



## Review

## Surface diffusion in reversed-phase liquid chromatography

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## ARTICLE INFO

## Article history:

Received 15 July 2009

Received in revised form

30 November 2009

Accepted 23 December 2009

Available online 22 January 2010

## Keywords:

Surface diffusion

Molecular diffusivity

Pore diffusion

Mass transfer kinetics

RPLC

HETP equations

Hole-making process

Jumping process

## ABSTRACT

More than 40 years ago, Giddings pointed out in “Dynamics of Chromatography” that surface diffusion should become an important research topic in the kinetics of chromatographic phenomena. However, few studies on surface diffusion in adsorbents used in chromatography were published since then. Most scientists use ordinary rate equations to study mass transfer kinetics in chromatography. They take no account of surface diffusion and overlook the significant contributions of this mass transfer process to chromatographic behavior and to column efficiency at high mobile phase flow rate. Only recently did the significance of surface diffusion in separation processes begin to be recognized in connection with the development of new techniques of fast flow, high efficiency chromatography. In this review, we revisit the reports on experimental data on surface diffusion and introduce a surface-restricted molecular diffusion model, derived as a first approximation for the mechanism of surface diffusion, on the basis of the absolute rate theory. We also explain how this model accounts for many intrinsic characteristics of surface diffusion that cannot properly be explained by the conventional models of surface diffusion.

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## 1. Introduction

Chromatography is now well established as an essential and powerful method that provides fine separations. Progress of this method depends on the pursuit of fundamental studies on separation theory, on the development of faster, higher efficiency columns, and on the production of suitable instruments to operate them. Most columns are packed with porous particles of adsorbents, most of which are made of fully-porous silica gels, the surface of which is chemically modified by bonding their silanol groups to various ligands. The great advantage of these porous media is their large specific surface area, which provides an important retention. Their major drawback is that analyte molecules must migrate across the intraparticulate space because adsorption sites are located on the inner walls of the meso- and micro-pores. Intraparticle mass transfer kinetics in porous materials controls their performance and particularly band broadening and column efficiency. The study of intraparticle mass transfer in high speed HPLC techniques will help to provide high throughput and high efficiency analyses, now very much in demand.

Surface diffusion contributes significantly to intraparticle mass transfer in reversed-phase liquid chromatography (RPLC). However, it is not recognized by separation scientists as an important factor in mass transfer kinetics. Although Giddings suggested that this was one of the major mass transfer processes in chromatographic columns [1], most analysts still ignore its very existence. They do not recognize its important contribution to column efficiency. Few kinetic studies consider its predominant contribution to mass transfer in RPLC stationary phases. We have little information on its intrinsic characteristics and mechanism. Actually, most investigations in chromatography deal with retention because chromatography primarily rests on phase equilibrium thermodynamics [2] and retention time measurements are easy. In contrast with innumerable reports on retention behavior and mechanisms in HPLC, there are few detailed and systematic studies quantitatively dealing with mass transfer phenomena and including surface diffusion, although various methods of experimental measurements of diffusivities and mass transfer coefficients in HPLC are available, for instance, (1) spectroscopic methods (e.g., fluorescence relaxation [3–14] and nuclear magnetic resonance [15–21]) and (2) column operations (e.g., frontal analysis [22–32], shallow bed method [33–37], and pulse on a plateau method [38,39]).

The most conventional method used in kinetic studies of chromatography consists in analyzing the dependence of the column HETP,  $H$ , on the mobile phase flow velocity. Fig. 1 illustrates such a correlation of  $H$  with the superficial velocity of the mobile phase ( $u_0$ ). The flow rate dependence of the HETP provides information on the kinetics of mass transfer in the column and in the stationary

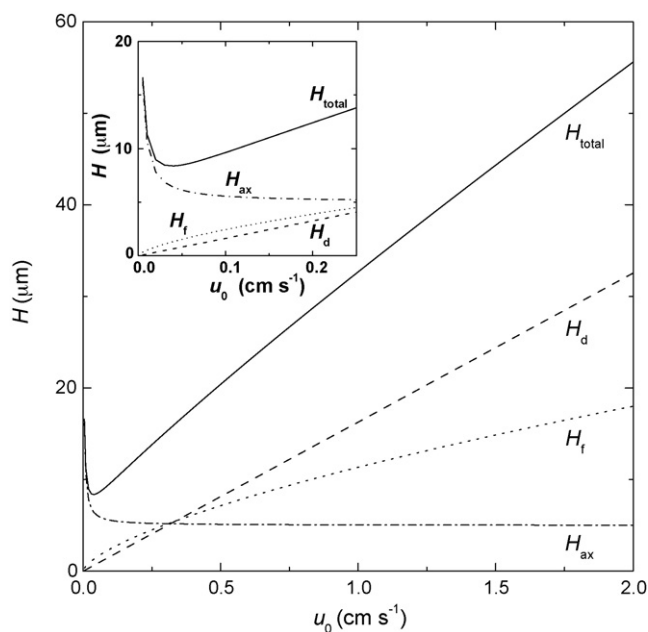
phase. However, it is difficult to extract enough important kinetic information from this correlation between  $H$  and  $u_0$ . The following three roadblocks probably prevent further progress of studies in HPLC kinetics.

First, in principle, kinetic studies require far more experimental data and information than studies of equilibria. While the latter require information on only the retention time ( $t_R$ ) or the first absolute moment ( $\mu_1$ ) of elution peaks, the former needs knowledge of the peak variance or of the second central moment ( $\mu'_2$ ) of peaks, as well as of  $t_R$  and  $\mu_1$ . While retention equilibrium constants ( $K$  or  $K_a$ ) and retention factors ( $k$ ) can be derived from one single measurement, in contrast, numerous elution peak profiles should be recorded for kinetic studies. For example, it is essential for the accurate derivation of some kinetic parameters to measure the curve in Fig. 1 in a wide range of  $u_0$ .

Second, it is more difficult to accurately measure  $\mu'_2$  than  $\mu_1$ . Thus, the errors are larger for HETP than for  $K$ ,  $K_a$ , and  $k$ . In order to accurately determine the value of  $\mu'_2$ , it is necessary to integrate the elution peak profile in a wider range of time than for  $\mu_1$  [39]. Difficulties in the accurate measurement of  $\mu'_2$  lead to a larger error made on the second than on the first moment analysis. So, it is fundamentally more difficult to accurately measure the flow rate dependence of HETP than to determine those of  $K$ ,  $K_a$ , and  $k$ .

Third, the van Deemter and the Knox equations are widely used in chromatography to account for the flow rate dependence of HETP [1,2,40–45]. These ordinary rate equations are very popular but are not useful for the quantitative derivation of information on mass transfer kinetics because they are empirical and contain fitting parameters with unclear physical definitions. Soundly justified quantitative information on mass transfer kinetics in columns cannot be derived from experimental HETP curves like that in Fig. 1 by using these ordinary rate equations. The moment analysis method is more suitable to analyze chromatographic processes in detail [2,38,39,46–57]. However, this approach has rarely been used as an effective fundamental tool for the study of HPLC mass transfer kinetics.

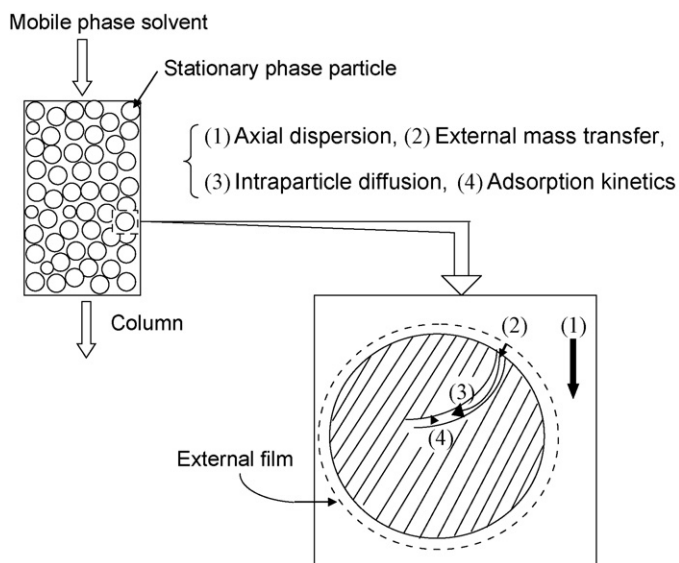
Fig. 2 illustrates mass transfer phenomena in a column and a stationary phase particle. According to the general rate model of chromatography, band broadening results from the contributions of four kinetic processes: (1) axial mixing in the mobile phase percolating through the separation medium (axial dispersion,  $H_{ax}$ ); (2) external or film mass transfer of analyte molecules between the percolating mobile phase and the solution stagnant in the particles (fluid-to-particle mass transfer,  $H_f$ ); (3) diffusive migration through the pores inside the particles (intraparticle diffusion,  $H_d$ ); and (4) adsorption–desorption on the adsorption sites on the stationary phase surface (adsorption–desorption kinetics,  $H_{ads}$ ) [2,38,39,46,47]. Axial dispersion is frequently assumed to consist



**Fig. 1.** Flow rate dependence of HETP ( $H_{\text{total}}$ ) and the contribution to  $H_{\text{total}}$  of axial dispersion ( $H_{\text{ax}}$ ), external mass transfer ( $H_f$ ), and intraparticle diffusion ( $H_d$ ) in a column packed with spherical particles under the following hypothetical conditions, column:  $d_p = 5 \mu\text{m}$ ,  $\varepsilon_e = \varepsilon_i = 0.4$  ( $\varepsilon_t = 0.64$ ); retention equilibrium:  $K_d = 10$  ( $k = 5.6$ ); kinetic parameters:  $D_m = 1 \times 10^{-5} \text{ cm}^2 \text{ s}^{-1}$ ,  $D_p = D_s = 1 \times 10^{-6} \text{ cm}^2 \text{ s}^{-1}$ .

in two mechanisms, molecular and eddy diffusion [2]. Intraparticle mass transfer is explained by the parallel contributions due to pore and surface diffusion [47]. The contribution of  $H_{\text{ads}}$  to  $H_{\text{total}}$  is usually neglected in RPLC because adsorption rate are very fast in physical adsorption [47]. In Fig. 1, the contribution of  $H_{\text{ax}}$  to  $H_{\text{total}}$  decreases with increasing flow rate. Although both  $H_f$  and  $H_d$  increase with increasing  $u_0$ ,  $H_d$  is larger than  $H_f$  in the high flow rate range, suggesting that the influence of  $H_d$  on  $H_{\text{total}}$  must be studied in detail, a worthwhile study because surface diffusion plays a predominant role in mass transfer kinetics in RPLC stationary phases, as explained later.

The main goals of this review are: (1) to summarize the results of previous work on surface diffusion; (2) to provide informa-



**Fig. 2.** Schematic illustration of the mass transfer steps in a column and in the stationary phase particle.

tion on the intrinsic characteristics of surface diffusion in RPLC; and (3) to present a new model accounting for the mechanism of surface diffusion. Section 2 provides a brief explanation of surface diffusion and information on previous related studies with which chromatographers are not familiar. Section 3 analyses surface diffusion data measured in RPLC systems along three lines (1) the dependence of surface diffusion coefficients on retention strength, (2) the correlation between surface and molecular diffusion, and (3) the thermodynamic properties of surface diffusion. Using these results, a discussion of the mechanism of surface diffusion permits the development of a new model, which consistently accounts for important features of surface diffusion.

Although abundant semantic discussions tried to define the retention mechanism in RPLC as “partition” or “adsorption”, we consider it as an adsorption phenomenon in the sense that analyte molecules equilibrate between mobile and stationary phases, the sample molecules concentrating on this surface. Chromatographic data are analyzed in the framework of the adsorption theory, in order to derive important information on retention equilibria, mass transfer kinetics, their thermodynamic and extrathermodynamic properties. Molecules adsorbed on the stationary phase surface can diffuse in the potential field of adsorption. This process in the adsorbed state is “surface diffusion”.

## 2. Surface diffusion in RPLC

### 2.1. Brief explanation of surface diffusion

Because surface diffusion is unfamiliar to most chromatographers, a brief explanation of this type of molecular migration needs to be provided. Molecules migrate across particles through two possible mechanisms, pore and surface diffusion.

#### 2.1.1. Kinetic aspects

In pore diffusion, molecules diffuse through the mobile phase that stagnates in the particle pores, the driving force being their concentration gradient. No interaction takes place between the molecules and the inner wall of the pores. However, molecules adsorbed on these walls can also diffuse while remaining in the adsorbed state, the gradient of their concentration in the adsorbed state being the driving force of this surface diffusion. The mass flux ( $J_s$ ) of adsorbate migrating by way of surface diffusion is given by [46,47]

$$J_s = -D_s \rho_p \frac{dq}{dx} \quad (1)$$

where  $\rho_p$  is the density of the packing particles,  $q$  the concentration of adsorbate at equilibrium with the mobile phase, and  $x$  the distance. The ratio  $dq/dx$  is the concentration gradient of adsorbate. According to Eq. (1), the surface diffusion coefficient ( $D_s$ ) is a proportionality coefficient. In chromatography, the symbol  $D_s$  is conventionally used as a kinetic parameter related to diffusive transport in the stationary phase; e.g., Giddings referred to  $D_s$  as the molecular diffusion coefficient in the stationary phase [1].

Horváth and Lin proposed a rate equation including the contributions of axial dispersion, external mass transfer, intraparticle diffusion, and adsorption–desorption kinetics to band broadening [42,44]. To account for intraparticle diffusivity, they introduced the internal porosity and the tortuosity factor but they did not consider surface diffusion, although they considered pore diffusion as “intraparticle diffusion”. Actually, most kinetic studies in chromatography have so far been carried out without recognizing the contribution of surface diffusion. There is no conventional kinetic theory nor rate equation including the contribution of surface diffusion to mass transfer kinetics, although, more than 40 years ago,

Giddings [1] had pointed out its significance as one of the important processes involved in this kinetics.

### 2.1.2. Thermodynamic aspects

Fig. 3 illustrates some thermodynamic characteristics of adsorption and surface diffusion [58]. When molecules are adsorbed from a solution onto a solid surface, an amount of heat, the isosteric heat of adsorption ( $Q_{st}$ ), is released and an enthalpy change, usually negative, takes place. Inversely, an activation energy corresponding to  $Q_{st}$  is required for adsorbate molecules to be completely desorbed from the surface. However, adsorbate molecules can migrate along the surface while remaining adsorbed, i.e., in the potential field of adsorption. This migration on the adsorbent surface is called “surface diffusion”. It is an activated mass transfer process. When adsorbate molecules gain an activation energy ( $E_s$ ), they surpass the boundary energy barrier between two adsorption sites and may migrate to an adjacent site. It is not necessary that  $E_s$  be larger than  $-Q_{st}$  since, in order to diffuse, adsorbate molecules do not need to be completely desorbed.

To date, the fundamental characteristics of surface diffusion have mostly been studied by applying the Arrhenius-type equation to the dependence of  $D_s$  on temperature [46,47,59].

$$D_s = D_{s0} \exp\left(\frac{-E_s}{RT}\right) \quad (2)$$

where  $D_{s0}$  and  $E_s$  are the frequency factor and the activation energy of surface diffusion, respectively,  $R$  the gas constant, and  $T$  the absolute temperature. Experimental results gave ratios of  $E_s$  to  $-Q_{st}$  ranging from ca. 0.3 to 1 for surface diffusion in gas–solid phase systems [47,59–62]. So,  $E_s$  is assumed to be correlated with  $Q_{st}$  as in

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

where  $\alpha$  is a positive parameter, smaller than unity. Combining Eqs. (2) and (3) gives

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

Eq. (4) has frequently been used as the basic formula in many studies of the dependence of  $D_s$  on temperature and on the amount adsorbed ( $Q_{st}$  depends on the adsorbate concentration). However, Eq. (4) has some drawbacks as discussed later.

### 2.1.3. Definition of stationary phase and surface diffusion in RPLC

It is important to define clearly the words “stationary phase” and “surface diffusion” because fundamental characteristics and mechanisms of surface diffusion and related parameters, such as  $D_s$ ,  $E_s$ , and  $D_{s0}$ , need to be discussed in detail. Silica gels bonded to alkyl ligands are the most popular packing materials for RPLC. They consist of two parts, the porous silica base material and the layer of hydrophobic alkyl ligands bonded to the silica surface. The stationary phase is the layer in which retention takes place. It is made of the bonded ligands, of adsorbed solvent molecules, and possibly include small, isolated patches of bare silica. The ligand chains are too weakly soluble in aqueous solutions of the organic modifiers used as mobile phases and interact together too strongly to float in the mobile phase. Actually, the bonded layer is adsorbed on the silica surface. This model of alkyl chains collapsed against the surface is consistent with the findings of Pages et al. [63] on the freedom of movement of these chains and with those of Rustamov et al. [64] on the internal porosity of RPLC packing materials. This layer is hardly penetrated by solvent molecules [64]. The bonded layer is in contact with a layer of adsorbed solvent molecules that is richer in organic modifier than the bulk mobile phase, is denser than the bulk solvent, and is better organized.

Surface diffusion is a mass transfer process that takes place in the potential field of adsorption, due to the existence of the surface. Combined with restricted diffusion of analyte molecules in the solvent filling the mesopores, it accounts for intraparticle diffusion. It takes place as long as there are adsorptive interactions between adsorbate molecules and the adsorbent surface, even if the magnitude of these interactions is weak. No surface diffusion takes place on the bare silica surface because no molecule adsorbs directly on this surface under the usual experimental conditions of RPLC. Only the structural characteristics (tortuosity and constriction) of the mesopores of the silica support may affect surface diffusion. Under certain conditions, however, the silica surface affects the adsorption phenomenon and this influence considerably complicates the interpretation of all the chromatographic properties concerning retention equilibrium, mass transfer kinetics, and their related thermodynamics.

These difficulties of interpretation are due to the lack of sufficiently detailed information on the composition, structure, and certain physico-chemical properties of the stationary phase (as defined above). The concentration of the organic modifier in the liquid layer adsorbed on the bonded alkyl ligands differ from that in the bulk mobile phase, due to its preferential attraction to the hydrophobic surface of non-polar stationary phases. The structure of the adsorbed mobile phase layer seems different from that of the bulk mobile phase because the polar solvent molecules surrounding long alkyl chains such as  $C_{18}$  ligands are more organized by the hydrophobic interactions and repulsions. Therefore, some physico-chemical properties, e.g., the viscosity, of the adsorbed layer are different from those of the bulk mobile phase, due to their different composition and structure. Finally, the mobility of the bonded ligands is very restricted compared to that of dissolved n-alkane molecules, due to their bonding to the solid surface and to their strong adsorption on it [63].

