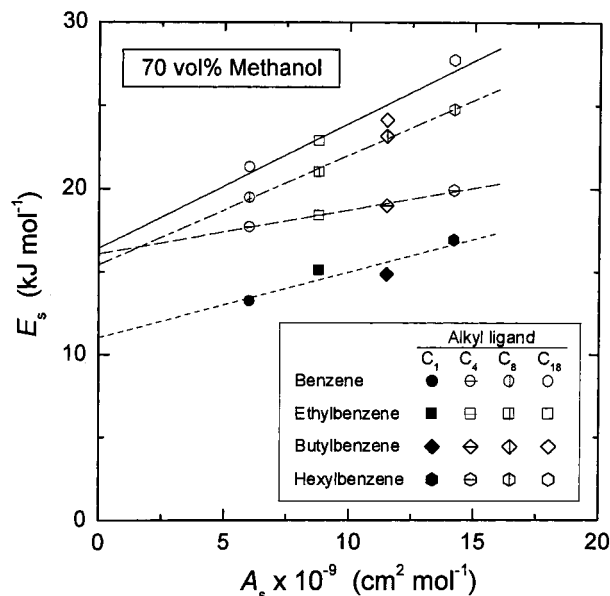


Figure 6. Plot of activation energy of surface diffusion against hydrophobic surface area of sample compounds. Lines refer to Figure 3.

the surface of the C_1 -silica gel. In contrast with the case of short alkyl ligands, almost all of the sample molecules used in this study could penetrate into a layer of long alkyl ligands and interact with them.^{35,36} On the other hand, the linear lines do not approach the origin even as A_s tends toward $0 \text{ cm}^2 \text{ mol}^{-1}$. The intercepts of the four straight lines at $A_s = 0 \text{ cm}^2 \text{ mol}^{-1}$ are $\sim 11\text{--}16 \text{ kJ mol}^{-1}$. Although the intercept on the ordinate is hypothetically of the same order of magnitude with E_s for nearly nonretained compounds, the result in Figure 6 suggests that there is an energy barrier for the diffusive migration of molecules in liquid/solid adsorption systems even when the weakly retained imaginary molecules diffuse in the manner of surface diffusion. The height of the energy barrier probably depends on the length of the alkyl ligands.

Similar to the analysis of the temperature dependence of D_s described earlier, the values of K at the different temperature conditions were analyzed according to the van't Hoff equation.

$$K = K_0 \exp(-Q_{st}/RT) \quad (2)$$

where K_0 is the value of K at $Q_{st} = 0 \text{ kJ mol}^{-1}$ or $1/T = 0 \text{ K}^{-1}$. Linear correlations were observed between $\ln K$ and $1/T$. Correlation coefficients more than 0.99 were obtained irrespective of the RPLC conditions concerning the length of the alkyl chains on the stationary phases and that in the sample molecules.

Similar to Figures 4 and 6, Figure 7 shows the correlation of Q_{st} estimated from the slope of the linear van't Hoff plots with A_s . It seems that Q_{st} is linearly correlated with A_s as predicted from the linear lines in Figure 3. Although there is some scatter, the linear lines are extrapolated to the intercepts on the ordinate ranging from about -2 to $+3 \text{ kJ mol}^{-1}$. Although these values are not completely equal to 0 kJ mol^{-1} , they obviously show a different tendency from the intercepts of the straight lines between E_s and A_s in Figure 6. The values of the intercepts in Figure 7 are small enough in comparison with those in Figure 6. The result in Figure 7 suggests that the adsorptive interaction between the

