



Use of isopycnic plots in designing operations of supercritical fluid chromatography: I. The critical role of density in determining the characteristics of the mobile phase in supercritical fluid chromatography

Abhijit Tarafder, Georges Guiochon*

Department of Chemistry, University of Tennessee, Knoxville, TN, USA

ARTICLE INFO

Article history:

Received 10 January 2011

Received in revised form 25 March 2011

Accepted 11 May 2011

Available online 20 May 2011

Keywords:

Isopycnic plot

SFC

Supercritical chromatography

Operating conditions

ABSTRACT

In Supercritical Fluid Chromatography (SFC), the key chromatographic parameters of any compound, its retention and efficiency, are known to strongly depend on the density of the mobile phase. This indicates that iso-density, also called isopycnic, plots drawn on the pressure–temperature plane can provide an effective tool to analyze how SFC systems may operate under different combinations of inlet and outlet pressures and column temperature. To effectively use these isopycnic plots in designing the operations of SFC systems, however, a deeper understanding of the factors behind the dependence of the performance of these systems on the mobile phase density is required. The nature of this density dependence is explored with reference to the key physical properties of the mobile phase, its viscosity, diffusivity and solubility. This study is focused on the use of pure carbon dioxide as the mobile phase, but this method of investigation is applicable for other mobile phase combinations as well.

© 2011 Elsevier B.V. All rights reserved.

1. Introduction

Supercritical Fluid Chromatography (SFC) is the general name commonly used to refer to a mode of chromatography performed with a mobile phase that uses carbon dioxide as its main component, whether this fluid is liquid and subcritical or under the supercritical state. Therefore, the word SFC, which is the acronym of SFC, has now acquired an independent, broader meaning, making its use more correct than the full name.

Although Klesper et al. [1] used supercritical dichlorodifluoromethane and monochlorodifluoromethane as the mobile phases in their first demonstration of SFC, CO₂ was soon identified as a far more attractive fluid because it is relatively inexpensive, is not flammable, is not toxic at concentrations below ca. 2% in air, and, being manufactured as the byproduct of other industrial processes, is generally considered as carbon neutral. Furthermore, the critical properties of CO₂ ($P_c = 73.773$ bar, $T_c = 304.13$ K) are close to ambient conditions. So, it is more convenient to reach supercritical conditions with CO₂ than with most other competing fluids. Although many current applications of SFC use standard organic solvents like methanol or acetonitrile as modifiers to CO₂, in order to improve the solubility of sample components and increase the applicability of SFC, the analysis and discussions presented in this

work will be limited to neat CO₂ and the words “mobile phase” and CO₂ will be used interchangeably. Although neat CO₂ is now rarely used in SFC, understanding the role of CO₂ in the various physico-chemical aspects of SFC is critical to further its usefulness and ease of application because the typicality of SFC operations originates from this behavior.

Within the temperature and pressure ranges normally employed in current SFC operations, the physical properties of CO₂ can be widely modulated, leading to very different values of the retention factors and the column efficiencies of the analytes. In contrast to what happens in HPLC, changing the operating pressure in SFC may considerably affect retention factors and column efficiencies. Understandably, this tunability of the mobile phase in SFC has drawn considerable attention from the beginning and much effort was made to understand the effects of the primary operating variables – temperature and pressure – on the retention and efficiency. However, Van Wasen and Schneider [2] noted quite early that when retention factors are plotted against the density of the mobile phase (neat CO₂), the isothermal curves are almost parallel, much simpler than the convoluted curves obtained when the same data are plotted against the pressure. Peaden and Lee [3] observed that it is the density, not the pressure of the mobile phase, which controls the retention behavior in SFC. They proposed a linear relationship between the logarithm of analyte retention factors and the density of CO₂. They stated that, at constant mass flow rate along the column, the column efficiency should remain nearly constant, even if the pressure decreases significantly, because the

* Corresponding author. Tel.: +1 8659740733; fax: +1 8659742667.

E-mail address: guiochon@utk.edu (G. Guiochon).

efficiency should not vary much when the product of the mobile phase velocity, its viscosity and its density remains constant along the column, which is approximately true when the column is operated at constant mass flow rate. Martire [4] developed an elaborate theory on adsorption chromatography in which solute retention is predicted to be a function of the reduced temperature and density of the eluent. He observed that the mobile phase density is a more convenient and natural state variable than pressure to determine and investigate isothermal distribution functions in all the modes of chromatography, gas, liquid or supercritical. Poe and Martire [5] developed a general expression for the column efficiency as a function of the capacity factor and the mobile phase density. Lou et al. [6] investigated in detail the effects of temperature and pressure on retention in SFC and showed that, up to a certain pressure, the retention factors of three PAHs increase rapidly and continuously with increasing temperature. At higher pressures, however, these retention factors decrease first, then increase with increasing temperature. They observed a relationship between the nature of the changes in the solubility of these solutes when changing the operating conditions and that of their retention factors. Based on this observation, they suggested that retention factors are inversely proportional to solubility and directly proportional to an affinity factor of the solute for the stationary phase. Lauer et al. [7] investigated the retention behavior of several solutes in the near-critical region. These authors reported that, at constant mobile phase density, the logarithm of their capacity factors vary linearly with the reciprocal of the temperature, with no change of the slope of ordinate of these straight lines across the critical isotherm. They also pointed out that, within the pressure and temperature ranges that are useful to SFC operation, changes in mobile phase viscosity can be avoided along the constant density lines. Chester and Innis [8] experimentally demonstrated the utility of plotting the logarithm of retention data against reciprocal temperature, at constant density rather than constant pressure, to develop a linear relationship. Wu et al. [9] worked with relatively volatile compounds, like phenyl-ethanol, and detected that retention factors in SFC, at pressures near 150 bar, decrease with increasing temperature from the ambient to the critical temperatures. Above the critical temperature, however, retention factors increase significantly, reach a maximum at a higher temperature, and then drop. At increasing temperatures, the competing effects of the decreasing eluent density and the increasing solute vapor pressures explain this behavior.