Since we know so little on the properties of the adsorbed layer of mobile phase, we ignore where and how surface diffusion takes place. It should take place in the potential field of adsorption, which is due to the existence of the adsorbent surface. The alkyl ligands bonded to the surface contribute to the formation of this field. However, it is improbable that surface diffusion takes place between the bonded ligands because they are collapsed [63,64]. In conclusion, we cannot completely distinguish the contributions of the silica support and of the bonded alkyl layer to the kinetics and thermodynamics of mass transfer processes in packing materials. Although the porous base silica and the hydrophobic layer of bonded alkyl

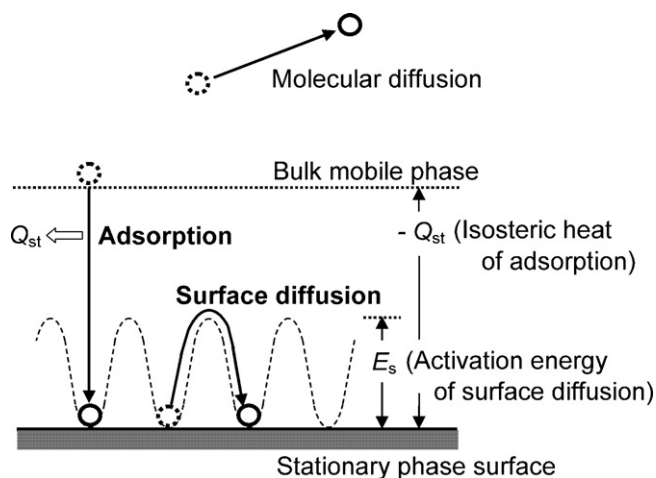


Fig. 3. Schematic illustration of the thermodynamic properties relating to the retention and surface diffusion of sample molecules on stationary phase surface. (Reproduced with permission from Ref. [58].)



ligands that make the adsorbent can be distinguished, their contributions to its properties are too strongly interdependent for their separate influences to be assessed quantitatively. In this review, the “stationary phase” is defined as the whole particles, consisting of the porous silica base material and the alkyl ligands bonded phase. We recognize that “surface diffusion” is the molecular migration of adsorbate molecules in the vicinity of the surface while remaining under an adsorbed state.

## 2.2. Overview of previous studies on surface diffusion

Surface diffusion was studied by various methods [46,47,59,65], such as permeability measurement [60,61,66,67], batch adsorption [68–73], Wicke-Kallenbach type steady-state diffusion [74,75], chromatography [38,39,76–78], shallow-bed adsorption [37], and fluorescence spectroscopy [3–14].

### 2.2.1. Surface diffusion in gas–solid and liquid–solid phase adsorption systems

The concept of surface diffusion was originally advanced to explain the unusually large effectiveness factors measured for catalytic reactions and the unexpectedly large mass transfer rates of gases through porous materials [65]. Then, the mechanism of surface diffusion was studied along with that of pore diffusion in evaluations of the total mass transfer rate in porous media. It is now well known in chemical engineering that surface diffusion contributes most importantly to intraparticle diffusion in many cases of gas–solid and liquid–solid adsorption [46,47,59]. Many studies on surface diffusion were carried out in order to elucidate the characteristics and the mechanism of surface diffusion on the basis of the “Hopping model”, “Two-dimensional Fick’s law model”, and “hydrodynamic model” [47,59]. The most important research subjects of these studies were the dependence of  $D_s$  on the temperature and on the amount adsorbed [46,47,59]. The mechanism of molecular migration by surface diffusion was discussed on the basis of experimental results concerning the temperature and the concentration dependence of  $D_s$ . However, there are few studies analyzing surface diffusion from the viewpoints of the adsorptive interactions between adsorbate molecules and the adsorbent surface.

The temperature dependence of  $D_s$  was first interpreted through the Arrhenius equation, Eq. (2), in both gas and liquid phase adsorption systems, an essential strategy to study thermodynamic properties of kinetic processes. The concentration dependence of  $D_s$  was frequently discussed in connection with changes in the heat of adsorption. As shown in Eq. (3), Gilliland et al. [60] correlated  $E_s$  with  $Q_{st}$  in gas–solid systems and suggested that changing the amount adsorbed affects  $D_s$  through changes in the heat of adsorption. Sladek et al. [61] showed that many experimental data in a wide energy range from physisorption to chemisorption are well interpreted on the basis of Eqs. (2)–(4), confirming the validity of the concept.

There are also many reports on surface diffusion in liquid phase adsorption. Komiyama and Smith [68,69] studied surface diffusion of benzaldehyde in a liquid–solid system consisting of Amberlite (porous polystyrene) particles and methanol/water mixtures of various compositions. They reported that increasing the methanol content in these mixtures decreases the adsorption capacity and increases  $D_s$ . They interpreted their experimental observations on the basis of two-step processes for surface diffusion, which rests on the absolute rate theory proposed by Eyring and co-workers [79]. They assumed that diffusion in the liquid phase consists of two hypothetical steps, first the formation of a hole (cavity) in the bulk solvent (hole-making step), then the migration of a solute molecule from an equilibrium position to the next hole (jumping step). The activation energy of surface diffusion is also divided into two conceptual contributions, related to the hole-making and the jumping

steps, respectively. Komiyama and Smith suggested that the contribution of the jumping step can be approximated as a certain fraction of the heat of adsorption.

Sudo et al. [70] interpreted the concentration dependence of  $D_s$  on the basis of a function of the amount adsorbed. Neretnieks [80] studied the decrease in the heat of adsorption due to the increase of the amount adsorbed in the case of the Temkin isotherm and suggested an exponential function of the adsorbed-phase concentration. Suzuki and Fujii [75] studied the adsorption of propionic acid from water onto activated carbon from the viewpoints of adsorption equilibrium, mass transfer kinetics, and related thermodynamic properties. They reported that the adsorption isotherm was represented by a Freundlich’s equation and that  $D_s$  increased with increasing amount adsorbed. They explained the strong concentration dependence of  $D_s$  by considering the variation in the heat of adsorption, which originates from changes in the surface coverage by propionic acid.

Itaya et al. [71] experimentally determined  $D_s$  in the aqueous adsorption of phenol derivatives onto macroreticular (Amberlite) resins by means of the finite bath adsorption. They analyzed the concentration dependence of  $D_s$  and indicated that  $E_s$  is a linear function of  $Q_{st}$ . On the basis of the concept of molecular diffusion, they assumed that the slope and intercept of the linear correlation between  $E_s$  and  $Q_{st}$  respectively correspond to the contributions of the jumping (bond-breaking) step and of the hole-making step to  $E_s$ . The ratio of the energy contribution of the jumping step to  $-Q_{st}$  was estimated to be 0.4–0.6. The results agreed with those of Komiyama and Smith [68,69].

Muraki et al. [81] also measured  $D_s$  of benzene derivatives on an activated carbon using a finite bath aqueous adsorption system and analyzed the concentration dependence of  $D_s$ . They reported that the ratio of  $E_s$  to the adsorption energy is almost equal to 0.5, even in liquid phase adsorption. Moon and Lee [82] investigated a liquid phase adsorption of phenols in a batch adsorber containing activated carbon and explained the concentration dependence of  $D_s$  by a simple empirical equation of the time and particle-volume average value of the amount adsorbed.

Miyahara and Okazaki [72,73] made batch kinetic experiments of aqueous adsorption of benzene derivatives and reported a significant dependence of  $D_s$  on the amount adsorbed. They applied Eyring’s rate theory to interpret the concentration dependence of  $D_s$  by assuming that  $E_s$  consists of two contributions due to the hole-making and to the jumping step, as in the previous studies [69,71], and that the rate-controlling step is hole-making under the potential field of adsorption. The value of  $E_s$  was regarded as a certain fraction of the sum of the evaporative energy ( $\Delta E_v$ ) of the adsorbate (not the solvent) and the adsorption potential ( $E_{ap}$ ). They reported that their concept is effective for interpreting the influence of both concentration and temperature on  $D_s$  in the adsorption of benzene derivatives from water onto activated carbon.

In contrast with results for gas–solid adsorption [47,59–62], ratios of  $E_s/(-Q_{st})$  larger than unity are often reported in liquid phase adsorption [38,39,78,83–89], although values of  $E_s$  smaller than  $-Q_{st}$  were also observed, even in liquid–solid adsorption [68,71,75,81]. There is no appropriate model or theory to quantitatively and consistently explain all situations between  $E_s$  and  $Q_{st}$ , i.e.,  $E_s > -Q_{st}$  and  $E_s < -Q_{st}$ , in liquid phase adsorption. This is one of the phenomena that cannot be properly explained by conventional models of surface diffusion, i.e., Eq. (4).

### 2.2.2. Studies on surface diffusion in RPLC

As described above, activated carbons and macroreticular organic resins were used as adsorbents in many liquid–solid adsorption studies. Experimental data on surface diffusion or on lateral diffusion in RPLC were also measured by the fluorescence method [3–14] and the shallow-bed method [37].

Bogar et al. [3] used fluorescence spectroscopy to measure of lateral diffusion coefficient of pyrene in a phase system consisting of a C<sub>18</sub>-silica gel and a methanol/water mixture. The microviscosity of the C<sub>18</sub>-RP was estimated by fluorescence measurements. The authors reported that solvated C<sub>18</sub>-RP is a dynamic medium, in which solutes could be dissolved. Stahlberg et al. [4] measured the mobility of pyrene on RP packing materials by the fluorescence method. They estimated the activation energy for the diffusion of pyrene on RP-18 by analyzing its temperature dependence and suggested that the surface of RP-18 has liquid-like properties. Hansen and Harris [7] measured the diffusion coefficient of rubrene on a C<sub>18</sub>-bonded phase in equilibrium with water and two aqueous solutions of methanol (0/100, 10/90 and 20/80, v/v). The diffusion coefficient increases with increasing methanol concentration. They reported that the lateral diffusion coefficient is 2–3 orders of magnitude smaller than molecular diffusivity in the bulk solution. Wong and Harris [5] reported  $D_s$  of iodine on a C<sub>1</sub> bonded silica in contact with methanol/water solutions. They reported that  $D_s$  is of 2–3 orders of magnitude smaller than molecular diffusivity in the bulk solvents and that  $D_s$  increases with increasing methanol composition in the aqueous mobile phase. Zulli et al. [6] measured the lateral diffusion coefficient of acridine orange at the water/C<sub>18</sub> interface and compared this coefficient with its diffusivity in bulk water. As described above, experimental values of  $D_s$  were reported in RPLC systems. However, the fluorescence method needs to use a water-rich solvent to achieve the immobilization of the probe molecules on the surface. This is a peculiar prerequisite for this method. Wirth et al. [14] investigated strong adsorption phenomena in RPLC by single-molecule spectroscopy. They used a cationic dye, i.e., 1,1'-dioctadecyl-3,3,3',3'-tetramethylindocarbocyanine perchlorate, as fluorophor in an RPLC system consisting of chemically modified silica and aqueous solution of acetonitrile. They analyzed the lateral diffusion data measured at the solid–liquid interface and indicated the existence of three different strong adsorption processes. Bujalski and Cantwell [37] applied the shallow-bed method to the measurement of the desorption rates of 1,2-dimethyl-4-nitrobenzene from octadecylsilyl bonded silica particles ( $d_p = 12 \mu\text{m}$ ). They derived some items of information on the mass transfer kinetics in an RPLC system using 50% methanol and reported the value of  $D_s$ , which were well within the range of  $D_s$  previously reported.

### 2.2.3. Studies on surface diffusion in various LC systems

Guiochon, Miyabe and co-workers provided quantitative analysis of mass transfer kinetics, including surface diffusion in different modes of chromatography, (1) anion exchange of bovine serum albumin (BSA) [27,29], (2) chiral separation of S/R Tröger's base on cellulose triacetate [28], (3) RPLC on C<sub>18</sub>-silica gel particles and monoliths [32,90–93], and (4) enantiomeric separations on molecularly imprinted stationary phases [30,94,95]. Mass transfer rate coefficients were derived from breakthrough curves measured by frontal analysis and from elution peaks recorded in the pulse on a plateau method [2]. They analyzed the dependence of the rate coefficients on the mobile phase flow velocity, the solute concentration, the average size of stationary phase particles, the affinity of analytes for the stationary phase, the heterogeneity of the adsorbent surface, and the temperature, in order to derive quantitative information on the characteristics of the mass transfer processes taking place in the column, (1) axial dispersion, (2) external (fluid-to-particle) mass transfer, (3) intraparticle diffusion, and (4) adsorption–desorption kinetics. The contributions of these four kinetic processes were individually evaluated.

Some information on surface diffusion was also obtained from the results of these studies. For instance, surface diffusion plays a major role in the kinetic properties of BSA in its anion exchange elution [29] and in those of phenylalanine anilide in its enan-

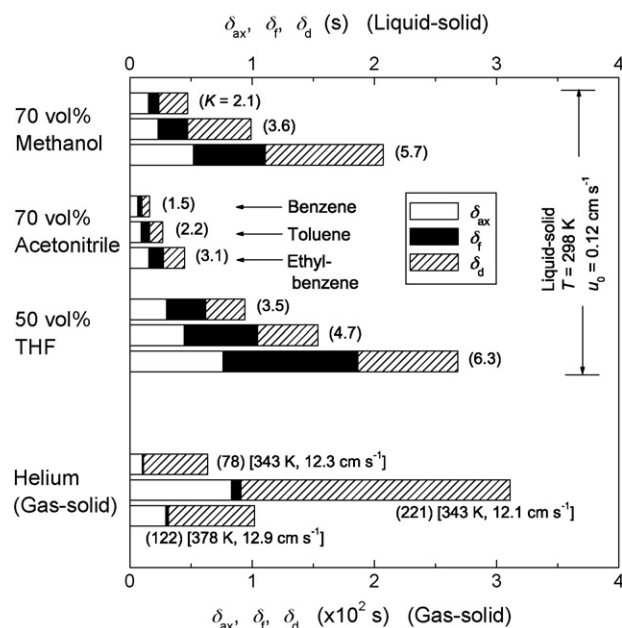


Fig. 4. Comparison of the contribution to  $\mu_2$  of axial dispersion ( $\delta_{ax}$ ), external mass transfer ( $\delta_f$ ), and intraparticle diffusion ( $\delta_d$ ) in column. (Reproduced with permission from Ref. [138].)

tiomeric separation [30]. The linear concentration dependence of the lumped mass transfer rate coefficient seemed to originate from that of  $D_s$ . The positive concentration dependence of  $D_s$  itself could be interpreted by an heterogeneous surface model [29,30], suggesting a wide distribution of adsorption energies on the surfaces of the anion exchangers and of imprinted chiral stationary phases. The predominant contribution of surface diffusion to mass transfer kinetics was confirmed in other chromatographic systems [92,94,95].

### 2.3. Significance of the study on surface diffusion in RPLC

There are three main reasons why surface diffusion should be studied in detail. First, as illustrated in Fig. 1, band broadening under linear isotherm conditions depends on the contributions of the mass transfer processes in the column [2,38,39,46,47]. Fig. 4 compares the contributions to  $\mu_2$  of these three processes, axial dispersion ( $\delta_{ax}$ ), external mass transfer ( $\delta_f$ ), and intraparticle diffusion ( $\delta_d$ ). The figures in parentheses give the retention equilibrium constant ( $K$ ). The contributions of  $\delta_{ax}$ ,  $\delta_f$ , and  $\delta_d$  are comparable, 25–40%, 20–40%, and 30–50%, respectively, in RPLC systems, irrespective of the mobile phase compositions (NB. the size of the C<sub>18</sub>-silica particles was relatively large,  $d_p = 45$  and  $54 \mu\text{m}$ ). On the other hand, Fig. 1 also shows that intraparticle diffusion has an important influence on band broadening, even under the conditions conventionally used in RPLC for analytical purposes. Although the contributions of  $\delta_{ax}$ ,  $\delta_f$ , and  $\delta_d$  are respectively 58%, 25% and 17% at  $u_0 = 0.1 \text{ cm s}^{-1}$ , they become comparable (i.e., 38%, 33%, and 30%, respectively) in the highest flow rate range (ca.  $u_0 = 0.25 \text{ cm s}^{-1}$ ) practically used. This means that the contribution of intraparticle diffusion to band broadening is not negligible. By contrast, the contribution of  $\delta_f$  is one to two orders of magnitude smaller than those of  $\delta_{ax}$  (ca. 15–30%) and  $\delta_d$  (ca. 70–80%) in gas–solid adsorption systems [38,62]. The figures in brackets indicate the temperature and the superficial velocity of the carrier gas (helium). Although the fractional contributions to  $\mu_2$  of  $\delta_{ax}$ ,  $\delta_f$ , and  $\delta_d$  are different, Fig. 4 shows that  $\delta_d$  has an important influence on  $\mu_2$  in both gas–solid and RPLC systems.

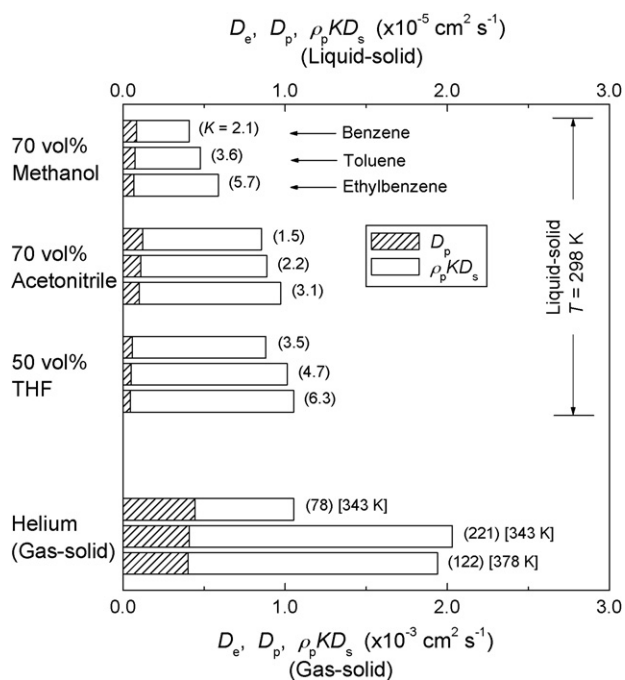


Fig. 5. Comparison of the contributions of pore diffusion and surface diffusion to intraparticle diffusion. (Reproduced with permission from Ref. [138].)