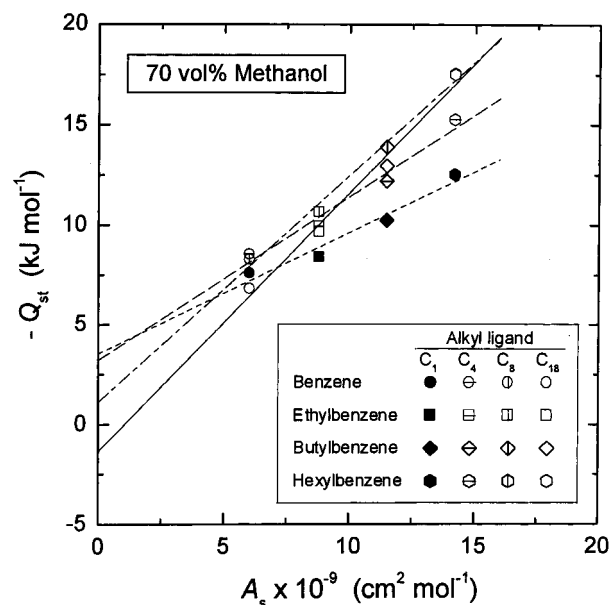


Figure 7. Plot of isosteric heat of adsorption against hydrophobic surface area of sample compounds. Lines refer to Figure 3.

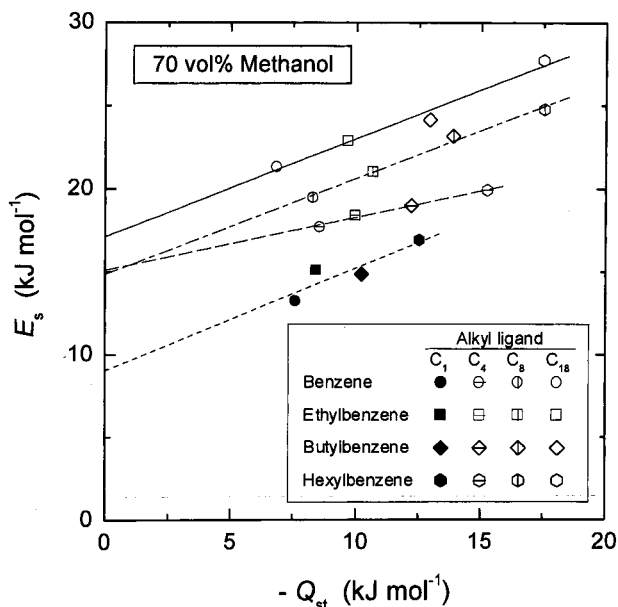


Figure 8. Correlation between activation energy of surface diffusion and isosteric heat of adsorption. Lines refer to Figure 3.

sample molecules and the alkyl ligands becomes small enough at $A_s = 0 \text{ cm}^2 \text{ mol}^{-1}$. From the results in Figures 6 and 7, it is predicted that there is a linear correlation between E_s and Q_{st} .^{17,27,28,38–40}

Figure 8 shows the plot of E_s against Q_{st} . As predicted, linear correlations are observed between the two thermodynamic parameters.

$$E_s = \alpha(-Q_{st}) + \beta \quad (3)$$

Although the straight line for the C_1 -silica gel shows a different

(38) Miyabe, K.; Guiochon, G. *J. Chromatogr., A* **2001**, 919, 231.

(39) Miyabe, K.; Guiochon, G. *J. Chromatogr., A*. In press.

(40) Miyabe, K.; Guiochon, G. *J. Phys. Chem. B* **2001**, 105, 9202.

tendency, the values of α and β range between about 0.3 and 0.6 and between 15 and 17 kJ mol⁻¹, respectively. The value of α suggests that it is not required for the molecules adsorbed on the stationary-phase surface to be completely desorbed from the surface to the bulk mobile phase when they migrate by surface diffusion. This result is reasonable because surface diffusion is the molecular migration process under an adsorbed state. On the other hand, the value of β is of the same order of magnitude with the activation energy of molecular diffusion (E_m), which was calculated as ~ 21 kJ mol⁻¹ from analyzing the temperature dependence of D_m estimated by the Wilke–Chang equation.^{1,19–21}

The following equation is derived by substituting eq 3 into eq 1.

$$D_s = D_{s0} \exp\left[\frac{-\alpha(-Q_{st}) - \beta}{RT}\right] = D_{s0} \exp\left(\frac{-\beta}{RT}\right) \exp\left[\frac{-\alpha(-Q_{st})}{RT}\right] \quad (4)$$