In conclusion, the literature suggests that, although density plays a strong role in controlling retention and efficiency, solubility also affects retention, as shown by Lou et al. [6]. Even at constant mobile phase density, retention factors vary with temperature, as confirmed by published results [2]. The intricacy of this interdependence deserves clarification. The goal of this work is a close investigation of the relative importance of the roles of density and temperature in controlling solute retentions and column efficiencies.

2. Properties of the mobile phase which influence SFC operation

Fundamentally, chromatographic separations result from the combined influences of all the interactions between the solute molecules, the surface of the stationary phase and the molecules of the mobile phase. While solute molecules are introduced into the chromatographic system through the mobile phase, they become more or less strongly associated with the stationary phase with which they interact with different energies. This leads to the selectivity of the system and to the eventual separation of the sample components. The transport of solute molecules by the mobile phase

may, on the other hand, have consequences that reduce selectivity to a degree, depending on how much the mobile phase velocity may affect band broadening, hence the column efficiency, a function of diffusion and of the mass transfer resistances. In Gas Chromatography (GC) the role of the mobile phase is limited to being the carrier of solute molecules, which have to be volatile because carrier gases have no dissolution power and exhibit only very weak molecular interactions. Liquid Chromatography (LC), on the other hand, separates only solute molecules that are dissolved in the mobile phase. In SFC, the situation may vary from gas-like to liquid-like behavior, depending on the operating conditions, particularly the density. A medley of chromatographic interactions can take place. Although the states of the solute molecules, which are successively associated with the stationary and the mobile phases, are controlled by their chemical potentials in their respective states, such interactions cannot be measured directly. For practical purposes the solubility of a solute in the mobile phase provides direct indications on the intensity of its interactions with this phase in the absence of the stationary phase. The adsorption isotherm on the other hand provides a measure of the overall interactions with both the mobile and the stationary phases. In LC the role of solubility is seldom explored, as it generally does not vary significantly during elution under isocratic conditions, and solute interactions are generally measured through the “adsorption” isotherms. In SFC, however, solubility may vary significantly with the local density and thus can be used as a reliable indicator of the retention behavior. Apart from solubility, two other basic physical properties of the mobile phase directly control its chromatographic properties, its viscosity and the solute diffusivity. The viscosity determines the pressure drop for the selected flow rate, hence the density profile and the state conditions along the column. This is important because the state conditions determine all the other properties of the mobile phase. So, understanding the role of viscosity is significant. The solute diffusivity on the other hand controls directly all the mass transfer phenomena inside the column, be it axial diffusion, mass transfer over the stagnant film around the particles, or diffusion inside the pores.

The above discussion shows that, among the mobile phase properties that are perceived to control solute retention in SFC, solubility is certainly a major one. The efficiency on the other hand is mainly controlled by the solute diffusivity, and to a lesser degree, by the retention factors of the sample components. The hydrodynamics of the column is controlled by the mobile phase viscosity. Because the properties of the mobile phase in SFC are tunable, the individual effects of each one of these three properties are important to understand when investigating SFC separation behavior. The most striking feature common to all these properties will be discussed further in this work; it is their strong dependence on the mobile phase density. This explains why density, which is more readily measurable than any other property, has always drawn the attention as being the controlling factor in SFC.

2.1. Viscosity versus density of CO₂

Due to the intense interest invested on CO₂ for the last three decades as a sustainable supercritical fluid useful in supercritical extraction and in SFC, its viscosity has been measured in wide ranges of pressure and temperature, hence of density, and has been reported. These data were modeled by Vesovic et al. [10,11] who developed an extensive set of equations providing ways to calculate this property. These equations were used by the National Institute of Standards and Technology (NIST) in the REFPROP software [12], which was used for the current work to retrieve the CO₂ viscosity data shown in Fig. 1, plotted against the CO₂ density. As REFPROP uses the most accurate equations available to calculate the thermodynamic and transport properties [12], it can be