It is usually assumed that intraparticle diffusion consists of the parallel contributions of pore and surface diffusion [46,47]

$$D_e = D_p + \rho_p K D_s \quad (5)$$

where  $D_e$  is the effective intraparticle diffusivity,  $D_p$  the pore diffusivity,  $\rho_p$  the particle density, and  $K$  the retention equilibrium constant. The contributions of these mechanisms to  $D_e$  are compared in Fig. 5. Note that the scales of the horizontal axes are different. The top X-axis is for RPLC and the bottom one for GC. In RPLC systems,  $D_e$  is of nearly one order of magnitude larger than  $D_p$ , suggesting that more than 90% of the sample molecules migrate by surface diffusion in the stationary phase. A similar situation is observed in gas–solid systems, although the values of  $D_e$ ,  $D_p$ , and  $\rho_p K D_s$  are about two orders of magnitude larger than those in RPLC systems. The results in Figs. 4 and 5 indicate that the contribution of surface diffusion to intraparticle mass transfer and to band broadening in the column is important [38,39].

The mass transfer steps in columns are classified into two categories: (1) mass transfer of molecules without physico-chemical interactions with the stationary phase surface (i.e., axial dispersion, external mass transfer, and pore diffusion) and (2) kinetic processes involving adsorptive interactions (surface diffusion and adsorption–desorption kinetics). Mass transfer and diffusive molecular migration classified in the first category has been abundantly investigated in chemical engineering because these processes are inherent to all operations using fixed beds packed with porous media. Some fundamental features have already been clarified for axial dispersion, external mass transfer, and pore diffusion [2,46,47,65]. Numerous correlations have been proposed for estimating related mass transfer and kinetic parameters such as molecular diffusivity [2,46,47,96–99] and external mass transfer coefficient [46,47,100–103]. In contrast, kinetic phenomena classified in the second category have not been sufficiently studied [46,47,59]. Most chromatographers do not yet recognize the existence of surface diffusion nor its important contribution to mass transfer in stationary phases and to column efficiency [1].

Second, surface diffusion can be regarded as an informative kinetic process. It is always affected by the retention of analytes

because it takes place in the adsorbed state, in the potential field of adsorption. This retention depends on physico-chemical parameters of the analytes (molecular size, chemical properties, and structure), the stationary phase (structural characteristics of pores and surface chemistry), the mobile phase (type, composition, and surface excess of organic modifier), and others (column temperature and pressure). It is expected that important information on the physico-chemical properties of liquid–solid interfaces can be gleaned from detailed analyses of surface diffusion.

Third, a renewed trend in chromatography is the development of fast HPLC techniques with high efficiency. As described above, Figs. 1 and 4 indicate that band broadening depends on the contributions of several mass transfer steps in the column, intraparticle diffusion being an important one at high flow rate. Figs. 4 and 5 indicate that surface diffusion plays a predominant role in intraparticle molecular migration and influences significantly the column efficiency. This is another reason why a quantitative study of surface diffusion is essential for the progress of high performance fast HPLC. In contrast to the abundance of studies on chromatographic retention, there is a dearth of works on mass transfer kinetics, especially on surface diffusion in stationary phases. Moreover, most kinetic studies were carried out using conventional rate equations, such as the van Deemter and the Knox equations [1,2,40–45], which are empirical and have weak theoretical basis. To the best of our knowledge, there is no rate equation that can fully explain the contribution of surface diffusion to HETP. Surface diffusion in chromatography has not yet been studied quantitatively and systematically in spite of its importance.

#### 2.4. Accuracy and precision of surface diffusion measurements

The accuracy of the measurements of  $D_s$  should now be considered. The following considerations suggest that the values of  $D_s$  are measured with an error of about 5–10%. As indicated in Fig. 1, information on intraparticle diffusion (hence, values of  $D_e$ ) are derived from  $H_d$  by subtracting the contributions of axial dispersion ( $H_{ax}$ ) and external mass transfer ( $H_f$ ) from  $H_{total}$ . Then,  $D_s$  is derived from  $D_e$  using Eq. (5). Even if the experimental values of  $\mu_1$  and  $\mu_2$  were accurately measured, some literature correlations are needed to estimate some related kinetic parameters, i.e., molecular diffusivity ( $D_m$ ), external mass transfer coefficient ( $k_f$ ), and  $D_p$ , which are necessary for determining  $D_s$ . The uncertainties in the estimation of their values limit the accuracy of the  $D_s$  value.

First, it is usually assumed that axial dispersion consists of two mechanisms, i.e., eddy diffusion and axial molecular diffusion, which respectively correspond to the A and B terms of the van Deemter equation and that the former shows no flow rate dependence, although the latter is inversely proportional to the mobile phase flow velocity. The value of the coefficient in the B term is comparable with  $D_m$  [1,2]. Some correlations, such as the Wilke–Chang equation, have been proposed for estimating  $D_m$  [2,46,47,96–99]. It has been reported that the average error on estimates of  $D_m$  is around 10% [98]. Experimental measurements of chromatographic data were carried out at relatively high flow rates because the contribution of axial molecular diffusion decreases with increasing flow rate. The mobile phase flow range was chosen so that its contribution to band broadening becomes negligibly small, for example, less than a few percent. A variation of  $D_m$  of about 10% has little influence on the selection of the suitable flow rate range in which the contribution of axial molecular diffusion is negligible. On the other hand, the contribution of eddy diffusion to band broadening can be separated from those of  $H_f$  and  $H_d$  by taking advantage of the differences in their flow rate dependence.

Second, the value of  $k_f$  must be estimated in order to subtract the contribution of  $H_f$  from  $H_{total}$ . Although other correlations were proposed [46,47,100–103], the Wilson–Geankoplis equation [101]



and the Kataoka equation [102] were proposed to estimate  $k_f$  in the laminar flow regime. They indicate that  $k_f$  is proportional to  $D_m^{2/3}$ . This means that the error in  $k_f$  due to that in  $D_m$  would be about 6% because  $D_m$  is estimated with an average error of around 10% as described above. In addition, we should compare two concrete values of  $k_f$  estimated by the two literature correlations. For example,  $k_f$  of benzene at 298 K was calculated as  $1.85 \times 10^{-2}$  and  $1.48 \times 10^{-2} \text{ cm s}^{-1}$  by the Wilson–Geankoplis equation and the Kataoka equation, respectively, on the assumption that  $u_0$  of 70 vol% methanol is  $0.12 \text{ cm s}^{-1}$  and  $D_m = 8.2 \times 10^{-6} \text{ cm}^2 \text{ s}^{-1}$ . The relative difference between these two values is 20–25%. As shown in Fig. 4, the contribution of the external mass transfer to band broadening is about 30% or less. It is concluded that the moderate inaccuracy in the estimation of  $k_f$  does not seriously influence the accuracy of  $D_s$ .

Finally, the error made in the estimation of  $D_p$  also influences the accuracy of  $D_s$  because, in Eq. (5), the contribution of  $D_p$  to  $D_e$  must be subtracted in order to calculate  $D_s$  from  $D_e$ . According to the parallel pore model,  $D_p$  is proportional to  $D_m$  [1,2,46,47], suggesting that the uncertainty in the estimation of  $D_p$  is of the same order of magnitude as the error made in the estimation of  $D_m$ . As illustrated in Fig. 5, surface diffusion has a predominant contribution to the intraparticle mass transfer in the RPLC systems, as much as about 80–90% or more. Because of the major role played by surface diffusion in intraparticle diffusion, it is expected that the influence of the error made in estimating  $D_p$  on the determination of  $D_s$  is negligibly small.

### 2.5. New approaches for study on surface diffusion

In this review, we revisit experimental data on surface diffusion and analyze them from four novel points of view. First, we study surface diffusion in RPLC systems, considering the correlation between surface diffusion and retention equilibrium. It is a new approach to analyze the dependence of  $D_s$  on retention equilibrium constant. Most previous studies on surface diffusion in liquid–solid systems have been carried out from the viewpoints of temperature and concentration dependence of  $D_s$ . Only the influence of the temperature and the amount adsorbed on  $D_s$  were regarded as important subject for clarifying the characteristics and mechanism of surface diffusion. The general consensus in adsorption studies was that adsorbents having large adsorption capacity and strong adsorptivity were desirable. Adsorption of organic compounds onto activated carbons or hydrophobic resins from aqueous solutions was frequently studied [46,47]. Admittedly, as indicated in Eq. (5), the contribution of surface diffusion to  $D_e$  becomes negligibly small irrespective of  $D_s$  when  $K$  is almost equal to zero. It is obvious that the intraparticle mass flux decreases with decreasing  $K$ . The development of adsorbents having a moderate adsorptivity was not an important topic of practical research and development. There was no idea that complex samples could be well separated by delicately adjusting separation conditions, using adsorbents having a moderate adsorptivity. Few studies were made on surface diffusion using adsorbents on which the adsorption constant is weak and the adsorption capacity small. Few detailed studies were so far made on the dependence of  $D_s$  on the strength of adsorptive interactions of adsorbate with the adsorbent surface because the contribution of surface diffusion to  $D_e$  is small at low  $K$  values.

In contrast, in chromatography, the components of complex mixtures are separated by taking advantage of small differences in their retention constants. These small differences are integrated and amplified during the chromatographic process. The authors studied previously surface diffusion in RPLC systems, not in the conventional liquid–solid systems using activated carbons and hydrophobic resins. The magnitude of retentive interactions can be controlled by changing some of the RPLC experimental con-

ditions involving the stationary phase (the length and density of alkyl ligands), the mobile phase (the organic modifier and its concentration), the sample compounds (nature and concentration of adsorbates), and temperature. Our first novel point consists in the high degree of freedom and the flexibility with which the retention behavior can be controlled.

Kinetic studies on surface diffusion showed that there is a tight correlation between surface diffusion and molecular diffusion and that surface diffusion is restricted due to the retention of analytes. Experimental data should be analyzed assuming that surface diffusion is a mass transfer process, similar to molecular diffusion but restricted by the potential field of adsorption. This is our second point.

Third, surface diffusion should be studied from the viewpoints of thermodynamics and extrathermodynamics, on the basis of the absolute rate theory [79]. The mechanism of surface diffusion was discussed using thermodynamic information on surface diffusion and on retention equilibrium:  $E_s$  is the sum of contributions of the hole-making and the jumping steps, which are correlated with the evaporation energy ( $\Delta E_v$ ) of the mobile phase and with  $-Q_{st}$  in liquid–solid phase systems, respectively.

Finally, the results of thermodynamic studies permit the comparison of surface diffusion data measured in both liquid–solid (RPLC) and gas–solid (GC) systems. Our last point is to compare surface diffusion in both RPLC and GC. Regarding the first point described above, RPLC has a higher degree of freedom than GC in the choice of chromatographic conditions because a wide variety of solvents can be used in the mobile phase, to control the elution strength by changing its composition. This is one of the essential reasons why RPLC is extensively used and became the prominent separation method. Also a huge number of chemicals having most different chemical properties and molecular structures can be used as analytes, as long as they are soluble in the mobile phase.

## 3. A new model of surface diffusion in RPLC

### 3.1. Drawbacks of conventional models of surface diffusion

In many previous studies of surface diffusion [46,47,59], the dependence of  $D_s$  on the temperature and the amount of analyte adsorbed ( $q$ ) is frequently discussed in order to clarify important characteristics of the mechanism of surface diffusion. The conventional model of surface diffusion, i.e., Eq. (4), is used in fundamental studies but this traditional model has drawbacks and cannot properly explain all the experimental data on surface diffusion in RPLC systems.

One of the major drawbacks of Eq. (4) is related to the correlation between  $E_s$  and  $Q_{st}$ . Table 1 [38] compares experimental data ( $K$ ,  $Q_{st}$ ,  $D_s$ , and  $E_s$ ) measured in liquid–solid (RPLC) and gas–solid (GC) systems. The value of  $E_s$  is larger than  $-Q_{st}$  in RPLC systems. This is inconsistent with the concept of surface diffusion, which is regarded as an activated mass transfer process of adsorbed molecules remaining in the adsorbed state (see Fig. 3). Molecules of adsorbates should gain  $E_s$  in order to overcome the energy barrier between two neighboring adsorption sites and migrate, but it is unnecessary that  $E_s$  be larger than  $-Q_{st}$  because molecules do not need to desorb completely from the surface to the bulk liquid phase, they merely need to move in the adsorbed layer of mobile phase. The ratio  $E_s/(-Q_{st})$  should be smaller than unity. However,  $E_s$  is larger than  $-Q_{st}$  for all compounds in Table 1 [38,78,83–86,88,89,104]. Surface diffusion is not expected to take place under such conditions because it would be energetically more advantageous for adsorbate molecules to desorb completely from the surface and diffuse through the mobile phase stagnant in the pores rather than to migrate along the surface.



**Table 1**  
Comparison of thermodynamic properties in liquid–solid and gas–solid phase systems.

Phase system Stationary phase Mobile phase	Liquid–solid C <sub>18</sub> -silica gel Methanol/water (70/30, v/v)				Liquid–solid C <sub>18</sub> -silica gel Acetonitrile/water (70/30, v/v)				Gas–solid C <sub>18</sub> -silica gel Helium			
	ln K <sup>a</sup>	–Q <sub>st</sub> (kJ mol <sup>–1</sup> )	ln D <sub>s</sub> <sup>a</sup>	E <sub>s</sub> (kJ mol <sup>–1</sup> )	ln K <sup>a</sup>	–Q <sub>st</sub> (kJ mol <sup>–1</sup> )	ln D <sub>s</sub> <sup>a</sup>	E <sub>s</sub> (kJ mol <sup>–1</sup> )	ln K <sup>a</sup>	–Q <sub>st</sub> (kJ mol <sup>–1</sup> )	ln D <sub>s</sub> <sup>a</sup>	E <sub>s</sub> (kJ mol <sup>–1</sup> )
Benzene	0.73	6.7	–12.8	19.4	0.43	5.8	–12.0	14.6	6.08	35.3	–12.4	13.5
Toluene	1.28	8.7	–13.0	20.5	0.79	5.8	–12.3	16.2	7.42	40.7	–12.7	17.5
Ethylbenzene	1.75	9.7	–13.2	22.0	1.12	6.1	–12.6	16.6	8.30	43.8	–13.2	23.2
<i>p</i> -Xylene	1.87	10.3	–13.1	23.4	1.17	6.5	–12.6	13.9	8.48	44.6	–13.0	21.1
<i>n</i> -Pentane	2.35	11.8	– <sup>b</sup>	– <sup>b</sup>	1.78	6.2	– <sup>b</sup>	– <sup>b</sup>	4.66	31.7	–12.0	10.2
<i>n</i> -Hexane	2.90	12.6	– <sup>b</sup>	– <sup>b</sup>	2.19	8.2	– <sup>b</sup>	– <sup>b</sup>	5.75	33.4	–12.1	14.1
<i>n</i> -Heptane	3.43	14.8	– <sup>b</sup>	– <sup>b</sup>	2.62	9.6	– <sup>b</sup>	– <sup>b</sup>	6.94	38.2	–12.2	14.4
<i>n</i> -Octane	3.98	17.2	– <sup>b</sup>	– <sup>b</sup>	3.05	10.9	– <sup>b</sup>	– <sup>b</sup>	8.16	43.4	–12.5	17.1
Cyclohexane	2.45	10.4	–13.6	22.2	1.88	6.7	– <sup>b</sup>	– <sup>b</sup>	5.92	33.0	–12.5	15.6
Chlorobenzene	1.20	8.1	–13.0	22.6	0.77	5.9	–12.4	13.8	7.74	40.5	–13.4	25.7

<sup>a</sup> At 298 K.

<sup>b</sup> Not determined.

There are a few papers, however, reporting  $E_s$  values smaller than  $-Q_{st}$  in liquid–solid systems [68,71,75,81]. In contrast,  $E_s/(-Q_{st})$  ratios smaller than unity were measured for surface diffusion in many gas–solid systems [38,47,59–62]. Eq. (4) cannot consistently interpret these contradictory correlations between  $E_s$  and  $Q_{st}$  in liquid–solid and gas–solid systems.

Eq. (4) has another major drawback relating to the value of  $D_{s0}$ . Table 2 [104] lists experimental data for  $Q_{st}$ ,  $K_0$ ,  $E_s$ , and  $D_{s0}$  in a RPLC system consisting of C<sub>18</sub>-silica gel and 70 vol% methanol. Eq. (4) obviously shows that  $D_s$  approaches  $D_{s0}$  when  $Q_{st}$  tends toward zero. Thus,  $D_s$  ranges between ca.  $10^{-3}$  and  $10^{-2}$  cm<sup>2</sup> s<sup>–1</sup> when the interactions of the adsorbate and the stationary phase surface decrease. As listed in Table 2,  $D_{s0}$  in RPLC systems ranges between ca.  $10^{-3}$  and  $10^{-2}$  cm<sup>2</sup> s<sup>–1</sup>. Similar values of  $D_{s0}$  were reported in other solid–liquid systems [38,59,68,69,75,78,81,83,86,88,104]. These results suggest that when  $-Q_{st}$  is small  $D_s$  is still several orders of magnitude larger than the molecular diffusivity ( $D_m$ ) because  $D_m$  is usually of the order of ca.  $10^{-6}$  to  $10^{-5}$  cm<sup>2</sup> s<sup>–1</sup> in liquid solutions [2,46,47,96–99]. This result is unreasonable because diffusion in the bulk cannot be affected by the adsorptive interactions. Surface diffusion should be more restricted and slower than molecular diffusion. It is hard to explain why surface diffusion could be orders of magnitude faster than molecular diffusion even when the analyte is weakly retained. This suggests that Eq. (4) should not be used to study surface diffusion when  $-Q_{st}$  is small. Finally, there is no information on the acceptable range of  $Q_{st}$ , in which Eq. (4) consistently explains the intrinsic characteristics of surface diffusion.

### 3.2. Correlation between surface diffusion and molecular diffusion

As explained above, Eq. (4) cannot be used for quantitative studies of surface diffusion. A new model of surface diffusion must be developed on the basis of analytical results and experimental data on surface diffusion. Chromatographic behavior depends on the nature of the stationary phase (length and density of alkyl ligands bonded to the base silica), the mobile phase (nature and concentration of organic modifiers), the analyte (molecular size, chemical properties, and concentration), and others (temperature) [1,2,38,39,105]. Surface diffusion data measured under different experimental conditions of RPLC were analyzed by taking the correlation between  $D_s$  and  $D_m$  into account [106].

#### 3.2.1. Influence of temperature on $D_s$

The temperature dependence of  $D_s$  and  $D_m$  is illustrated in Fig. 6 [106]. Fig. 6a shows plots of  $D_s$  for alkylbenzene derivatives at 288

and 308 K versus  $D_s$  at 298 K. The  $D_s$  value reasonably increases with increasing temperature. Fig. 6a also shows similar correlations for  $D_m$  of the same compounds at the same temperatures. The solid lines represent the correlation between the  $D_m$  values. The dotted lines are extrapolations of the solid lines. Although Fig. 6a shows a slight scatter, almost all the data-points for  $D_s$  are on the dotted lines, meaning that the temperature dependence of  $D_s$  is very close to that of  $D_m$ . The same conclusion was obtained for *p*-alkylphenol homologs [107].