In this equation, D_s approaches the product of D_{s0} and $\exp(-\beta/RT)$ when Q_{st} tends toward 0 kJ mol⁻¹. The value of the product is calculated as about 3×10^{-6} – 3×10^{-5} cm² s⁻¹ at room-temperature conditions because D_{s0} ranges between 2×10^{-3} and 2×10^{-2} cm² s⁻¹ as indicated in Figure 1 and the average value of β is ~ 16 kJ mol⁻¹. The calculated value of $D_{s0} \exp(-\beta/RT)$ is fairly in agreement with the range of D_m . In this paper, it is concluded that D_s decreases with increasing retention and that D_s is of the same order of magnitude as D_m when the retention is negligibly small. Equation 4 provides an appropriate interpretation to the characteristics of surface diffusion described in this paper and supports the validity of the surface-restricted molecular diffusion model, which has been proposed as a first approximation of the mechanism of surface diffusion.^{15,17,27,28,37–41}

CONCLUSION

The surface diffusion data were experimentally measured in the RPLC systems using the four silica gel packing materials bonded with alkyl ligands of the four different lengths. Some items of information about the characteristics and the mechanism of surface diffusion were derived by analyzing the thermodynamic properties of surface diffusion and the value of D_s . These results were also correlated with the retention behavior and the related thermodynamic data. Establishment of the extrathermodynamic relationships, that is, enthalpy–entropy compensation and linear free energy relationship, suggests that the mechanism of surface diffusion is the same even though the length of the alkyl ligands bonded on the surface of the stationary phases is changed. It was indicated that D_s increased with decreasing retention, which originated from the decrease in the hydrophobic surface area of the sample compounds and from the decrease in the carbon content of the stationary phases. The extrapolated values of D_s at nearly nonretained conditions are of the same order of magnitude as D_m . It was suggested from the analysis of the two thermodynamic properties relating to retention equilibrium and surface diffusion that E_s was represented as a linear function of $-Q_{st}$. The slope of the linear correlation is positive and smaller than unity, suggesting that the sample molecules must partially be desorbed

when they migrate along the surface. On the other hand, the intercept is roughly similar to E_m . The product of D_{s0} and the exponent of the ratio $-\beta/RT$ is comparable to the range of D_m . These results are consistent with the hypotheses that D_s of imaginary nonretained sample compounds is almost similar to D_m and that surface diffusion should take place in a potential field of adsorption. Equation 4, which is derived along the surface-restricted molecular diffusion model, appropriately provides quantitative interpretation for the characteristics and mechanism of surface diffusion. Additionally, we can now use other types of RP packing materials such as C₃₀-silica gels and hydrophobic polymers (e.g., styrene–divinylbenzene copolymer). Similar studies on the characteristics and mechanism of surface diffusion on the other separation media are in progress.

GLOSSARY

A_s	hydrophobic surface area of the sample compound (cm ² mol ⁻¹)
ΔA	reduction of total hydrophobic surface area due to adsorption (cm ² mol ⁻¹)
D_e	intraparticle diffusivity (cm ² s ⁻¹)
D_m	molecular diffusivity (cm ² s ⁻¹)
D_p	pore diffusivity (cm ² s ⁻¹)
D_s	surface diffusion coefficient (cm ² s ⁻¹)
D_{s0}	frequency factor of surface diffusion (cm ² s ⁻¹)
E_m	activation energy of molecular diffusion (kJ mol ⁻¹)
E_s	activation energy of surface diffusion (kJ mol ⁻¹)
K	retention factor (–)
K	adsorption equilibrium constant (cm ³ g ⁻¹)
K_0	K at $1/T = 0$ or $Q_{st} = 0$ (cm ³ g ⁻¹)
Q_{st}	isosteric heat of adsorption (kJ mol ⁻¹)
R	gas constant (J mol ⁻¹ K ⁻¹)
T	absolute temperature (K)
V_b	molar volume at normal boiling point (cm ³ mol ⁻¹)

Greek Symbols

α	coefficient in eq 3
α_s	separation factor
β	coefficient in eq 3
ϵ_p	intraparticle porosity (–)
μ_1	first moment (s)
μ_2'	second central moment (s ²)
ρ_p	particle density (g cm ⁻³)

ACKNOWLEDGMENT

This work was supported in part by a Grant-in-Aids for Scientific Research (12640581) from the Ministry of Education, Science and Culture of Japan.

Received for review November 15, 2001. Accepted February 11, 2002.

AC011184I

(41) Miyabe, K.; Guiochon, G. *Anal. Chem.* **1999**, *71*, 889.