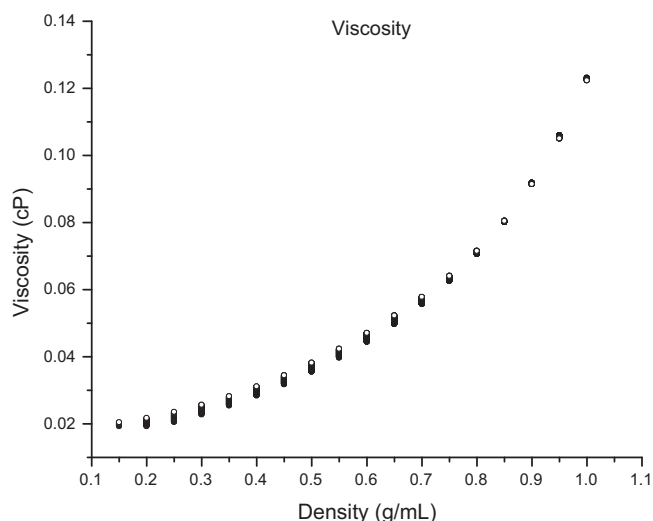


Fig. 1. The viscosity of CO₂ at different densities. The iso-density points were obtained by continuously varying the pressure and the temperature within the intervals of 74–300 bar and 280–347 K, respectively. Note that irrespective of the applied pressure and temperature, the viscosity depends essentially of density only.

asserted that this figure presents the most reliable data available today. According to NIST [12], the error made on CO₂ viscosity varies from 0.3% for the dilute gas, near room temperature, to 5% at the highest pressures under which viscosity was measured (8000.0 bar). However, the highest pressure considered in Fig. 1 is only 300 bar and the error made should be considerably lower than 5%.

The pressure and temperature ranges used for plotting the viscosity versus density data in Fig. 1 are approximately between 74 and 300 bar (reduced pressure, 1.003 and 4.07) and between 280 and 374 K (reduced temperatures, 0.921 and 1.210). These ranges can be considered as being the most useful for SFC operations. The critical pressure of CO₂ is 73.77 bar. A survey of the literature [13] shows that no SFC operation was reported as having been carried out under pressures below 74 bar. Although there are reports of analyses made under pressures higher than 300 bar, this is unusual. The selection of 280 K as the low temperature boundary is somewhat arbitrary. Although SFC operations are frequently carried out at subcritical temperatures, there are few instances of operations made below 280 K or above 374 K [13]. Within these temperature and pressure ranges, the density of CO₂ varies from 0.15 to 1.0 g/mL, which includes both subcritical (liquid) and supercritical CO₂.

The most important point to highlight here is that within this range, the viscosity of CO₂ depends practically only on its density (Fig. 1), irrespective of the temperature or the pressure applied to achieve this density. Although minor fluctuations of the viscosity can be noted below 0.7 g/mL, they can be neglected for practical purposes, given the reported accuracy of the data. Although such dependence of the viscosity on the density is known by scientists working on the measurement of CO₂ properties and on developing correlations between these properties [10,11,14], this issue is rarely discussed or highlighted in SFC related publications. Yet, this understanding is important to realize the actual importance of the role played by density in controlling the hydrodynamics of SFC systems.

2.2. Solute diffusivity versus density of CO₂

Although binary diffusion coefficients of numerous solutes in CO₂ have often been plotted and correlated with the temperature and the pressure of CO₂ [15–20], it was rarely noted that this property strongly depends on CO₂ density, almost irrespec-

tive of the combination of the temperature and the pressure which were applied to achieve that density. This observation is illustrated by the plots of the diffusivities of naphthalene, phenanthrene and hexachlorobenzene in CO₂ versus its density that are shown in Figs. 2 and 3. All the diffusivity data used in these plots were obtained from the literature [15,20] while the CO₂ density was calculated from the REFPROP [12] software, using the values of the temperatures and pressures published in the reports on the diffusivity data. The strong relationship between the diffusivities of various compounds and the CO₂ density is clearly illustrated in Figs. 2 and 3.

To check whether similar observations can be made for estimated data of diffusivity, the Takahashi method [21] was used to calculate the diffusivities of flurbiprofen and naphthalene in CO₂, in wide ranges of pressure, temperature and density. The results are plotted against the CO₂ density in Fig. 4. It can be noted from these profiles that even the estimated diffusivities exhibit a strong dependence on the density, irrespective of the operational temperature. Although investigations of the actual reasons behind such density dependence is outside the scope of the current report, it can be generally concluded from the results shown that density plays a significant role in determining the solute diffusion coefficients, at least in close temperature ranges.

2.3. Solubility versus density of CO₂

Solubility data in CO₂ for numerous solutes are available in the literature. Gupta et al. [24] compiled the solubility of more than 780 solutes in CO₂, including liquids, solids, polymers, and metal complexes. Traditionally, solubilities are plotted as isotherms against the operating pressures [22,23,25]. The main problem of this representation is the occurrence of isotherm crossovers [26], which implicates that in certain pressure ranges, solubility increases with increasing temperature while it decreases in other ranges. Thus, in the absence of a specific knowledge of the location of the crossovers points for a solute, it is impossible to estimate whether its solubility increases or decreases with increasing temperature at certain pressures. This is illustrated in Fig. 5, which shows that the crossover pressure of phenanthrene is around 125 bar and that of pyrene around 150 bar. Although solubility always increases with increasing pressure, it is impossible, without specific information on the crossover point, to estimate how the solubility of a compound may vary with the temperature at different pressures.