Similar correlations between  $D_s$  and  $D_m$  under different RPLC conditions are illustrated in Fig. 6b and c, which show  $D_s$  at the same three temperatures, measured for systems made of C<sub>18</sub>-silica gels having four different ligand densities and of methanol/water mixtures of three different compositions. The  $D_s$  values fluctuate around the dotted lines, which are the extrapolations of the solid lines correlating the corresponding  $D_m$  values. The results in Fig. 6a–c indicate that the temperature dependence of  $D_s$  is very close to that of  $D_m$ . Similar results were observed in RPLC systems using acetonitrile/water mixtures [108] and silica gels bonded to alkyl ligands of different lengths [109]. This suggests a close correlation between surface and molecular diffusion.

#### 3.2.2. Influence of chemical properties of sample compounds on $D_s$

Fig. 7 [106] illustrates the correlation between  $D_s$  for alkylbenzene and *p*-alkylphenol homologs. At any temperature, almost the same values of  $D_s$  were observed for analytes having the same alkyl chain (R–) in the two homologous series. The points scatter slightly around the dotted line. A similar correlation is observed for  $D_m$  of the two analyte series, which fit on the solid line. This suggests that the difference between the  $D_s$  values of analytes having the same R– originates from that between their values of  $D_m$ .

#### 3.2.3. Influence of mobile phase composition on $D_s$

Fig. 8 [110] illustrates the influence of the nature of the organic modifier on  $D_s$  and  $D_m$ . Methanol and acetonitrile (ACN) were selected because they are widely used as organic modifiers in RPLC and their influence on chromatographic behavior was studied in detail [111–113]. Values of  $D_s$  measured in RPLC systems using methanol/water (70/30, v/v) are compared with those using ACN/water (70/30, v/v). The points fluctuate slightly around a solid straight line and suggest that  $D_s$  is twice larger in 70 vol% ACN than in 70 vol% methanol. The ratio of the  $D_s$  values is almost constant, irrespective of the analyte and temperature, which was expected because the viscosity of 70 vol% methanol is about twice that of 70 vol% ACN [2,114]. Fig. 8 also illustrates the correlation of  $D_m$  in two RPLC systems using two different mobile phases. Almost all

**Table 2**  
Thermodynamic properties of retention equilibrium and surface diffusion in RPLC system.

Sample	$-Q_{st}$ (kJ mol <sup>-1</sup> )	$K_0$ (cm <sup>3</sup> g <sup>-1</sup> )	$E_s$ (kJ mol <sup>-1</sup> )	$D_{s0}$ (cm <sup>2</sup> s <sup>-1</sup> )	$\Delta H_v^a$ (kJ mol <sup>-1</sup> )	$E_s/-Q_{st}$ (-)
Benzene	6.8	$1.3 \times 10^{-1}$	21.3	$1.0 \times 10^{-2}$	33.8	3.1
Toluene	8.7	$1.1 \times 10^{-1}$	22.0	$9.5 \times 10^{-3}$	38.0	2.5
Ethylbenzene	9.7	$1.2 \times 10^{-1}$	22.9	$1.1 \times 10^{-2}$	42.2	2.4
<i>n</i> -Propylbenzene	11.4	$9.8 \times 10^{-2}$	22.8	$7.7 \times 10^{-3}$	46.2	2.0
<i>n</i> -Butylbenzene	13.0	$8.9 \times 10^{-2}$	24.1	$9.6 \times 10^{-3}$	51.4	1.9
<i>n</i> -Pentylbenzene	15.2	$6.1 \times 10^{-2}$	24.6	$8.7 \times 10^{-3}$	– <sup>b</sup>	1.6
<i>n</i> -Hexylbenzene	17.5	$4.1 \times 10^{-2}$	27.7	$2.3 \times 10^{-2}$	– <sup>b</sup>	1.6
<i>p</i> -Xylene	10.2	$1.0 \times 10^{-1}$	22.1	$8.1 \times 10^{-3}$	42.4	2.2
Phenol	8.3	$1.9 \times 10^{-2}$	20.2	$5.4 \times 10^{-3}$	57.8	2.4
<i>p</i> -Cresol	8.6	$2.7 \times 10^{-2}$	19.0	$2.9 \times 10^{-3}$	– <sup>b</sup>	2.2
<i>p</i> -Ethylphenol	9.9	$2.7 \times 10^{-2}$	20.6	$4.5 \times 10^{-3}$	– <sup>b</sup>	2.1
<i>p</i> -Propylphenol	11.3	$2.6 \times 10^{-2}$	21.1	$4.4 \times 10^{-3}$	– <sup>b</sup>	1.9
<i>p</i> -Butylphenol	13.1	$2.1 \times 10^{-2}$	22.4	$5.8 \times 10^{-3}$	– <sup>b</sup>	1.7
<i>p</i> -Hexylphenol	16.5	$1.6 \times 10^{-2}$	25.1	$1.0 \times 10^{-2}$	– <sup>b</sup>	1.5

<sup>a</sup> At 298 K.

<sup>b</sup> No datum.

the points for  $D_m$  are located on the straight dashed line having a slope unity. They are also twice larger in 70 vol% ACN than in 70 vol% methanol. The  $D_m$  ratio is close to the  $D_s$  ratio. Fig. 8 indicates that difference in  $D_s$  originates from differences in  $D_m$  and that  $D_s$  and  $D_m$  are closely correlated. The same situation is observed in Fig. 9 [115], irrespective of the nature of the organic modifiers, i.e., methanol and ACN, in the aqueous mobile phases.

The influence of the composition ( $\varphi$ ) of methanol/water mixtures on  $D_s$  was also studied. Fig. 10 [106] compares  $D_s$  at  $\varphi = 60$  and 80 vol% with  $D_s$  at  $\varphi = 70$  vol%. Most data points are close to the dotted straight lines. Fig. 10 indicates that variations in  $D_s$  due to changes in  $\varphi$  originate primarily from those in  $D_m$ . It is obvious that  $D_s$  increases with increasing  $\varphi$  in the range of 60–80 vol%. The dependence of  $D_s$  on  $\varphi$  is explained by observing that the viscosity of aqueous solutions of methanol decreases almost linearly with increasing  $\varphi$  between 60 and 80 vol% [2,114]. The results in Figs. 6b and 8–10 demonstrate that the mobile phase composition affects surface diffusion and that the influences of the mobile phase composition on surface and molecular diffusion are similar.

To the best of our knowledge, no correlation between surface and molecular diffusion has yet been demonstrated. So far, surface diffusion was assumed to be completely different from molecular diffusion and adsorbate molecules were thought to diffuse in the adsorbed-phase, on the adsorbent surface [47,59,72,73]. Although the influence of the mobile phase conditions on  $D_s$  was studied in RPLC systems [5,7], few studies in liquid–solid adsorption were devoted to this subject because surface diffusion was assumed to be independent of the chemical and physical properties of the mobile phase [47,59]. Most conventional adsorbents, e.g., activated carbons and hydrophobic resins, were used for the extraction and removal of certain organic compounds from aqueous solutions but solvents other than water were rarely considered. As explained earlier, the general consensus in conventional adsorption was that adsorbents with large adsorption capacity and strong adsorptivity were desirable. It was not conceived that adsorbents with modest adsorptivity could be used to separate selected compounds from complex mixtures, under well defined separation conditions. Because it was unimportant to develop adsorbents with moderate adsorptivity, few studies were made on surface diffusion taking place on adsorbents having small adsorption strength and capacity and almost none on the dependence of  $D_s$  on the intensity of the adsorptive interactions of the analytes.

These reasons explain why the intimate correlation between surface and molecular diffusion could not be recognized in previous studies on surface diffusion [46,47,59]. In contrast, chromatography separates analytes in complex mixtures by taking advantage of small differences in their retention strength on the stationary

phase, which are integrated and amplified during the elution process. Quantitative and detailed studies on surface diffusion in RPLC under weakly retentive conditions have allowed the demonstration of a correlation between surface and molecular diffusion.

### 3.2.4. Influence of the density of $C_{18}$ ligands on $D_s$

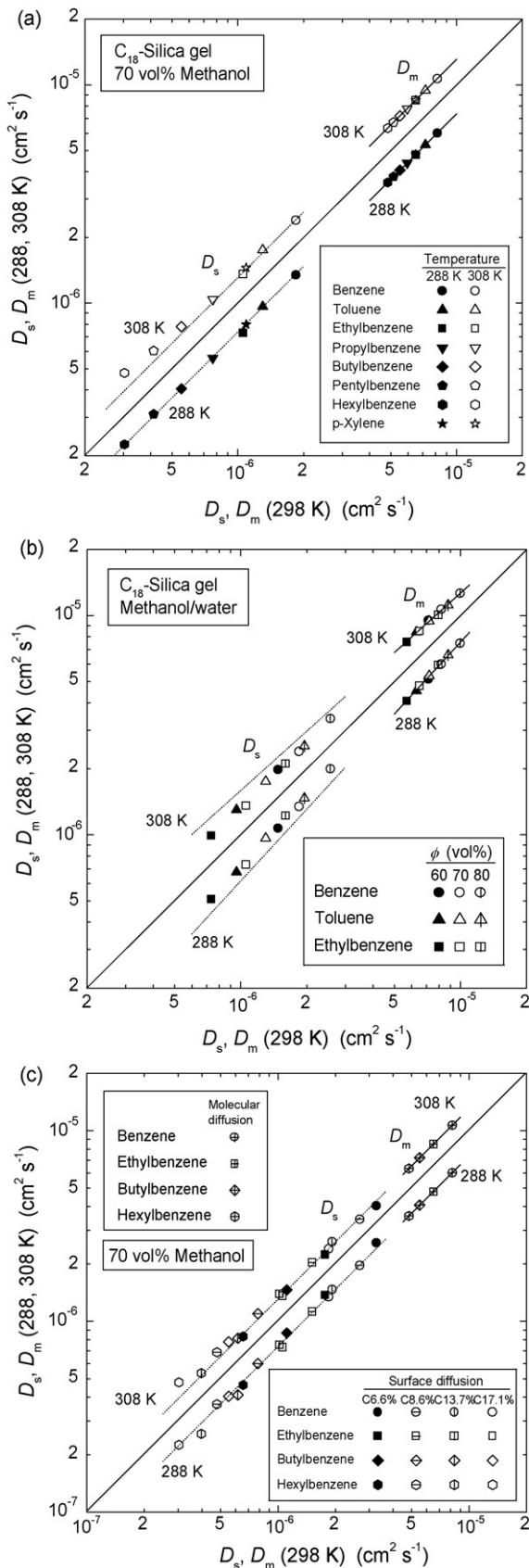
Fig. 11 [106] compares  $D_s$  on three  $C_{18}$  stationary phases, which have carbon contents of 6.6, 8.6, and 13.7 wt%, with  $D_s$  on another  $C_{18}$  phase containing 17.1 wt% carbon. Although the  $D_s$  values on the three  $C_{18}$  phases are different, the data are plotted on three straight lines, parallel to the line for the fourth  $C_{18}$  phase. Irrespective of temperature, the lower the carbon content, the larger is the  $D_s$  value. Fig. 11 also shows the  $D_m$  values, which are plotted on a straight line of slope unity because  $D_m$  is independent of the surface chemistry of the adsorbent. In contrast with the results in Figs. 6 and 8–10, the difference between the  $D_s$  values cannot be accounted for by considering only the change in  $D_m$ . It seems that some factors other than  $D_m$  should be taken into account to explain the influence of the chemical modifications of the stationary phase surface on  $D_s$ .

The influence of the surface chemistry on  $D_s$  was studied with several silica packing materials bonded with alkyl ligands, under various conditions [38,58,116]. The hydrophobicity of the packing materials depends on the length of the bonded alkyl chains and the density of  $C_{18}$  ligands. The retention strength increases with increasing length and density of these alkyl ligands. Surface diffusion becomes more restricted with increasing retention strength. The restriction due to retention could be one of the factors described above. This subject is discussed in the following to develop a new model for surface diffusion.

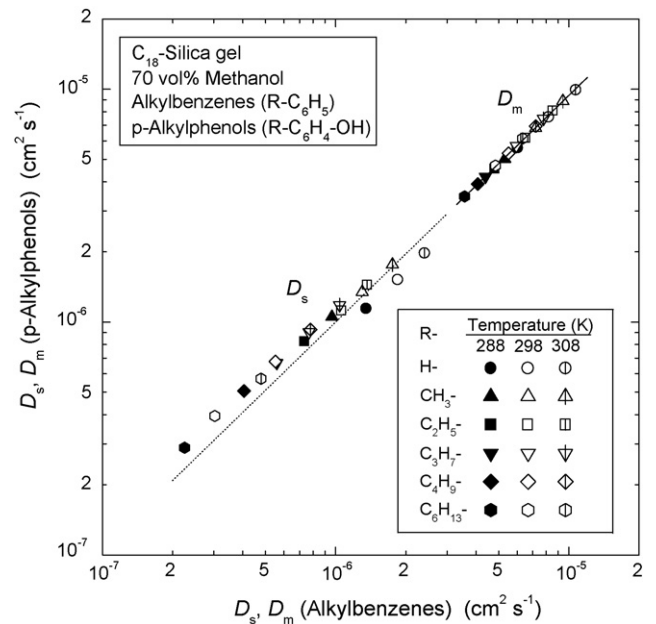
### 3.3. A surface-restricted molecular diffusion model for surface diffusion based on the absolute rate theory

Eq. (4) has conventionally been used as the most important basic formula for discussing the characteristics and mechanism of surface diffusion. However, Eq. (4) has the drawbacks explained above. It cannot consistently interpret contradictory observations on the kinetic and thermodynamic properties of surface diffusion in RPLC systems. A new model and equations must be developed to comprehensively describe the characteristics and mechanism of surface diffusion.

In this study, surface diffusion data measured in RPLC systems were analyzed on the basis of molecular diffusion because surface and molecular diffusion are correlated, as previously explained. It seems that surface diffusion is a diffusive migration of analyte molecules, which originally corresponds to molecular diffusion,



**Fig. 6.** Comparison of temperature dependence of surface diffusion coefficient with that of molecular diffusivity in RPLC systems using (a) alkylbenzene derivatives, (b) methanol/water mobile phases of three different compositions, and (c) four  $C_{18}$  stationary phases of different ligand densities. (Reproduced with permission from Ref. [106].)



**Fig. 7.** Comparison of surface diffusion coefficient with molecular diffusivity of alkylbenzene and p-alkylphenol derivatives at three different temperatures. (Reproduced with permission from Ref. [106].)

but is restricted due to their retention on the adsorbent surface. On this assumption, a surface-restricted molecular diffusion model was proposed as a first approximation for the mechanism of surface diffusion and formulated by applying the absolute rate theory [79].

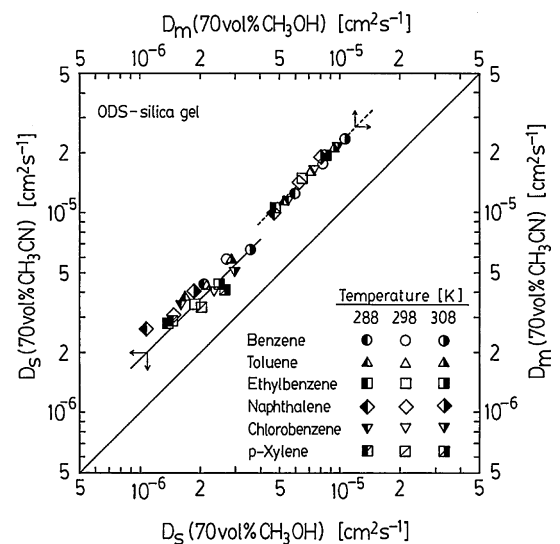
### 3.3.1. Theory

Molecular diffusion in liquid phase is regarded as an activated process

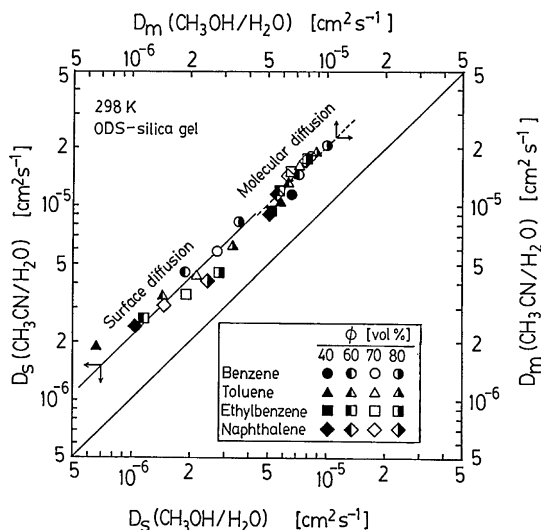
$$D_m = D_{m0} \exp\left(\frac{-E_m}{RT}\right) \quad (6)$$

Another formula, based on the absolute rate theory [79] represents molecular diffusivity ( $D_m$ ) [117]

$$D_m = \lambda^2 \tau \quad (7)$$



**Fig. 8.** Comparison between surface diffusion coefficient and molecular diffusivity for methanol/water and acetonitrile/water mobile phase systems. (Reproduced with permission from Ref. [110].)



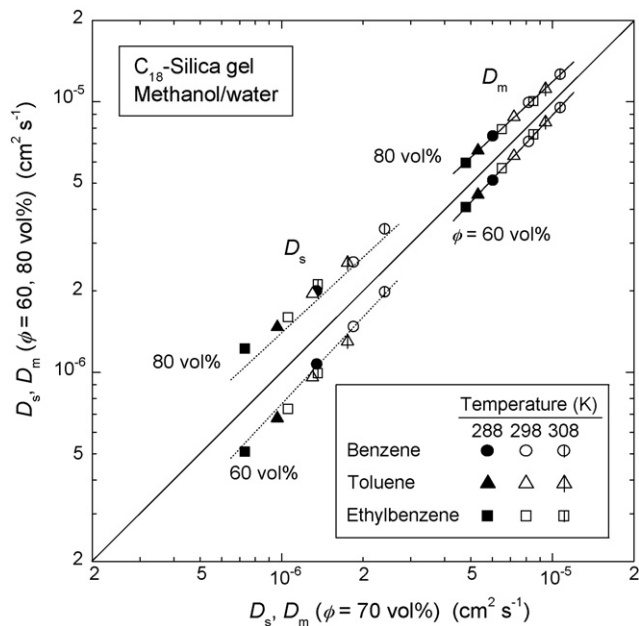
**Fig. 9.** Comparison between surface diffusion coefficient and molecular diffusivity for methanol/water and acetonitrile/water mobile phase systems. (Reproduced with permission from Ref. [115].)

where  $\lambda$  is the distance between two neighbor equilibrium positions and  $\tau$  the rate constant, given as follows when the transmission coefficient is unity.

$$\tau = \left( \frac{k_B T}{h} \right) \left( \frac{F^\ddagger}{F} \right) \exp \left( \frac{-E_m}{RT} \right) \quad (8)$$

where  $F$  and  $F^\ddagger$  are the partition functions for the initial and the activated states, respectively. The ratio of  $F$  to  $F^\ddagger$  is represented as follows when  $F^\ddagger$  contains other contributions than the one due to translation in the direction of the mass transfer in comparison with  $F$ .

$$\frac{F}{F^\ddagger} = \frac{(2\pi m k_B T)^{1/2} v_f^{1/3}}{h} \quad (9)$$



**Fig. 10.** Comparison of dependence of surface diffusion coefficient on mobile phase composition with that of molecular diffusivity in RPLC using methanol/water mixtures of three different compositions. (Reproduced with permission from Ref. [106].)

where  $m$  is the molecular weight,  $k_B$  the Boltzmann constant,  $h$  the Planck constant, and  $v_f$  the free volume. The activation energy of molecular diffusion ( $E_m$ ) should be correlated with the evaporation energy ( $\Delta E_v$ ) of a solvent when the hole-making process in the solvent is essential for the diffusive molecular migration.

$$E_m = \alpha \Delta E_v \quad (10)$$

The following formula for  $D_m$  is derived from Eqs. (7)–(10):

$$D_m = \left( \frac{\lambda^2}{v_f^{1/3}} \right) \left( \frac{k_B T}{2\pi m} \right)^{1/2} \exp \left( \frac{-\alpha \Delta E_v}{RT} \right) \quad (11)$$

$$v_f^{1/3} = \left( \frac{V_{sv}}{N_A} \right)^{1/3} \left( \frac{CRT}{\Delta E_v} \right) \quad (12)$$

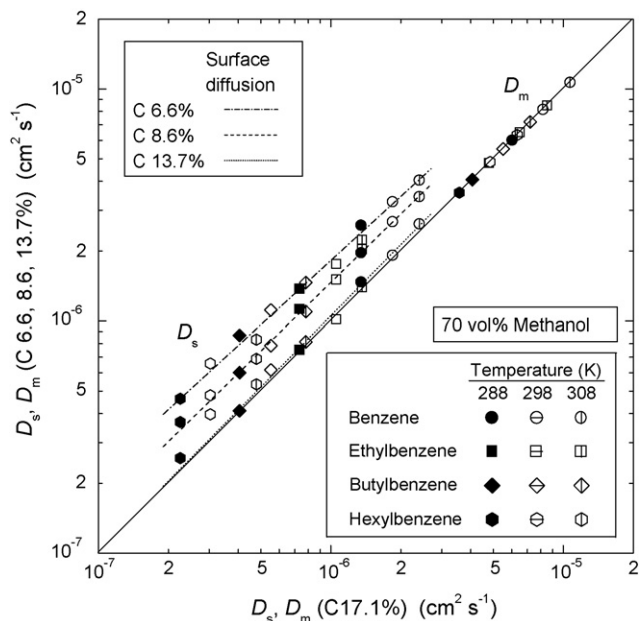
where  $V_{sv}$  is the molar volume of the solvent,  $N_A$  the Avogadro number, and  $C$  a numerical constant. The following formula for  $D_{m0}$  is derived from Eqs. (6) and (11)

$$D_{m0} = \left( \frac{\lambda^2}{v_f^{1/3}} \right) \left( \frac{k_B T}{2\pi m} \right)^{1/2} \quad (13)$$

The value of  $D_{m0}$  can be approximated using Eq. (13). When the absolute rate theory [79] is used to study molecular diffusion, the values of the parameters in Eq. (11),  $\lambda$ ,  $v_f$ ,  $\Delta E_v$ , should be calculated from the intrinsic values of the solute and solvent molecules, by considering the molar fraction of the two components. However, the values of these parameters are almost equal to those of the pure solvent when analyte concentrations are low. The  $D_{m0}$  values estimated by Eq. (13) range from  $3 \times 10^{-3}$  to  $6 \times 10^{-3} \text{ cm}^2 \text{ s}^{-1}$ , values nearly equal to those for self-diffusion of solvent molecules. On the other hand (see Table 3),  $D_{m0}$  values calculated from Arrhenius plots of  $D_m$  range from  $3 \times 10^{-3}$  to  $2 \times 10^{-2} \text{ cm}^2 \text{ s}^{-1}$ . The discrepancy between the two sets of  $D_{m0}$  values increases with increasing molecular weight of analytes. The size difference between solute and solvent molecules affects the accuracy of  $D_{m0}$  estimates.

According to the absolute rate theory [79],  $E_s$  is assumed to consist in the contributions of a hole-making process ( $E_h$ ) and a jumping (bond-breaking) process ( $E_j$ ) [69,71]

$$E_s = E_h + E_j \quad (14)$$



**Fig. 11.** Comparison of surface diffusion coefficient on four different  $C_{18}$  stationary phases with molecular diffusivity. (Reproduced with permission from Ref. [106].)



**Table 3**  
Thermodynamic properties of mass transfer kinetics in liquid–solid phase systems.

Adsorbate	Adsorbent	Solvent	$D_{m0}$ ( $\text{cm}^2 \text{s}^{-1}$ )	$E_m$ ( $\text{kJ mol}^{-1}$ )	$E_{vis}$ ( $\text{kJ mol}^{-1}$ )	$D_{s0}$ ( $\text{cm}^2 \text{s}^{-1}$ )	$E_s$ ( $\text{kJ mol}^{-1}$ )	$\Delta E_v$ ( $\text{kJ mol}^{-1}$ )
<i>p</i> -tert-Octylphenol	C <sub>18</sub> -silica gel (45 μm)	Methanol/water (70/30, v/v)	$2.1 \times 10^{-2}$	21.1	18.1	$3.5 \times 10^{-2}$	27.7	43.3
<i>p</i> -tert-Octylphenol	C <sub>18</sub> -silica gel (24 μm)	Methanol/water (70/30, v/v)	$2.1 \times 10^{-2}$	21.1	18.1	$8.5 \times 10^{-2}$	30.1	43.3
<i>n</i> -Butylbenzene	C <sub>18</sub> -silica gel (45 μm)	Methanol/water (70/30, v/v)	$2.1 \times 10^{-2}$	21.1	18.1	$3.9 \times 10^{-2}$	25.6	43.3
<i>n</i> -Hexylbenzene	C <sub>18</sub> -silica gel (45 μm)	Methanol/water (70/30, v/v)	$2.1 \times 10^{-2}$	21.1	18.1	$7.9 \times 10^{-2}$	28.3	43.3
Anthracene	C <sub>18</sub> -silica gel (45 μm)	Methanol/water (70/30, v/v)	$2.1 \times 10^{-2}$	21.1	18.1	$5.4 \times 10^{-2}$	27.1	43.3
Benzene	NaX Zeolite (10 μm)	Cyclohexane	$2.1 \times 10^{-3}$	14.5	12.7	$1.2 \times 10^{-3}$	37.0	30.2
Benzene	NaX Zeolite (10 μm)	<i>n</i> -Hexane	$2.1 \times 10^{-3}$	10.6	7.4	$1.2 \times 10^{-3}$	32.7	26.1
Benzene	NaX Zeolite (20 μm)	<i>n</i> -Hexane	$2.1 \times 10^{-3}$	10.6	7.4	$3.8 \times 10^{-3}$	35.8	26.1
Phenol	Amberlite XAD-7	Water	$2.1 \times 10^{-2}$	17.8	16.3	$7.1 \times 10^{-4}$	23.5	38.0
Phenol	Amberlite XAD-4	Water	$2.1 \times 10^{-2}$	17.8	16.3	$1.1 \times 10^{-1}$	41.6	38.0
Benzaldehyde	Amberlite XAD-7	Water	$2.1 \times 10^{-2}$	17.5	16.3	$1.4 \times 10^{-1}$	39.8	38.0
Benzaldehyde	Amberlite XAD-4	Water	$2.1 \times 10^{-2}$	17.5	16.3	$1.1 \times 10^{-3}$	28.8	38.0
Acetone	Alumina	Cyclohexane	$2.1 \times 10^{-3}$	14.7	12.7	$5.1 \times 10^{-3}$	21.6	30.3
Ethylacetate	Alumina	Cyclohexane	$2.1 \times 10^{-3}$	14.7	12.7	$2.7 \times 10^{-3}$	19.2	30.3
1-Nitropropane	Alumina	Cyclohexane	$2.1 \times 10^{-3}$	14.7	12.7	$4.6 \times 10^{-4}$	16.6	30.3
Propionic acid	Activated carbon	Water	$2.1 \times 10^{-2}$	18.9	16.3	$5.2 \times 10^{-1}$	35.0	38.1

Adsorbate	Adsorbent	Solvent	$\alpha$	$E_{vis}/\Delta E_v$	$-Q_{st}$ ( $\text{kJ mol}^{-1}$ )	$E_s - E_m$ ( $\text{kJ mol}^{-1}$ )	$\beta$	Data no.	Ref. no.
<i>p</i> -tert-Octylphenol	C <sub>18</sub> -silica gel (45 μm)	Methanol/water (70/30, v/v)	0.49	0.42	16.9	6.6	0.39	1	83
<i>p</i> -tert-Octylphenol	C <sub>18</sub> -silica gel (24 μm)	Methanol/water (70/30, v/v)	0.49	0.42	16.2	9.0	0.56	2	83
<i>n</i> -Butylbenzene	C <sub>18</sub> -silica gel (45 μm)	Methanol/water (70/30, v/v)	0.49	0.42	13.0	4.5	0.35	3	110
<i>n</i> -Hexylbenzene	C <sub>18</sub> -silica gel (45 μm)	Methanol/water (70/30, v/v)	0.49	0.42	17.5	7.2	0.41	4	110
Anthracene	C <sub>18</sub> -silica gel (45 μm)	Methanol/water (70/30, v/v)	0.49	0.42	15.7	6.0	0.38	5	110
Benzene	NaX Zeolite (10 μm)	Cyclohexane	0.48	0.42	24.3	22.5	0.93	6	78
Benzene	NaX Zeolite (10 μm)	<i>n</i> -Hexane	0.41	0.28	23.9	22.1	0.92	7	78
Benzene	NaX Zeolite (20 μm)	<i>n</i> -Hexane	0.41	0.28	25.1	25.2	1.0	8	78
Phenol	Amberlite XAD-7	Water	0.47	0.43	23.6	5.7	0.24	9	71
Phenol	Amberlite XAD-4	Water	0.47	0.43	33.8	23.8	0.70	10	71
Benzaldehyde	Amberlite XAD-7	Water	0.46	0.43	18.3	22.4	1.2	11	68
Benzaldehyde	Amberlite XAD-4	Water	0.46	0.43	46.9	11.3	0.24	12	68
Acetone	Alumina	Cyclohexane	0.49	0.42	15	6.9	0.46	13	88
Ethylacetate	Alumina	Cyclohexane	0.49	0.42	16	4.5	0.28	14	88
1-Nitropropane	Alumina	Cyclohexane	0.49	0.42	11	1.9	0.17	15	88
Propionic acid	Activated carbon	Water	0.49	0.43	45.6	16.1	0.35	16	75

A linear correlation between  $E_j$  and  $Q_{st}$  was assumed, so  $E_s$  is linearly correlated with  $Q_{st}$  [69,71]

$$E_s = E_h + \beta(-Q_{st}) \quad (15)$$

The two terms in the right hand side (RHS) of Eq. (15) represent the contributions to  $E_s$  of the hole-making and the jumping process, respectively. The hole (cavity) is generated by removing solvent molecules, in the potential field of adsorption. The value of  $E_h$  should be correlated with that of  $\Delta E_v$  of the solvent.

After a hole is made, an analyte molecule can transfer from a neighbor adsorption site into the hole. The jumping process requires the gain of the activation energy needed for breaking the retention of the sample molecule onto the adsorbent surface. It is probably sufficient for the molecule to gain the amount of activation energy that is necessary for surmounting the retentive interactions and migrating to the hole in the potential field of adsorption. Because  $Q_{st}$  is the stabilization energy of the analyte molecule,  $E_j$  should be correlated with  $Q_{st}$ . The ratio of  $E_j$  to  $-Q_{st}$  is expressed as  $\beta$ , the value of which should be positive and smaller than unity. Eq. (15) is represented as follows:

$$E_s = \alpha \Delta E_v + \beta(-Q_{st}) \quad (16)$$

The following equation is derived by combining Eqs. (10) and (16)

$$E_s = E_m + \beta(-Q_{st}) \quad (17)$$

As a first approximation, the first term in the RHS of Eq. (16) is assumed to be equal to  $E_m$ . The retentive interactions between analyte molecules and the adsorbent surface make the difference between molecular and surface diffusion, as illustrated in Fig. 12 [118].

It would be possible to estimate  $D_{s0}$  using Eq. (13) and following an approach similar to that used for  $D_{m0}$ . This would require appropriate information on the parameters,  $\lambda$ ,  $v_f$ , and  $m$ . Unfortunately, however, the parameters in Eqs. (12) and (13) cannot accurately be estimated in a potential field of adsorption. The absolute rate theory recommends that the value of the parameters be calculated from the intrinsic properties of both solvent and solute by considering their molar fractions. However, it is quite difficult to determine molar fractions in the vicinity of the adsorbent surface

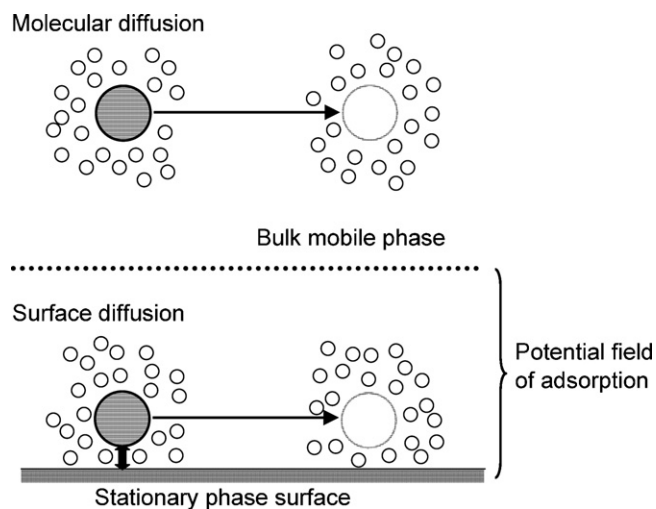


Fig. 12. Schematic illustration of surface diffusion and molecular diffusion. (Reproduced with permission from Ref. [118].)

and the physical properties and structural characteristics are probably different in the potential field of adsorption from what they are under unrestricted conditions in the bulk phase. The values of  $\lambda$ ,  $\nu_f$ , and  $C$  must be adjusted. It is concluded that accurate value of  $D_{s0}$  cannot be calculated at present.

We assume that the parameters of Eq. (13) are almost constant in a narrow temperature range. A temperature change has probably little effect on  $D_{s0}$  which is proportional to  $T^{-1/2}$ . Then it is possible to quantitatively analyze  $D_s$  in the assumption that  $D_{s0}$  is independent of the temperature in a narrow temperature range. Although  $D_{s0}$  cannot be accurately estimated,  $D_{s0}$  seems to be of the same order of magnitude as  $D_{m0}$  when the properties of the solvent and the analyte molecules are similar. Therefore, the following equations derived from Eqs. (2), (16), and (17) are proposed [110,117]

$$D_s \approx D_{s0} \exp \left[ \frac{-(E_m + \beta(-Q_{st}))}{RT} \right] \quad (18)$$

$$D_s \approx D_{s0} \exp \left[ \frac{-(\alpha \Delta E_v + \beta(-Q_{st}))}{RT} \right] \quad (19)$$

Eqs. (18) and (19) are valid at zero surface coverage of the adsorbate.

The dependencies of  $D_s$  on the temperature and on the amount adsorbed were the topics of many studies. The temperature and concentration dependencies of  $D_s$  reflect some important characteristics of surface diffusion. At first, the Arrhenius-type equation serves to represent the temperature dependence of  $D_s$  because surface diffusion is regarded as an activated process. On the other hand, the concentration dependence of  $D_s$  is frequently explained by considering the gradient of chemical potential ( $d \ln C / d \ln q$ ) or the value of  $Q_{st}$ , which originates from the change in  $q$  as the driving force. The value of  $D_s$  for a certain amount adsorbed ( $D_s(q)$ ) is represented as the product of  $D_s$  at zero surface coverage ( $D_s(0)$ ) and the value of ( $d \ln C / d \ln q$ )

$$D_s(q) = D_s(0) \left( \frac{d \ln C}{d \ln q} \right) \quad (20)$$

The following equation is derived from Eqs. (18) and (20)

$$D_s(q) = D_{s0} \left( \frac{d \ln C}{d \ln q} \right) \exp \left[ \frac{-(E_m + \beta(-Q_{st}))}{RT} \right] \quad (21)$$

Eq. (21) explains both the temperature and the concentration dependencies of  $D_s$ .

The change in  $Q_{st}$  originating from the change in  $q$  is correlated with the change in the adsorption potential ( $E_{ap}$ ) [71–73,119]

$$Q_{st} = q_{st} - E_{ap} \quad (22)$$

$$Q_{st} = q_{st} - RT \ln \left( \frac{C_s}{C} \right) \quad (23)$$

where  $C$  and  $C_s$  are the concentration and the saturation concentration of the adsorbate in the solvent, respectively. The value of  $q_{st}$  is the isosteric heat of adsorption at  $C = C_s$ . It may be constant irrespective of  $q$  and equal to the heat of solution [119]. The following equation is obtained from Eqs. (21) and (22)

$$D_s(q) = D_{s0} \left( \frac{d \ln C}{d \ln q} \right) \exp \left[ \frac{-(E_m + \beta(-q_{st} + E_{ap}))}{RT} \right] \quad (24)$$

The influence of  $q$  on  $D_{s0}$  is not considered in Eq. (24), which explains the concentration dependence of  $D_s$  in terms of the change in both ( $d \ln C / d \ln q$ ) and  $E_{ap}$ . Eq. (24) is also effective for consistently explaining the temperature dependence of  $D_s$  [117].