The solubility relationship with density, on the other hand, is much simpler. To understand the nature of its dependence on density, the solubility of phenanthrene [22], pyrene [22], fluorene [22] and 2-chlorobiphenyl [23], obtained from the literature are plotted in Figs. 6 and 7. Note that for pyrene and phenanthrene (Fig. 6), the data used are the same as those used for Fig. 5. These figures show that although the solubility of all compounds vary significantly with the density as well as with the temperature, the variations with density have clear, specific trends. Under isothermal conditions, the solubility increases monotonically with increasing density, while at constant density it increases monotonically with increasing temperature. It can be noted from all the solubility plots that, between approximately the critical density and the lowest density points at which data are available, the solubility does not vary with the temperature at constant density but can be defined only by the density of the solvent.

Thus, simple relationships between solubility, density and temperature permit the derivation of several empirical correlations between them [27,28]. The simplest one was suggested by Chrastil [27]:

$$\ln(y) = A_0 \ln(\rho) + \frac{A_1}{T} + A_2 \quad (1)$$

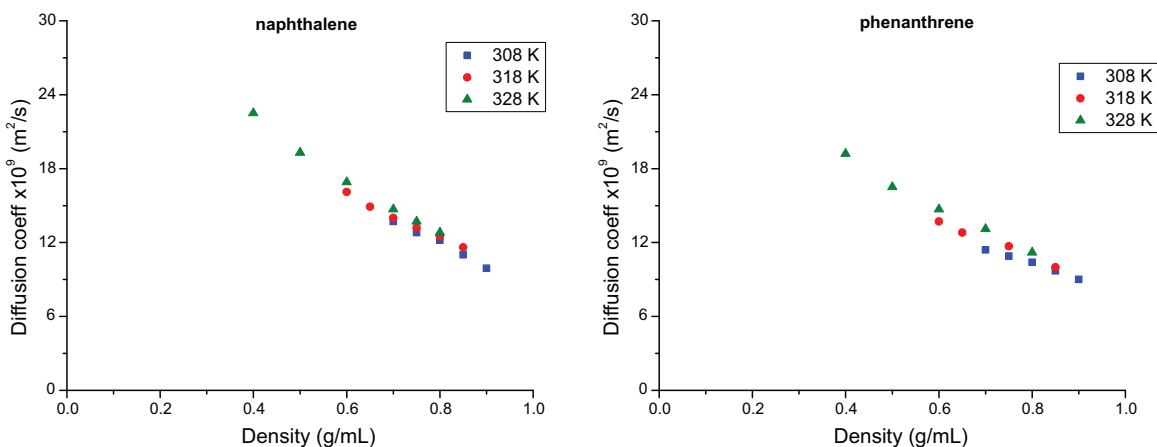


Fig. 2. Diffusivity of naphthalene and phenanthrene in carbon dioxide. Calculated from data found in Ref. [15].

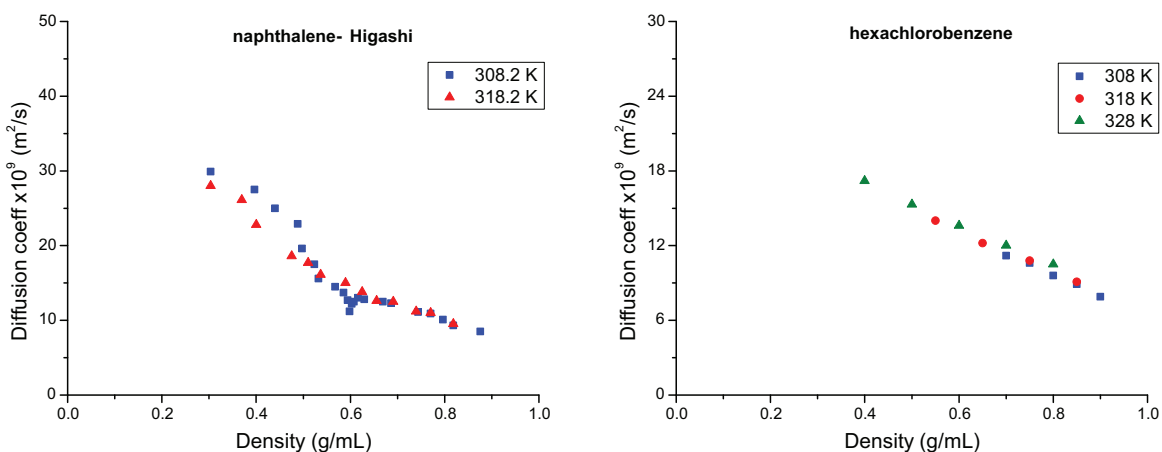


Fig. 3. Diffusivity of naphthalene and hexachlorobenzene in carbon dioxide. Calculated from data found in Refs. [15,20].

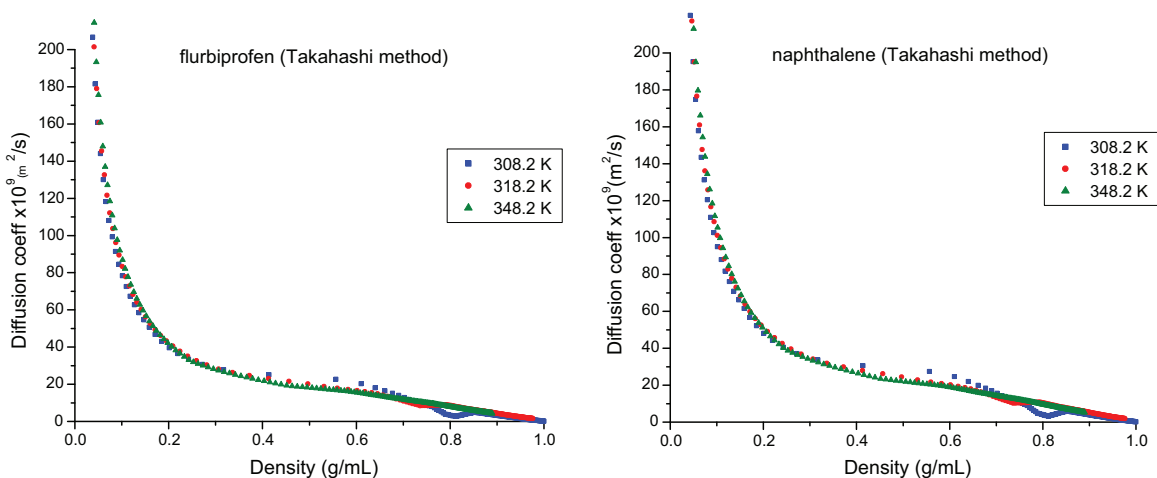


Fig. 4. Diffusivity of flurbiprofen and naphthalene in carbon dioxide. Data calculated following the Takahashi method obtained from Refs. [19,21].

where y is the solubility of the analyte and A_0 , A_1 , and A_2 are two empirical coefficients.

Although density does not influence the solubility as strongly as it influences the other properties discussed above, solubility has a much simpler relationship with density than do other properties, e.g., pressure. This can be utilized to develop a clearer understanding of the effect of the operating conditions on the chromatographic performances.

3. Influence of the density on the chromatographic parameters of SFC

3.1. Retention versus density of CO₂

The influence of the density on solute retentions in SFC has been noted by several researchers [2–6,29,30]. It was also noted that, even at constant density, the temperature plays an important role

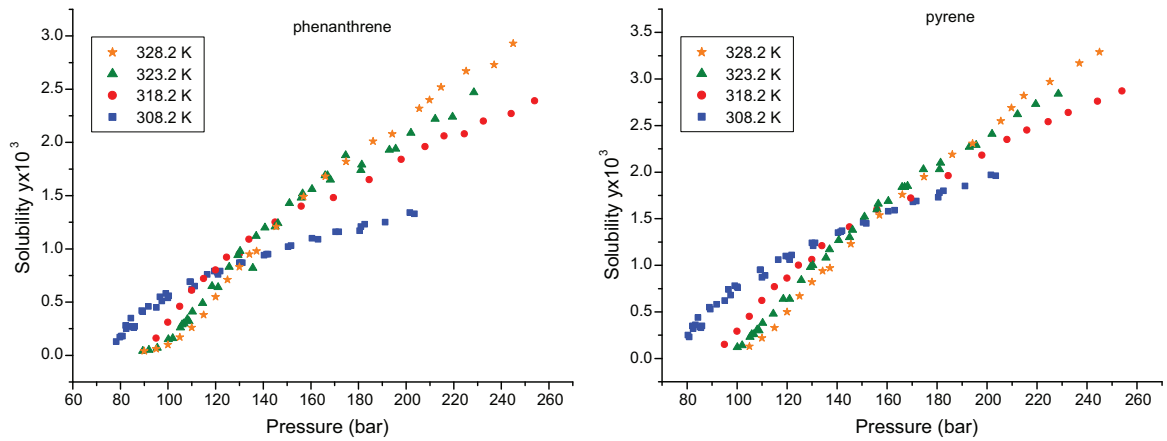


Fig. 5. Solubility (in mole fraction) of phenanthrene and pyrene in carbon dioxide plotted as a function of pressure. Data obtained from Ref. [22].

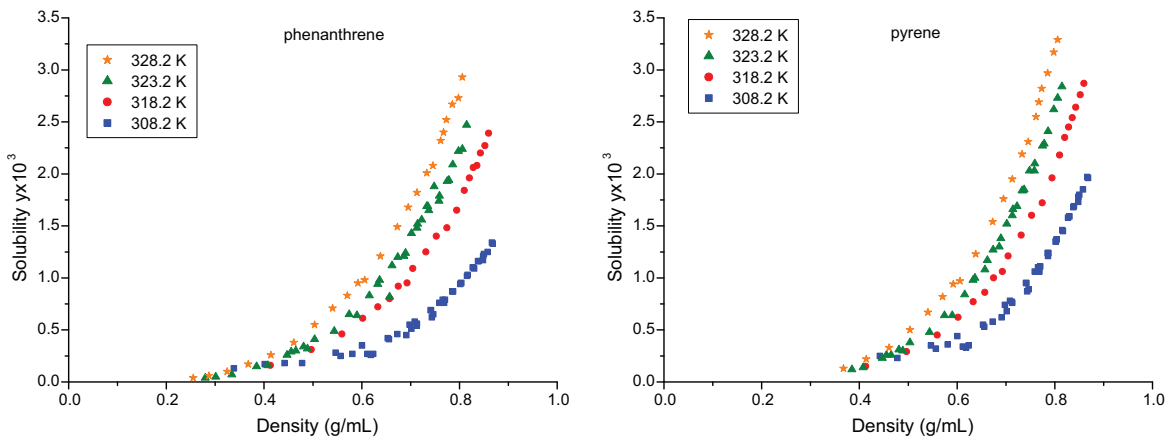


Fig. 6. Solubility (in mole fraction) of phenanthrene and pyrene in carbon dioxide. Calculated from data found in Ref. [22].