The contribution of  $E_{ap}$  to  $E_h$  must be considered when solvent molecules are also adsorbed on the surface. The total value of  $E_h$  is the sum of  $\Delta E_v$  of the solvent and  $E_{ap}$ , which is the free energy required for the transfer of adsorbed solvent molecules from the

potential field of adsorption to the bulk phase and is calculated by the following equation:

$$E_{ap} = RT \ln \left( \frac{C_s}{C} \right) \quad (25)$$

However,  $E_{ap}$  of adsorbable solvents is probably smaller than  $\Delta E_v$ , which frequently ranges around 30–40 kJ mol<sup>-1</sup>, because the concentration of the solvent is usually so high. On the other hand, it is not required to consider the influence of  $E_{ap}$  on  $E_h$  when the solvent is not adsorbed on the surface. In conclusion, the value of  $E_m$  is probably equal to  $E_h$  in the activation process of surface diffusion.

### 3.3.2. Analysis of molecular diffusion on the basis of the absolute rate theory

There is an intimate correlation between surface and molecular diffusion and the intrinsic characteristics and mechanism of surface diffusion should be studied by taking those of molecular diffusion into account. At first, some characteristics of molecular diffusion are analyzed on the basis of the absolute rate theory [79].

Table 3 [110] lists  $E_m$  in Eq. (6), calculated from the temperature dependence of  $D_m$ . The average value of  $\alpha$  in Eq. (10) ( $=E_m/\Delta E_v$ ) is estimated as about 0.47. The activation energy of the viscosity ( $E_{vis}$ ) of various solvents is calculated as about 40% of  $\Delta E_v$ , as listed in Table 3. Similar values of  $E_{vis}/\Delta E_v$  in the range from ca. 0.25 to 0.33 were reported [79]. It seems that similar values are observed for  $E_m$  and  $E_{vis}$  because the mechanisms of diffusion and viscosity are similar. The viscosity of a solvent results from the migration of its molecules through a crowd of the same molecules. In molecular diffusion, different molecules (those of the analyte) migrate through the solvent molecules. The size of the cavity must be larger for molecular diffusion than for viscosity because analyte molecules are usually larger than solvent molecules. The value of  $E_m$ , being slightly larger than  $E_{vis}$  probably reflects the difference in the sizes of the cavities. It was shown that the absolute rate theory predicts  $E_h$  to be sufficiently larger than  $E_j$  [71,73,79] and almost equal to  $E_m$  [79].

### 3.3.3. Analysis of surface diffusion on the basis of the absolute rate theory

Some surface diffusion data in various liquid–solid systems including RPLC are analyzed in order to prove the validity of the surface-restricted molecular diffusion model for surface diffusion [38,39,106,107,110,115–117,120–125].

3.3.3.1. Analysis of temperature dependence of  $D_s$ . According to Eq. (18), the value of ( $\ln D_s + E_m/RT$ ) is plotted against ( $-Q_{st}/RT$ ) in Figs. 13–15 [110]. The value of  $\beta$  derived from the slopes of the linear correlations in Figs. 13–15 is between 0.2 and 0.5 in most cases (see Table 3), which means that adsorbate molecules must gain an activation energy between one fifth and one half of  $-Q_{st}$ , in order to overcome the adsorptive interactions and jump into the next hole. This is consistent with the results for surface diffusion in gas–solid adsorption [59–62]. Similarly,  $D_{s0}$  are calculated from the intercept of the linear correlations. Table 3 shows that  $D_{s0}$  is of the order of magnitude of  $D_{m0}$  in many cases, although their values are not in complete agreement. Similar values of  $D_{s0}$  were previously reported for various adsorbates [38,84–86] (see Table 3). As described above, the discrepancy between  $D_{s0}$  and  $D_{m0}$  may partially be attributed to the influence of  $E_{ap}$ , due to the presence of the adsorbent.

An error in the determination of  $D_{s0}$  may also be a cause of discrepancy. For instance,  $D_{s0}$  is calculated as  $3.2 \times 10^{-2} \text{ cm}^2 \text{ s}^{-1}$  if  $D_s$  is  $1 \times 10^{-5} \text{ cm}^2 \text{ s}^{-1}$  at 298 K and  $E_s$  is 20 kJ mol<sup>-1</sup>. Similarly, if  $E_s$  is 21 kJ mol<sup>-1</sup>,  $D_{s0}$  is  $4.8 \times 10^{-2} \text{ cm}^2 \text{ s}^{-1}$ . A 5% error in  $E_s$  may cause an error of 50% in  $D_{s0}$ . This hypothetical calculation indicates that accurate determinations of  $D_{s0}$  are difficult if the conventional

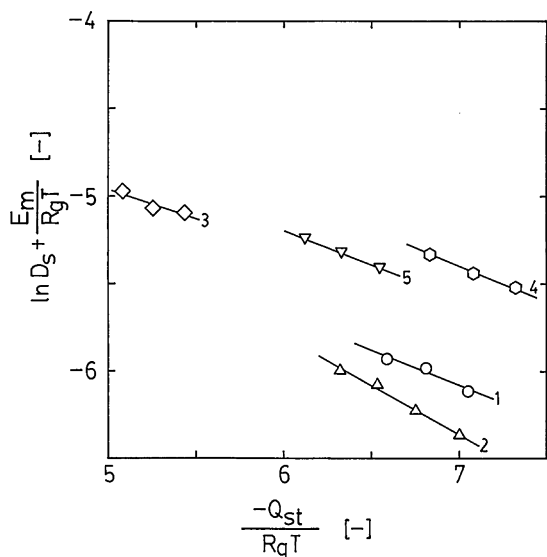


Fig. 13. Correlation of  $(\ln D_s + E_m/R_g T)$  with  $-Q_{st}/R_g T$  for RPLC systems. Data numbers: refer to Table 3. (Reproduced with permission from Ref. [110].)

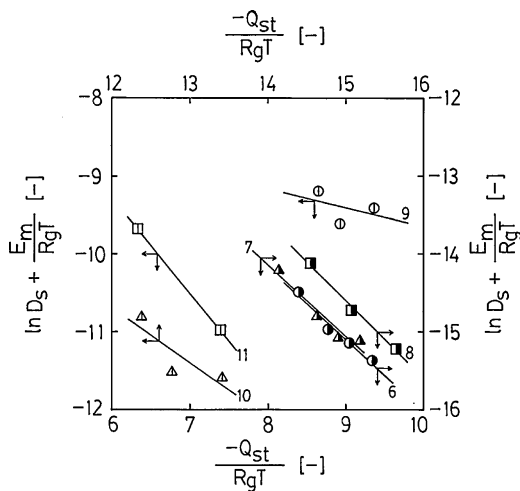


Fig. 14. Correlation of  $(\ln D_s + E_m/R_g T)$  with  $-Q_{st}/R_g T$  for liquid phase adsorption systems. Data numbers: refer to Table 3. (Reproduced with permission from Ref. [110].)

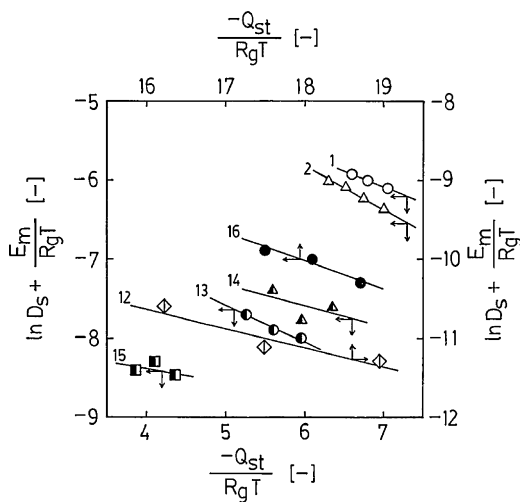


Fig. 15. Correlation of  $(\ln D_s + E_m/R_g T)$  with  $-Q_{st}/R_g T$  for liquid phase adsorption systems. Data numbers: refer to Table 3. (Reproduced with permission from Ref. [110].)

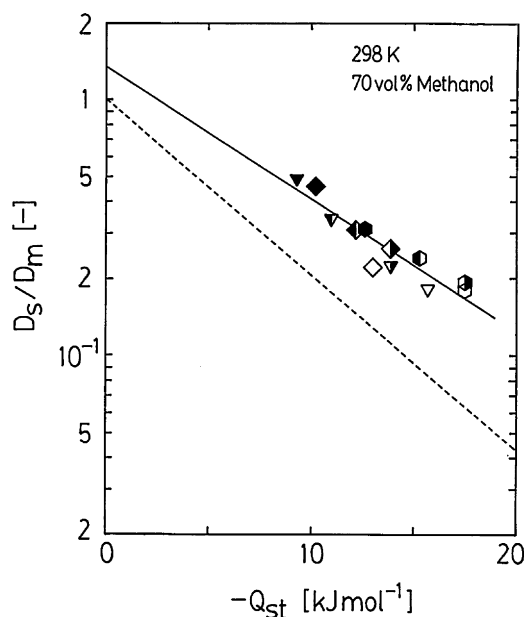
Arrhenius plot is used. Similarly, Krug et al. [126–128] severely criticized the drawbacks of the conventional Arrhenius plot and pointed out two major problems. One is the dependence of the intercept on the slope of the Arrhenius plot. The intercept of the extrapolated Arrhenius plot varies in connection with a change in its slope. The other one is the long distance between the intercept of the extrapolated line and the data points plotted in the range of experimental temperatures. The potential for the error is extremely high when the intercept at  $1/T = 0 \text{ K}^{-1}$  is far from the experimental data points. A small fluctuation of the slope causes a large variation in the intercept. Chromatographic experiments in RPLC are mostly carried out between ca. 273 and 323 K. The distance between the intercept and the data points, of the order of  $1/298$ , is more than five times larger than the experimental range,  $1/273\text{--}1/323$ . The important scatter observed for aqueous adsorption systems in Figs. 14 and 15 suggests that the influence of changes in the chemical properties and structure of water molecules on molecular diffusivity must be considered in quantitative analyses of  $D_{s0}$ . Further progress through fundamental studies of the properties and structure of solvents are essential.

In previous papers [69,71,84],  $E_s$  was linearly correlated with  $Q_{st}$  as suggested in Eq. (17). The values of  $E_m$  and  $-Q_{st}$  correspond to the hole-making and the jumping steps, respectively. Itaya et al. [71] reported a linear correlations between  $\ln D_s$  and  $(-Q_{st}/RT)$  and found that  $\beta$  ranges from 0.3 to 0.6, in sufficient agreement with the  $\beta$  values listed in Table 3. Itaya et al. [71] showed that  $E_m$  is larger for Amberlite XAD-4 than for XAD-7 and that this result cannot be explained because XAD-7 is more hydrophilic than XAD-4 and because water molecules should be more adsorbed on XAD-7 than on XAD-4. However, when polar solvent molecules interact with a hydrophobic surface, they mutually repulsed each other. The solvent molecules may be compressed and their interactions may be amplified by the structure-making effect. The larger value of  $E_m$  for the more hydrophobic adsorbent XAD-4 probably originates from the solvent structure-making effect because the values of  $v_f$  and  $C$  in Eqs. (11)–(13) would also change. According to the absolute rate theory [79],  $E_m$  is regarded as the activation energy for the hole-making step and is correlated with  $\Delta E_v$  of the solvent. Solvent structure-making is accelerated when the solvent molecules are significantly attracted on the adsorbent surface or repulsed from the surface. In such cases, the larger value of  $E_m$  may be expected.

**3.3.3.2. Analysis of the dependence of  $D_s$  on the retention strength.** In the surface-restricted diffusion model, the influence of the adsorptive interactions on surface diffusion is considered by correlating  $Q_{st}$  with the activation energy of the jumping step,  $E_j$ . The dependence of  $D_s$  on the retention strength was studied by changing the chain length of the alkyl ligands bonded to a silica gel. Although the influence of chemical modifications of the silica surface on  $D_{s0}$  cannot exactly be evaluated, a correlation of  $D_s$  with the retention strength was attempted by assuming that the parameters in Eq. (11) are constant, irrespective of the alkyl chain length. The following equation is derived from Eqs. (6) and (18):

$$\ln \left( \frac{D_s}{D_m} \right) = \ln \left( \frac{D_{s0}}{D_{m0}} \right) - \beta \left( \frac{-Q_{st}}{RT} \right) \quad (26)$$

Eq. (26) suggests that  $\ln(D_s/D_m)$  is linearly correlated with  $-Q_{st}$ . The almost linear plot in Fig. 16 [110] proves the validity of Eq. (26). From the slope of this plot,  $\beta$  is estimated to be about 0.4 for RPLC systems based on ODS-silica gel. Fig. 16 also illustrates a linear correlation (dotted line) between  $\ln(D_s/D_m)$  and  $-Q_{st}$ , which was calculated by assuming  $\beta = 0.4$  and  $D_{s0} = D_{m0}$ . The dotted and solid lines are nearly parallel, which correlates the experimental data. However, the solid line is two to three times higher than the dotted, a discrepancy probably due to errors made in estimating  $D_{s0}$  and  $D_{m0}$ . Fig. 17 [110] illustrates the correlation (dotted line)



**Fig. 16.** Ratio of surface diffusion coefficient to molecular diffusivity as a function of isosteric heat of adsorption. Symbols: refer to Fig. 17. (Reproduced with permission from Ref. [110].)

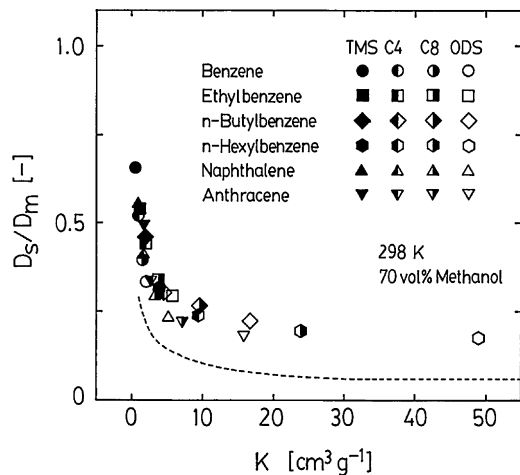
between  $D_s/D_m$  and  $K$ , calculated on the basis of the dotted line in Fig. 16. The temperature dependence of  $K$  is usually represented by the van't Hoff equation

$$K = K_0 \exp\left(\frac{-Q_{st}}{RT}\right) \quad (27)$$

where  $K_0$  is  $K$  at  $1/T=0\text{ K}^{-1}$  or  $Q_{st}=0\text{ kJ mol}^{-1}$ . The combination of Eqs. (26) and (27) provides the following equation:

$$\frac{D_s}{D_m} = \left(\frac{D_{s0}}{D_{m0}}\right) \left[\exp\left(\frac{Q_{st}}{RT}\right)\right]^\beta = \left(\frac{D_{s0}}{D_{m0}}\right) \left(\frac{K_0}{K}\right)^\beta \quad (28)$$

Eq. (28) shows that  $D_s/D_m$  is inversely proportional to  $K$  (see Fig. 17). The results in Figs. 16 and 17 indicate that  $D_s$  can be approximated on the basis of the retention strength even when  $K$  or  $-Q_{st}$  are quite small. The influence of the retention strength on surface diffusion is further discussed in the following section.



**Fig. 17.** Ratio of surface diffusion coefficient to molecular diffusivity as a function of adsorption equilibrium constant. (Reproduced with permission from Ref. [110].)

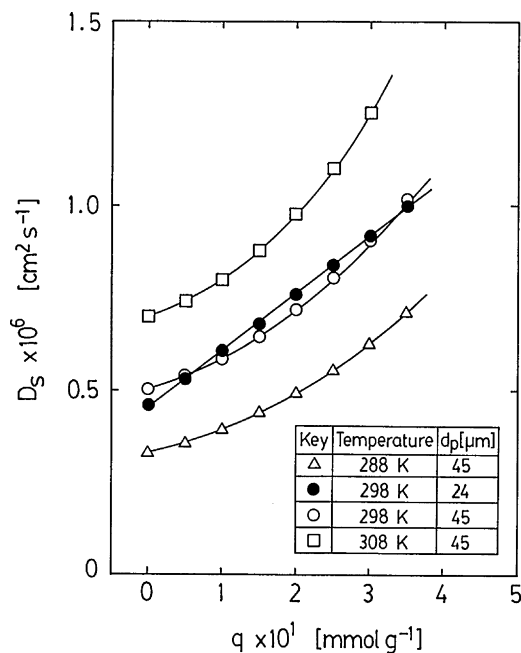
### 3.4. Comprehensive interpretation of the temperature and concentration dependencies of surface diffusion

Eq. (24) was applied to quantitatively analyze important characteristics of surface diffusion in liquid–solid systems with different equilibrium isotherms, the Langmuir, Freundlich and Jossens type isotherms [117]. Only the results for Langmuir systems are reported in this review because this model is more frequently used to represent adsorption isotherms in RPLC systems than the other two isotherms. However, Table 4 [117] compares the characteristic features of these different adsorption systems.

Fig. 18 [117] illustrates the concentration dependence of  $D_s$  at different temperatures. As the amount of *p*-tert-octylphenol (PTOP) adsorbed increases to ca. 60% of saturation ( $0.67\text{ }\mu\text{mol g}^{-1}$ ),  $D_s$  increases two to three times. Eq. (24) includes two factors,  $(d \ln C/d \ln q)$  and  $E_{ap}$ , which depend on  $q$ . The adsorption isotherm of PTOp on a  $C_{18}$ -silica from 70 vol% methanol is represented by the Langmuir equation [38,83]

$$q = \frac{q_\infty K_L}{1 + K_L C} \quad (29)$$

where  $q_\infty$  and  $K_L$  are the saturation capacity and the adsorption constant, respectively. At each surface coverage of PTOp,  $|Q_{st}|$  ranges from ca. 16 to 18  $\text{kJ mol}^{-1}$  regardless of  $q$  and the particle size of the  $C_{18}$ -silica gel, suggesting that  $E_{ap}$  is probably constant during the adsorption process. On the other hand,  $E_s$  was about 25–28  $\text{kJ mol}^{-1}$  ( $d_p = 45\text{ }\mu\text{m}$ ,  $q = 0\text{--}0.3\text{ }\mu\text{mol g}^{-1}$ ) and about 30  $\text{kJ mol}^{-1}$  ( $d_p = 24\text{ }\mu\text{m}$ ,  $q = 0\text{ }\mu\text{mol g}^{-1}$ ), irrespective of  $q$ . The surface of the  $C_{18}$ -silica particles can be regarded as energetically homogeneous because (1)  $Q_{st}$  and  $E_s$  are almost constant, irrespective of  $q$ ; and (2) the adsorption isotherm can be expressed by the simple Langmuir equation. The apparent homogeneity of the  $C_{18}$ -silica surface was also assumed in a theoretical analysis of adsorption behavior of 2-phenylethanol and 3-phenylpropanol from a methanol/water mixture [129]. These results indicate that the concentration dependence of  $D_s$  in the RPLC system cannot be accounted for by considering only the changes in  $Q_{st}$  and  $E_{ap}$ .