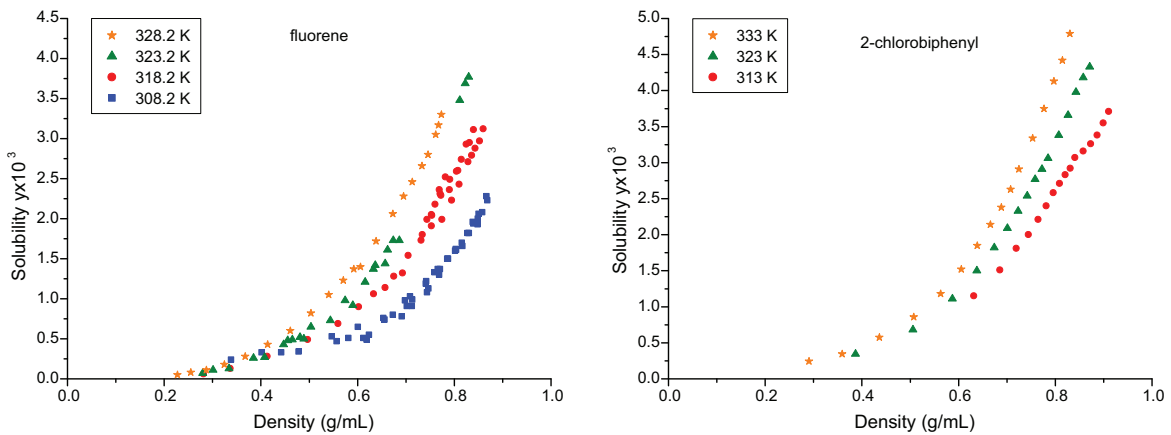


Fig. 7. Solubility (in mole fraction) of fluorene and 2-chlorobiphenyl in carbon dioxide. Calculated from data found in Refs. [22,23].

in defining the retention [2,4,29]. Martire [4] probably developed the most comprehensive approach in this direction and proposed general equations, under the umbrella of unified chromatographic theory, expressing solute retentions as functions of the averaged mobile phase density. Rajendran et al. [30] took a simpler approach and expressed the local retention as a power function of the local mobile phase density, from which the overall retention can be derived through integration. Although Martire [4] clearly observed the dependence of retention factors on both the density and the temperature of the mobile phase, to simplify the resultant

formulation, he assumed that the temperature distribution along the column is negligible and considered the density as the sole variable in expressing the retention factor. Perrut [31], following the work of van Wasen and Schneider [2], proposed an expression comprising both a density and a temperature terms, as:

$$\left(\frac{\partial \ln \rho k_i}{\partial P} \right)_T = \frac{V_{i,sol} - V_{i,ads}}{RT} - \kappa \quad (2)$$

where k_i is the retention factor of component i , and $V_{i,sol}$ and $V_{i,ads}$ are its partial molar volumes in the solution and the adsorbed

phase, respectively. Derivation of the above expression assumes thermodynamic equilibrium of the solute between the two phases at infinite dilution, which is certainly true for SFC operations under linear conditions. Now, in the supercritical region, $V_{i,sol}$ is proportional to the isothermal compression coefficient and can be written as [31]:

$$\frac{V_{i,sol}}{RT} = -\lambda \left(\frac{\partial \ln \rho}{\partial P} \right)_T \quad (3)$$

where λ is a coefficient depending on the experimental conditions. If the partial molar volume in the mobile phase is assumed to be much larger than the partial molar volume in the stationary phase, which is certainly true at moderate pressures (as it is in GC) but might become merely approximate at high pressures, the RHS of Eq. (2) reduces to the LHS of Eq. (3) and the overall expression can be written as

$$\left(\frac{\partial \ln \rho k_i}{\partial P} \right)_T = -\lambda_i \left(\frac{\partial \ln \rho}{\partial P} \right)_T \quad (4)$$

which can be finally integrated to

$$\ln(k_i) = -(\lambda_i + 1) \ln(\rho) + \ln(f_i(T)) \quad (5)$$

Eq. (5) shows the dependence of the retention factors on the density as well as on the temperature of the mobile phase. This characteristic expresses the overall behavior of the solubility, as discussed in the last sub-section. The similarity between Eqs. (1) and (5) is remarkable. This conforms with the outcome of the earlier discussion in this section, that solubility strongly influences retention factors in SFC by virtue of the interactions of the molecules of the solute and of the mobile phase. Because retention factors represent the overall interactions between the solute molecules and both the mobile and the stationary phases, the complete interpretation of experimental data is complex. Nevertheless, the nature of the dependence of retention on both the density and the temperature of the mobile phase, as discussed above, can be effectively used to estimate how retention data vary with the operating conditions. It should be noted at this point that the final retention factor of a compound in an SFC system will depend on the extent of the variations of the state conditions along the column, which are controlled by the mobile phase viscosity and the system properties, like the column and the particle dimensions.

3.2. Efficiency versus density of CO₂

Mass-transfer phenomena in chromatographic columns are mainly controlled by axial diffusion along the column, eddy dispersion resulting from the unevenness of the flow velocity distribution throughout the column, and the mass-transfer kinetics of solute molecules accessing the porous particles. This last contribution is itself composed of three terms [32], due to the mass-transfer resistances across the stagnant film of mobile phase existing against the surface of the porous packing particles, diffusion along the stationary phase surface and diffusion through the porous particles. The basic property which scales all these phenomena is the diffusivity of the solute in the mobile phase [33]. Given the strong dependence of diffusivity on the mobile phase density (Section 2.2) in SFC, it can be expected that the overall mass-transfer kinetics is strongly influenced by the density of CO₂ in SFC systems.

Although the efficiency of a chromatographic column is primarily defined by the mass-transfer kinetics, the mobile phase velocity and the retention factor are the two major agents modulating the consequences of the finite rate of the mass transfer phenomena. Because the density of the mobile phase directly controls the flow velocity (at constant mass flow rate, which is true for any operations under steady-state) and strongly influences retention factors (see

Section 3.1), it can easily be understood that density plays a major role in determining the overall column efficiency. This dependence of the column efficiency on the mobile phase density, however, can be quite complicated. The simplest measure of the column efficiency is the height equivalent to a theoretical plate (HETP). Bartmann and Schneider [34] showed that, in SFC the HETP can be expressed as follows

$$H = B \frac{\bar{u} d_p \rho}{\eta} + \frac{1.3 D_m}{\bar{u}} + \frac{1.5 k}{(1+k)^2} \frac{\bar{u} d_p F}{D_m} \quad (6)$$

where B is a coefficient that depends on the homogeneity of the packed bed and on its geometry, which the authors estimated to be of the order of magnitude of 0.1, $\bar{u} = L/t_0$ is the average linear velocity of the mobile phase along the column (with L column length and t_0 hold-up time), d_p is the average particle diameter, ρ is the mobile phase density, η is its viscosity, D_m is the solute diffusion coefficient, k is the retention factor and F is a constant. Although expressions of the HETP equation vary according to the treatment used to account for the mass-transfer resistances, Eq. (6) expresses the general dependence of the HETP on the mobile phase density. Eq. (6) shows that a change in the density will affect all three terms of Eq. (6), but in different and conflicting ways. For example, a decrease in the density causes, in the first term, an increase in the average mobile phase velocity, \bar{u} , but a decrease in the viscosity, η . In the second term, both the numerator and the denominator increase with a decrease in the mobile phase density, D_m like \bar{u} . The variation of the third term with decreasing density is more complex since k depends on the density as well as the temperature (Section 3.1). Overall, it can be concluded that, although each one of the three terms of Eq. (6) is ultimately a function of the density and/or the temperature of the mobile phase, it is really difficult to predict how the column efficiency varies when the density or the temperature are changed. However, under certain experimental conditions, it is possible to show that the relative contributions of all three terms follow approximately a general trend. For example, Shah and Taylor [29] observed from experimental results that the general trend is for the efficiency to increase with decreasing density and to decrease with increasing temperature. To explain these trend these authors neglected the contribution of the retention factor, as it happens under certain experimental conditions, and also that of any property variation along the column. The increase of the column efficiency with decreasing density was explained by the strong role played by diffusivity in the absence of other effects.

In summary, this discussion shows that, although column efficiency in SFC systems is ultimately controlled by the density and the temperature of the mobile phase, general estimates of the nature of the variations of the column efficiency when these factors change are difficult to derive. One can, however, estimate general trends for specific instances, supported by useful approximations.

4. Conclusion

The density of the mobile phase is often viewed as the most influential physical property in the operation of SFC columns because both the retention factor and the separation efficiency, the two critical performance parameters in chromatography, are often correlated with the mobile phase density. While this statement is definitely supported by strong reasons, we are of the opinion that these two parameters, retention factors and column efficiencies, depend primarily on the diffusivity of the analytes and their solubility. These two factors, in turn, are strongly controlled by the mobile phase density and, to a lesser extent, by the column temperature. Our analysis of the literature shows that solute diffusivities depend more strongly on the mobile phase density alone, irrespec-

tive of the temperature and the pressure combined to achieve it. The solubility, on the other hand, can be conveniently related to both the mobile phase density and its temperature, rather than to the pressure and the temperature, because otherwise, if solubility is related to pressure and temperature, any general conclusion could be falsified by the occurrence of a pressure crossover phenomenon [26]. This last insight is important because, although the eluent density is not the sole controller of the physical properties which control SFC operations, it is possible to reach a clearer understanding of the effects of the operating conditions on chromatographic performance by following the changes in both the density and the temperature, rather than observing those of the pressure and the temperature. This indicates that it should be much easier to follow the consequences of changing the operating conditions by following the displacement relative to the isopycnic lines of the point of coordinates (P , T) that represents the changes in the state of the system studied in the pressure–temperature plane, rather than by following its migrations relative to the isotherms and the isobars themselves.