**Fig. 18.** Concentration dependence of  $D_s$ . (Reproduced with permission from Ref. [117].)



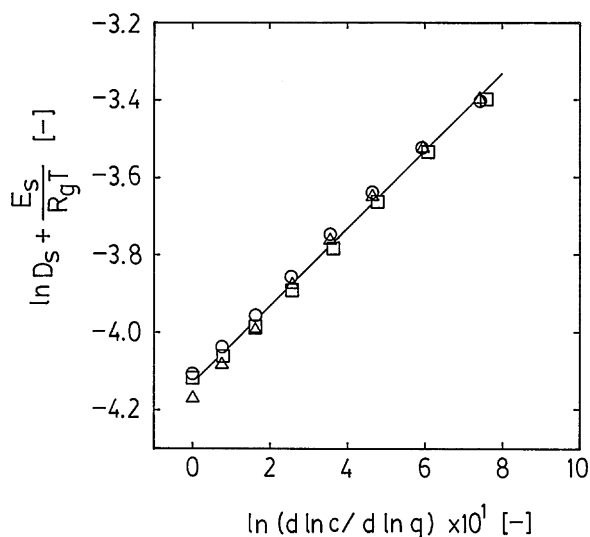
**Table 4**  
Comparison of temperature and concentration dependence of  $D_s$  in three different liquid–solid phase adsorption systems.

Reference	#83	#75	#71
Experimental conditions			
Isotherm	Langmuir	Freundlich	Jossens
$q = q_0 K_L c / (1 + K_L c)$	$q = K_F c^{1/n}$	$c = (q/H) \exp(K_J q^p)$	
Adsorbent	C <sub>18</sub> -silica gel	Activated carbon (HGR513)	Amberlite XAD-4, XAD-7
Solvent	Methanol/water (70/30, v/v)	Water	Water
Adsorbate	<i>p</i> - <i>tert</i> -Octylphenol	Propionic acid	Phenol
Temperature	288, 298, 308 K	293, 303, 313 K	303 K
Method	Pulse response-moment analysis	Steady-state diffusion experiment	Batch adsorption
Concentration dependence			
$d \ln c / d \ln q$	$1 + K_L c$	$n$	$1 + K_J p q^p$
Not constant	Constant	Not constant	
$Q_{st}$	Constant	Not constant	Not constant
$E_{ap}$	Constant	Not constant	Not constant
Results			
$\beta$ (average)	0.31	0.56	0.25 (XAD-4), 0.55 (XAD-7)
$q_{st}$	Not determined	$-5.9 \text{ kJ mol}^{-1}$	$-9.2 \text{ kJ mol}^{-1}$ (XAD-4), $-1.9 \text{ kJ mol}^{-1}$ (XAD-7)
Remarks			
	Concentration dependence of $D_s$ is attributed to the change in $(d \ln q / d \ln c)$ , and cannot be explained by considering the change in $Q_{st}$ and $E_{ap}$ .	Concentration dependence of $D_s$ is attributed to the change in $Q_{st}/E_{ap}$ , and cannot be explained by considering the change in $(d \ln q / d \ln c)$ .	Concentration dependence of $D_s$ is attributed to the change in both $Q_{st}$ ( $E_{ap}$ ) and $(d \ln q / d \ln c)$ , and can be explained by Eq. (24).
	Both temperature and concentration dependence of $D_s$ can be interpreted by Eq. (21) or Eq. (24).	Both temperature and concentration dependence of $D_s$ can be interpreted by Eq. (24).	No information was obtained for the applicability of Eq. (24) to the interpretation of temperature dependence of $D_s$ .

In the case of Langmuir isotherm,  $D_s(q)$  should be correlated with  $(d \ln C / d \ln q)$ .

$$\frac{d \ln C}{d \ln q} = 1 + K_L C \quad (30)$$

The data in Fig. 18 are transformed to a full-logarithmic plot between  $D_s(q)$  and  $(d \ln C / d \ln q)$  [117]. Linear correlations with a slope close to unity are obtained between  $\ln D_s(q)$  and  $\ln(d \ln C / d \ln q)$  at each temperature. A similar linear correlation is observed for the 24  $\mu\text{m}$  C<sub>18</sub>-silica at 298 K. These results suggest that the positive concentration dependence of  $D_s$  can be explained by considering the changes in  $(d \ln C / d \ln q)$ . Fig. 19 [117] shows the plot of  $(\ln D_s + E_s / RT)$  versus  $(d \ln C / d \ln q)$ , according to Eqs. (17) and (21), assuming that  $D_{s0}$  is independent of  $q$ . The plots at the different temperatures can be represented by a single straight line of slope unity. Fig. 19 demonstrates that Eq. (21) can comprehensively



**Fig. 19.** Correlation between  $(\ln D_s + E_s / R_g T)$  and  $\ln(d \ln C / d \ln q)$  in a Langmuir-type adsorption system. Keys: refer to Fig. 18. (Reproduced with permission from Ref. [117].)

interpret both the temperature and the concentration dependencies of  $D_s$  in Langmuir-type adsorption. Table 4 summarizes some characteristics of the three types of adsorption systems [117].

### 3.5. Restriction energy for surface diffusion

Some experimental results emphasize two important characteristics of surface diffusion, i.e., (1) there is a close correlation between surface and molecular diffusion; and (2) molecular migration by diffusion on the adsorbent surface is restricted by retentive interactions because surface diffusion is the mass transfer of analyte molecules in the adsorbed state. It is effective to consider the mechanism of surface diffusion as similar to that of molecular diffusion and to analyze the correlation between surface diffusion and retention strength. On the basis of these results,  $D_s$  can be represented as follows:

$$D_s = D_m \exp\left(-\frac{E_r}{RT}\right) \quad (31)$$

where  $E_r$  is the restriction energy for surface diffusion due to the retentive interactions, which should be correlated with  $Q_{st}$ . Fig. 20 [107] illustrates the correlations between  $E_r$ , which is calculated from the values of  $D_s$  and  $D_m$  at 298 K, and  $Q_{st}$ . The points are scattered around a straight line, irrespective of the type of analyte. Its slope is 0.3, suggesting that the restriction for surface diffusion corresponds to about one-third of the enthalpy change due to retention. Fig. 21 [58] shows a similar plots between  $E_r$  and  $Q_{st}$ . The slope of the linear correlations ranges from 0.28 to 0.35. These results are reasonable because adsorbed analyte molecules do not need to be completely desorbed from the adsorbent surface when they migrate by surface diffusion.

Finally, the intercepts of the straight lines in Fig. 21 [58] depend on the surface chemistry of the adsorbent. The intercept fluctuates around  $0 \text{ kJ mol}^{-1}$  in the case of a low density of C<sub>18</sub> ligands and short alkyl chain (C<sub>1</sub>). It seems that it increases with increasing density of C<sub>18</sub> ligands. This probably reflects the physico-chemical situation of the mobile phase near the adsorbent surface because surface diffusion takes place in the vicinity of this boundary layer. The solvent properties in the potential field of adsorption are different from those of the bulk solvent. When

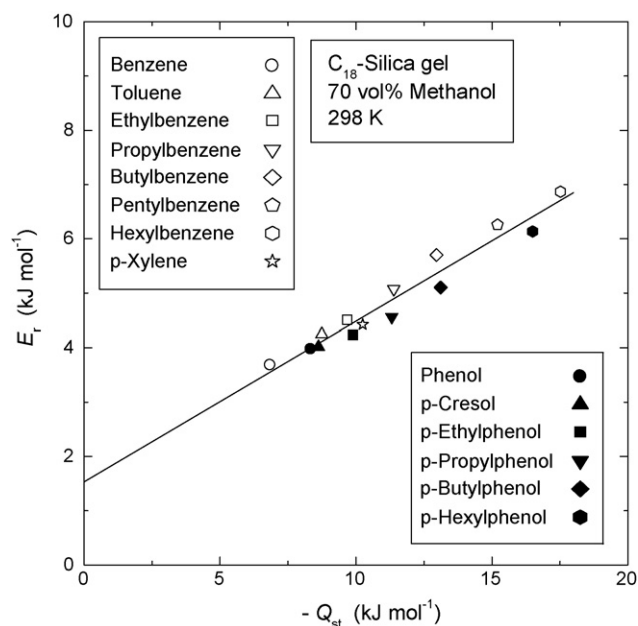


Fig. 20. Correlation between restriction energy of surface diffusion and isosteric heat of adsorption. (Reproduced with permission from Ref. [107].)

polar solvent molecules contact a hydrophobic surface, a mutual repulsion takes place between solvent molecules and surface. This structure-making effect causes the compression of the polar solvent molecules, an enhancement of their mutual interactions, and the restriction of their mobility. The solvent structure-making is also accelerated when solvent molecules are significantly attracted to the hydrophobic surface. The organic modifier in the aqueous mobile phases used in RPLC is preferentially adsorbed onto the hydrophobic surface of the stationary phase. The concentration of the organic modifier is higher near the surface than in the bulk mobile phase. The decrease in mobility of the solvent molecules may be predicted because the interactions between them are prob-

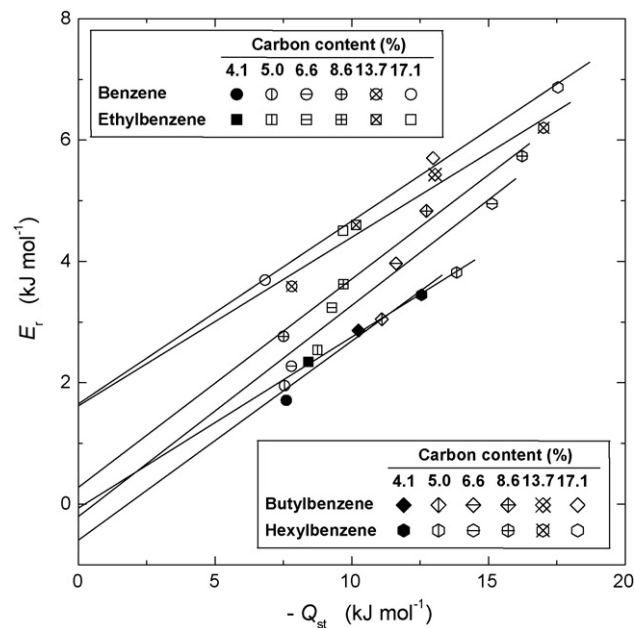


Fig. 21. Correlation between restriction energy for surface diffusion and enthalpy change due to retention. Conditions: mobile phase, methanol/water (70/30, v/v); column temperature, 298 K. (Reproduced with permission from Ref. [58].)

ably amplified under such conditions. It seems that the longer the length of the alkyl chain or the higher the density of  $C_{18}$  ligands, the more rigid the structure of the mobile phase solvent. These assumptions probably explain the change in the intercept in Fig. 21 [58].

### 3.6. Interpretation for the drawbacks of conventional models of surface diffusion with the new model

As indicated earlier, the conventional model for surface diffusion, i.e., Eq. (4), has two major drawbacks.

- (1) Eq. (4) cannot quantitatively explain the correlation between  $E_s$  and  $Q_{st}$ . In liquid–solid systems,  $E_s$  larger than  $-Q_{st}$  was frequently measured, which is inconsistent with surface diffusion. However,  $E_s$  smaller than  $-Q_{st}$  was also reported in liquid–solid adsorption. Values of  $E_s$  smaller than  $-Q_{st}$  are usual in gas–solid systems. Eq. (4) cannot interpret these contradictory situations in liquid–solid and gas–solid systems.
- (2) Eq. (4) cannot explain  $D_{s0}$  values between  $10^{-3}$  and  $10^{-2} \text{ cm}^2 \text{ s}^{-1}$ , which is much larger than  $D_m$ , which is usually of the order of  $10^{-6}$ – $10^{-5} \text{ cm}^2 \text{ s}^{-1}$  in solutions. This means that surface diffusion of weakly retained compounds would be faster than molecular diffusion because  $D_{s0}$  is equal to  $D_s$  at  $Q_{st} = 0 \text{ kJ mol}^{-1}$  in Eq. (4). This conclusion is not reasonable. The range of  $Q_{st}$  in which Eq. (4) is valid and can be used is not clear.

These drawbacks limit the validity of Eq. (4). The way in which the surface-restricted molecular diffusion model can explain the intrinsic characteristics of surface diffusion, which Eq. (4) cannot, is demonstrated in this section.

#### 3.6.1. Interpretation of various correlations between $E_s$ and $Q_{st}$ in liquid–solid adsorption systems

Fig. 22 shows plots of values of  $E_s$  versus  $-Q_{st}$  measured (1) for n-alkylbenzene homologs and p-alkylphenol derivatives in an RPLC system consisting of a  $C_{18}$ -silica column eluted with a methanol/water mixture (70/30, v/v); and (2) for various ana-

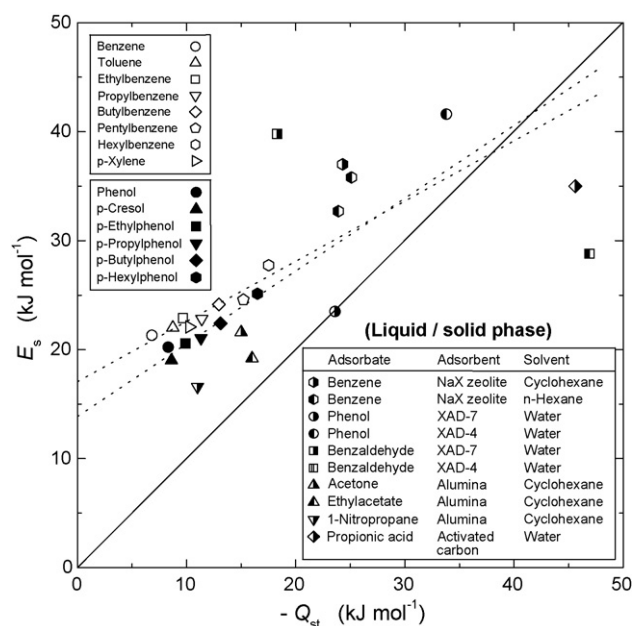


Fig. 22. Correlation between activation energy of surface diffusion and isosteric heat of adsorption.

lytes in many different systems. Similar to what happens in other liquid–solid systems [78,83–86,88,89,104,116],  $E_s$  is larger than  $-Q_{st}$  in most systems, meaning that there is no surface diffusion since it would be more advantageous for adsorbed molecules to be completely desorbed from the surface into the bulk liquid phase and migrate by pore diffusion than to migrate by surface diffusion. However, values of  $E_s$  smaller than  $-Q_{st}$  have also been reported in liquid–solid adsorption [68,75,81]. These opposite correlations between  $E_s$  and  $Q_{st}$  in liquid–solid systems can be explained on the basis of Eqs. (16)–(18).

The derivation of Eqs. (16)–(18) assume  $E_h$  to be almost equal to  $E_m$  and probably proportional to  $\Delta E_v$  of the solvent. As indicated earlier, the average value of  $\alpha$  ( $=E_m/\Delta E_v$ ) is about 0.47. The ratio of  $E_{vis}/\Delta E_v$  for various solvents is reported to be about 0.25–0.33 [79]. The contribution of the hole-making step was calculated to be between 15 and 20 kJ mol<sup>-1</sup> because  $\Delta E_v$  of solvents usually ranges between 30 and 40 kJ mol<sup>-1</sup>. The jumping step contribution is correlated with  $Q_{st}$  of analytes. When  $Q_{st}$  is  $-20$  kJ mol<sup>-1</sup>,  $E_j$  is about 8 kJ mol<sup>-1</sup> because the average value of  $\beta$  is close to 0.4 for surface diffusion in liquid–solid systems (see Table 3). Since  $E_s$  is about 23 to 28 kJ mol<sup>-1</sup> in this case,  $E_s$  would be larger than  $-Q_{st}$  as illustrated in Fig. 22. In contrast, when  $Q_{st}$  is  $-50$  kJ mol<sup>-1</sup>,  $E_j$  is estimated at about 20 kJ mol<sup>-1</sup>, in which case the ratio  $E_s/(-Q_{st})$  should be smaller than unity because  $E_s$  is about 35 to 40 kJ mol<sup>-1</sup>.  $E_s$  should be smaller than  $-Q_{st}$  since  $E_h$ , which is between 15 and 20 kJ mol<sup>-1</sup>, is smaller than  $-Q_{st}$  by a factor of ca. 0.6. In this case,  $|Q_{st}|$  would be larger than about 35 kJ mol<sup>-1</sup>. Data in Fig. 22 explain this assumption.

Fig. 22 shows plots of  $E_s$  against  $-Q_{st}$  data measured in various liquid–solid systems. The dotted lines correlating the experimental data for the two homologous series intersect the diagonal at around  $Q_{st} = -40$  kJ mol<sup>-1</sup> because their slope (hence,  $\beta$ ) is smaller than unity. This means that  $E_s$  is smaller than  $-Q_{st}$  when  $-Q_{st}$  is larger than about 40 kJ mol<sup>-1</sup>, a prediction consistent with the critical value of 35 kJ mol<sup>-1</sup> given above. This explanation is supported by the experimental data obtained in other liquid–solid systems [68,75], in which an activated carbon and hydrophobic polymers were used as adsorbents. In Fig. 22, the two experimental data points at  $-Q_{st} > 40$  kJ mol<sup>-1</sup> are below the diagonal, indicating that  $E_s$  is smaller than  $-Q_{st}$ .

In contrast, the value of  $-Q_{st}$  in RPLC systems usually ranges between 10 and 20 kJ mol<sup>-1</sup> as listed in Tables 1–3, values smaller than the threshold [38,114,130–136]. As explained above, the values of  $E_s$  should be larger than  $-Q_{st}$  under such conditions. Although the range of  $E_s$  values in gas–solid systems is almost the same as in RPLC systems, the ratio of  $E_s/(-Q_{st})$  in gas–solid adsorption is smaller than unity (see Table 1). The difference in the values of  $E_s/(-Q_{st})$  between the liquid–solid and gas–solid systems is partially explained by considering the influence of the solvent on  $Q_{st}$ . There is no solvent effect on  $Q_{st}$  in gas–solid adsorption, but  $Q_{st}$  in RPLC system is determined by the presence of the solvent. As listed in Table 1, the values of  $-Q_{st}$  are smaller in RPLC systems than in GC systems.

In conclusion, the contributions to  $E_s$  of the processes of (1) hole-making in the liquid phase and (2) partial desorption of adsorbate molecules from the adsorbent surface are important. These contributions should be taken into account when the mechanism of surface diffusion is discussed from a thermodynamic point of view. Unfortunately, the contribution of the hole-making process to  $E_s$  is not considered in conventional models of surface diffusion. This is why Eq. (4) is inconsistent with the experimental observation that  $E_s$  is larger than  $-Q_{st}$  in liquid–solid adsorption systems. On the other hand, the surface-restricted molecular diffusion model provides effective quantitative explanations of some intrinsic characteristics and of the mechanism of surface diffusion [38,39,106,107,110,115–117,120–125].