Acknowledgements

This work was supported in part by financial and technical support by Waters Technologies Corporation and by the cooperative agreement between the University of Tennessee and the Oak Ridge National Laboratory. We thank Uwe Neue and Martin Gilar (Waters Technologies Corp, Milford, MA, USA) for fruitful discussions.

References

- [1] E. Klesper, A.H. Corwin, D.A. Turner, *J. Org. Chem.* 27 (1962) 700.
- [2] U. van Wasen, G.M. Schneider, *Chromatographia* 8 (1975) 274.
- [3] P.A. Peaden, M.L. Lee, *J. Chromatogr.* 259 (1983) 1.
- [4] D.E. Martire, *J. Chromatogr.* 461 (1989) 165.
- [5] D.P. Poe, D.E. Martire, *J. Chromatogr.* 517 (1990) 3.
- [6] X. Lou, H.-G. Janssen, C.A. Cramers, *J. Chromatogr. A* 785 (1997) 57.
- [7] H.H. Lauer, D. McManlglill, R.D. Board, *Anal. Chem.* 55 (1983) 1370.
- [8] T.L. Chester, D.P. Innis, *J. High Resolut. Chromatogr.* 8 (1985) 561.
- [9] N. Wu, Z. Chen, J.C. Medina, J.S. Bradshaw, M.L. Lee, *J. Microcolumn Separations* 12 (2000) 454.
- [10] V. Vesovic, W.A. Wakeham, G.A. Olchoway, J.V. Sengers, J.T.R. Watson, J. Millat, *J. Phys. Chem. Ref. Data* 19 (1990) 763.
- [11] A. Fenghour, W. Wakeham, V. Vesovic, *J. Phys. Chem. Ref. Data* 27 (1998) 31.
- [12] E.W. Lemmon, M. Huber, M.O. McLinden, D.G. Friend, National Institute of Standards and Technology, Standard Reference Data Program, Gaithersburg 8.0.
- [13] G. Guiochon, A. Tarafder, *J. Chromatogr. A* 1218 (2011) 1037.
- [14] H. Iwasaki, M. Takahashi, *J. Chem. Phys.* 74 (1981) 1930.
- [15] A. Akgerman, C. Erkey, M. Orejuela, *Ind. Eng. Chem. Res.* 35 (1996) 911.
- [16] P.R. Sassi, P. Mourier, M.H. Caude, R.H. Rosset, *Anal. Chem.* 59 (1987) 1164.
- [17] H. Weingärtner, U. Klask, G.M. Schneider, *Z. Phys. Chem.* 219 (2005) 1261.
- [18] H. Higashi, Y. Iwai, Y. Arai, *Ind. Eng. Chem. Res.* 39 (2000) 4567.
- [19] R.C. Reid, J.M. Prauznitz, B.E. Poling, *The Properties of Gases and Liquids*, 4 ed., McGraw Hill, New York, NY, 2001, 1987.
- [20] H. Higashi, Y. Iwai, Y. Nakamura, S. Yamamoto, Y. Arai, *Fluid Phase Equilibria* 166 (1999) 101.
- [21] S. Takahashi, *J. Chem. Eng. Jpn.* 7 (1974) 417.
- [22] K.D. Bartle, A.A. Clifford, S.A. Jafar, *J. Chem. Eng. Data* 35 (1990) 355.
- [23] G. Anitescu, L. Tavlarides, *J. Supercritical Fluids* 14 (1999) 197.
- [24] R.B. Gupta, J.-J. Shim, *Solubility in Supercritical Carbon Dioxide*, 1st ed., CRC Press, Boca Raton, FL, 2006.
- [25] C. Garlapati, G. Madras, *J. Chem. Eng. Data* 55 (2010) 273.
- [26] N.R. Foster, G.S. Gurdial, J.S.L. Yun, K.K. Liang, K.D. Tilly, S.S.T. Ting, H. Singh, J.H. Lee, *Ind. Eng. Chem. Res.* 30 (1991) 1955.
- [27] J. Chrastil, *J. Phys. Chem.* 86 (1982) 3016.
- [28] C. Garlapati, G. Madras, *Thermochim. Acta* 500 (2010) 123.
- [29] S. Shah, L.T. Taylor, *Chromatographia* 29 (1990) 453.
- [30] A. Rajendran, O. Kräuchi, M. Mazzotti, M. Morbidelli, *J. Chromatogr. A* 1092 (2005) 149.
- [31] M. Perrut, *J. Chromatogr. A* 658 (1994) 293.
- [32] G. Guiochon, A. Felinger, A.M. Katti, D.G. Shirazi, *Fundamentals of Preparative and Nonlinear Chromatography*, Elsevier, Amsterdam, The Netherlands, 2006.
- [33] K. Miyabe, G. Guiochon, *J. Chromatogr. A* 1217 (2010) 1713.
- [34] D. Bartmann, G.M. Schneider, *J. Chromatogr.* 83 (1973) 135.