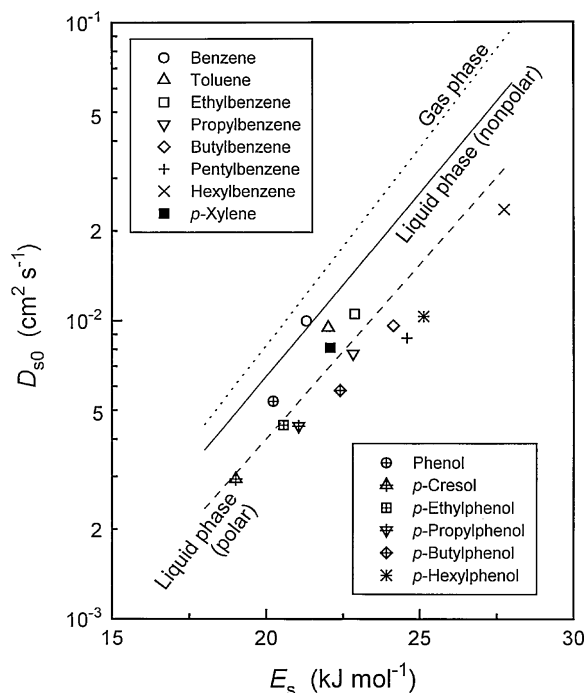


Fig. 23. Correlation of frequency factor with activation energy of surface diffusion. Solid, dashed, and dotted lines represent the correlations between  $D_{s0}$  and  $E_s$  in previous papers [38,84]. (Reproduced with permission from Ref. [120].)

### 3.6.2. Interpretation of correlation between $E_s$ and $Q_{st}$ in gas–solid adsorption systems

In gas–solid phase adsorption, the ratio  $E_s/(-Q_{st})$  usually ranges between 0.3 and 1 for surface diffusion [38,47,59–62]. However, values of  $E_s/(-Q_{st})$  larger than unity have also been reported in the case of gaseous micropore diffusion. In the following, the surface-restricted molecular diffusion model is used to explain the various situations of the correlation between  $E_s$  and  $Q_{st}$  in gas–solid adsorption systems.

**3.6.2.1. Similarity of the mass transfer mechanisms of surface diffusion.** Fig. 23 [120] illustrates an enthalpy–entropy compensation (EEC) for surface diffusion [38,108,109,137–140]. Similar linear correlations between  $\ln D_{s0}$  and  $E_s$  were observed with different combinations of stationary phases, mobile phases, and analytes. The solid and dashed lines represent correlations for non-polar and polar compounds in various RPLC systems, respectively [84]. The dotted line corresponds to gas–solid systems made of a C<sub>18</sub>-silica column and helium [62]. Correlations between  $\ln D_{s0}$  and  $E_s$  in both gas–solid and RPLC systems are represented by the same linear function, suggesting that there is an EEC for surface diffusion on C<sub>18</sub>-silica gel [138]. However, Krug et al. [126–128] claimed that a rigorous verification based on their four approaches is necessary to prove an EEC when  $D_{s0}$  and  $E_s$  are estimated from the linear regression of the Arrhenius plots. Surface diffusion data measured under various RPLC conditions were analyzed in detail by applying the four methods proposed by Krug et al. [126–128]. It was concluded that a true EEC based on substantial physico-chemical effects is observed for surface diffusion in RPLC systems. This EEC implies that molecular migration by surface diffusion is governed by the same mechanism in both gas–solid and liquid–solid systems. This means that the characteristics and the mechanism of surface diffusion in these systems can be explained in the same manner.

**3.6.2.2. Interpretation of  $E_s$  and  $Q_{st}$  in gas–solid phase system.** If the mechanisms of surface diffusion are the same in principle,  $E_s$  in

**Table 5**  
Thermodynamic properties of retention equilibrium and surface diffusion in gas–solid phase system.

Sample	$-Q_{st}$ (kJ mol <sup>-1</sup> )	$(K/T)_{1/T \rightarrow 0}$ (cm <sup>3</sup> g <sup>-1</sup> K <sup>-1</sup> )	$E_s$ (kJ mol <sup>-1</sup> )	$D_{s0}$ (cm <sup>2</sup> s <sup>-1</sup> )	$\Delta H_v^a$ (kJ mol <sup>-1</sup> )	$-Q_{st}/\Delta H_v^a$ (-)	$E_s/-Q_{st}$ (-)
Benzene	35.3	$9.6 \times 10^{-7}$	13.5	$9.0 \times 10^{-4}$	33.8	1.04	0.38
Toluene	40.7	$4.2 \times 10^{-7}$	17.2	$3.6 \times 10^{-3}$	38.0	1.07	0.43
Ethylbenzene	43.8	$2.9 \times 10^{-7}$	23.2	$2.2 \times 10^{-2}$	42.2	1.04	0.53
<i>p</i> -Xylene	44.6	$2.5 \times 10^{-7}$	21.1	$1.2 \times 10^{-2}$	42.4	1.05	0.47
Chlorobenzene	40.5	$6.3 \times 10^{-7}$	25.7	$4.8 \times 10^{-2}$	41.0	0.99	0.63
<i>n</i> -Pentane	31.7	$9.8 \times 10^{-7}$	10.2	$3.7 \times 10^{-4}$	26.4	1.20	0.32
<i>n</i> -Hexane	33.4	$1.5 \times 10^{-6}$	14.1	$1.7 \times 10^{-3}$	31.6	1.06	0.42
<i>n</i> -Heptane	38.2	$7.1 \times 10^{-7}$	14.4	$1.7 \times 10^{-3}$	36.6	1.04	0.38
<i>n</i> -Octane	43.4	$2.9 \times 10^{-7}$	17.1	$3.8 \times 10^{-3}$	41.5	1.05	0.39
Cyclohexane	33.0	$2.0 \times 10^{-6}$	15.6	$2.0 \times 10^{-3}$	33.0	1.00	0.47

<sup>a</sup> At 298 K.

gas–solid systems ( $E_s^g$ ) should result from the activation energy of diffusion with no restriction ( $E_0^g$ ) and the contribution of the adsorptive interactions.

$$E_s^g = E_0^g + \beta(-Q_{st}) \quad (32)$$

The mechanism of surface diffusion in gas–solid systems seems correlated with Knudsen diffusion. Knudsen diffusivity is of the order of  $10^{-3}$  cm<sup>2</sup> s<sup>-1</sup> as shown by Knudsen equation [47], and so is smaller than  $D_m$ . The activation energy of Knudsen diffusion is calculated at 1.4 kJ mol<sup>-1</sup>, which corresponds to  $E_0^g$ . Because  $-Q_{st}$  in gas–solid systems ranges between 32 and 45 kJ mol<sup>-1</sup>, as listed in Tables 1 and 5, the contribution of the second term in the RHS of Eq. (32) to  $E_s^g$  is calculated to be between 16 and 23 kJ mol<sup>-1</sup>, if we assume  $\beta = 0.5$ . This value is larger than that of the first term, i.e.,  $E_0^g = 1.4$  kJ mol<sup>-1</sup>, by a factor of ca. 11–16. When  $E_0^g$  is negligible,  $E_s^g$  is approximately proportional to  $Q_{st}$  and the ratio  $E_s^g/(-Q_{st})$  is smaller than unity in this gas–solid system. On the other hand,  $E_s/(-Q_{st})$  in RPLC systems is obviously larger than unity and is not constant (see Tables 1 and 2). Consequently, the difference in the values of  $E_s/(-Q_{st})$  between gas–solid and liquid–solid systems originates from the difference between the contribution of  $E_h$  to  $E_s$  in Eq. (15) (liquid–solid systems) and that of  $E_0^g$  to  $E_s^g$  in Eq. (32) (gas–solid systems).

Tables 1–3 indicate that  $-Q_{st}$  in RPLC systems ranges between 7 and 18 kJ mol<sup>-1</sup>, which agrees with values reported in many other RPLC systems [38,114,130–136]. The contribution of  $E_j$  is calculated to be between ca. 3.5 and 9 kJ mol<sup>-1</sup> by taking  $\beta = 0.5$ . For surface diffusion in RPLC systems,  $E_h$  ranges from ca. 14 to 17 kJ mol<sup>-1</sup>, which is larger than  $\beta(-Q_{st})$ . The ratio of  $E_s/(-Q_{st})$  in RPLC systems, unreasonably larger than unity, is attributed to the large contribution of  $E_h$  to  $E_s$ . The surface-restricted diffusion model consistently proves the similarity of the migration mechanisms of surface diffusion in both gas–solid and liquid–solid systems, as illustrated in Fig. 23 [120].

### 3.6.3. Interpretation of $D_{s0}$

The second contradiction, which cannot be consistently explained by the conventional model of surface diffusion (Eq. (4)), is the correlation between  $D_s$  and  $D_m$  for weakly retained compounds. Equation (19) indicates that  $D_s$  is correlated with  $D_{s0}$ ,  $\Delta E_v$ , and  $Q_{st}$ . The products of  $D_{s0}$  and  $\exp(-\alpha\Delta E_v/RT)$  are between  $5 \times 10^{-6}$  and  $2 \times 10^{-5}$  cm<sup>2</sup> s<sup>-1</sup> at 298 K assuming that  $D_{s0}$  and  $\Delta E_v$  are  $1 \times 10^{-2}$  cm<sup>2</sup> s<sup>-1</sup> and 15–19 kJ mol<sup>-1</sup>, respectively. These values are of the same order of magnitude as those for  $D_m$  in the liquid phase. The second contradiction originates from the neglect of the important contribution of  $E_h$  to  $E_s$  in the conventional model of surface diffusion.

### 3.6.4. Acceptable range of $Q_{st}$

Figs. 16 and 17 [110] illustrate that  $D_s$  decreases continuously with increasing  $K$  and  $|Q_{st}|$  and that it is of almost the

same order of magnitude as  $D_m$  when  $K$  or  $-Q_{st}$  is close to zero [107,108,115,116,137]. This suggests that the mechanism of surface diffusion is similar to that of molecular diffusion, the migration of analyte molecules being restricted by their retentive interactions with the adsorbent surface. The surface-restricted molecular diffusion model has no limit concerning the range of  $K$  or  $Q_{st}$ . The new model represents the intrinsic characteristics of surface diffusion irrespective of the values of  $K$  and  $Q_{st}$ .

## 4. Conclusion

Surface diffusion is one of the major kinetic processes involved in mass transfer kinetics in chromatography. Yet, its importance remains ignored from chromatographers. We reviewed previous studies on surface diffusion and explained why the conventional model of surface diffusion cannot properly explain two important experimental results. (1) Values measured for the activation energy,  $E_s$ , of surface diffusion are frequently larger than  $-Q_{st}$ , the isosteric heat of adsorption in liquid–solid systems, which is inconsistent with surface diffusion. (2) The experimental values of the frequency factor of surface diffusion,  $D_{s0}$ , are between  $1 \times 10^{-4}$  and  $1 \times 10^{-1}$  cm<sup>2</sup> s<sup>-1</sup>, several orders of magnitude larger than  $D_m$  in the liquid phase (usually  $D_m$  is of the order of  $1 \times 10^{-6}$  to  $10^{-5}$  cm<sup>2</sup> s<sup>-1</sup>). This means that for weakly retained compounds,  $D_s$  would be several orders of magnitude larger than  $D_m$  because the conventional model implies that  $D_{s0}$  is the limit of  $D_s$  when  $Q_{st}$  tends toward zero. The conclusion that  $D_s$  could be larger than  $D_m$  is not reasonable.

The study of surface diffusion phenomena from the kinetic and thermodynamic points of view shows that there is a profound correlation between surface and molecular diffusion and that the thermodynamic and extrathermodynamic properties of surface diffusion are correlated with those of the retention equilibrium. The comparison of surface diffusion data measured in gas–solid and liquid–solid systems supports the surface-restricted molecular diffusion model [38,39]. This model was formulated by applying the absolute rate theory [79]. It is effective for a consistent interpretation of the intrinsic characteristics and mechanism of surface diffusion in gas–solid and liquid–solid systems. This model also quantitatively explains surprising experimental observations concerning surface diffusion, which cannot be explained by the conventional model (Eq. (4)).

The ordinary rate equations remain widely used in the chromatographic literature, although the experimental conditions under which chromatography is conducted have drastically changed since their derivation, 50 and 40 years ago. The recent development of fine particles, with average sizes between 1 and 2  $\mu$ m and of instruments able to operate them at pressures up to 1200 bar permits extremely fast analyses [141–143]. The friction of the mobile phase against beds packed with super-fine particles leads to the generation of heat and columns that are no longer isothermal in either their axial or radial directions. The influence



of the temperature distribution on the column efficiency and on the peak profile must be considered [144,145]. New types of separation media have been developed, such as monoliths [146–148] and shell-type particles [149–151]. The ordinary rate equations are not useful for the analysis of the chromatographic behavior or the efficiency of these packing materials because their structural characteristics are profoundly different from those of conventional fully-porous spherical particles. We must develop new approaches for the kinetic study of chromatography. Recently, new fundamental research has been published, for example, (1) the development of a detailed general rate model of chromatography [92,152], (2) the development of modeling methods for the determination of intraparticle diffusivity [153], (3) the development of a general rate model for multi-components systems [154,155], (4) new experimental procedure for measuring diffusivities including surface diffusion coefficient [156,157], and (5) new moment equations for various packing materials having different structural characteristics [158–160]. Although many research subjects still remain open, the results of the fundamental studies described above will contribute to a better understanding of mass transfer kinetics in chromatography.

## Nomenclature

### Symbols

$C$	concentration ( $\text{g m}^{-3}$ , $\text{mol m}^{-3}$ ), numerical constant in Eq. (12)
$C_s$	saturation concentration of sample compound in solvent ( $\text{g m}^{-3}$ )
$d_p$	particle diameter ( $\mu\text{m}$ )
$D_e$	effective intra-stationary phase diffusivity ( $\text{cm}^2 \text{s}^{-1}$ )
$D_m$	molecular diffusivity ( $\text{cm}^2 \text{s}^{-1}$ )
$D_{m0}$	frequency factor of molecular diffusion ( $\text{cm}^2 \text{s}^{-1}$ )
$D_p$	pore diffusivity ( $\text{cm}^2 \text{s}^{-1}$ )
$D_s$	surface diffusion coefficient ( $\text{cm}^2 \text{s}^{-1}$ )
$D_{s0}$	frequency factor of surface diffusion ( $\text{cm}^2 \text{s}^{-1}$ )
$D_s(q)$	$D_s$ at a certain amount adsorbed, $q$ ( $\text{cm}^2 \text{s}^{-1}$ )
$D_s(0)$	$D_s$ at zero surface coverage ( $\text{cm}^2 \text{s}^{-1}$ )
$E_{ap}$	adsorption potential ( $\text{kJ mol}^{-1}$ )
$E_h$	activation energy of hole-making step ( $\text{kJ mol}^{-1}$ )
$E_j$	activation energy of jumping step ( $\text{kJ mol}^{-1}$ )
$E_m$	activation energy of molecular diffusion ( $\text{kJ mol}^{-1}$ )
$E_r$	restriction energy for surface diffusion ( $\text{kJ mol}^{-1}$ )
$E_s$	activation energy of surface diffusion ( $\text{kJ mol}^{-1}$ )
$E_{vis}$	activation energy of viscosity ( $\text{kJ mol}^{-1}$ )
$E_0$	activation energy of molecular migration with no restriction ( $\text{kJ mol}^{-1}$ )
$\Delta E_v$	evaporative energy ( $\text{kJ mol}^{-1}$ )
$F$	partition function for initial state
$F^\ddagger$	partition function for activated state
$h$	Planck's constant (Js)
$H$	height equivalent to a theoretical plate (HETP) ( $\mu\text{m}$ )
$J_s$	mass flux of the adsorbate molecules due to surface diffusion ( $\text{g m}^{-2} \text{s}^{-1}$ )
$k$	retention factor
$k_B$	Boltzmann constant ( $\text{J K}^{-1}$ )
$K$	adsorption equilibrium constant ( $\text{cm}^3 \text{g}^{-1}$ )
$K_a$	adsorption equilibrium constant
$K_L$	Langmuir parameter ( $\text{cm}^3 \text{g}^{-1}$ )
$K_0$	$K$ at $1/T = 0 \text{ K}^{-1}$ or $Q_{st} = 0 \text{ kJ mol}^{-1}$ ( $\text{cm}^3 \text{g}^{-1}$ )
$m$	molecular weight
$N_A$	Avogadro number
$q$	concentration of sample molecules adsorbed on the stationary phase ( $\text{g g}^{-1}$ , $\text{mol m}^{-3}$ )

$q_\infty$	saturation amount of sample molecules adsorbed ( $\text{g g}^{-1}$ , $\text{mol m}^{-3}$ )
$q_{st}$	isosteric heat of adsorption at $C = C_s$ ( $\text{kJ mol}^{-1}$ )
$Q_{st}$	isosteric heat of adsorption ( $\text{kJ mol}^{-1}$ )
$R, R_g$	gas constant ( $\text{J mol}^{-1} \text{K}^{-1}$ )
$t_R$	retention time (s)
$T$	absolute temperature (K)
$u_0$	superficial velocity of the mobile phase ( $\text{cm s}^{-1}$ )
$V_{sv}$	molar volume of solvent ( $\text{cm}^3 \text{mol}^{-1}$ )
$x$	distance (m)

### Greek letters

$\alpha$	ratio of $E_s$ to ( $-Q_{st}$ ), ratio of $E_m$ to $\Delta E_v$ , ratio of $E_h$ to $\Delta E_v$
$\beta$	ratio of $E_j$ to ( $-Q_{st}$ )
$\delta$	contribution of each mass transfer process in column to $\mu'_2$ (s)
$\varepsilon_e$	external porosity
$\varepsilon_i$	internal porosity
$\varepsilon_t$	total porosity
$\lambda$	distance between neighboring equilibrium positions (nm)
$\mu_1$	first absolute moment (s)
$\mu'_2$	second central moment ( $\text{s}^2$ )
$v_f$	free volume ( $\text{cm}^3$ )
$\rho_p$	particle density ( $\text{g cm}^{-3}$ )
$\tau$	rate constant ( $\text{s}^{-1}$ )
$\varphi$	mobile phase composition ( $\%(v/v)$ )

### Superscript

$g$	gas–solid phase system
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### Subscripts

ads	adsorption
ax	axial dispersion
d	intraparticle diffusion
f	external (fluid-to-stationary phase) mass transfer
total	total value

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