

Short Communication

Influence of pressure on solute retention in liquid chromatography

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ABSTRACT

Confirming recent, independent experimental results, simple considerations of thermodynamics show that the logarithm of the retention factors of solutes vary linearly with increasing pressure, in the pressure range most commonly used (0–200 atm). The coefficient of this dependence increases linearly with the difference between the partial molar volumes of the solute in the stationary and the mobile phases. For homologues, this coefficient increases linearly with the number of carbon atoms and with the difference, ΔV_{CH_2} , between the partial molar volumes of a CH_2 group in the two phases. The pressure dependence of the retention factor may be significant because for a C_{18} –methanol system $\Delta V_{\text{CH}_2}/V_{\text{CH}_2}$ is of the order of 6%.

In the early days of liquid chromatography, Martire and Locke [1] suggested and Bidlingmeyer and Rogers [2] reported that important retention and even selectivity changes can be observed at very high pressures. Conventional wisdom has it so far, however, that pressure-induced changes in retention data are negligible under conventional experimental conditions (*i.e.*, at pressures below 5000 p.s.i.). In a recent paper, McGuffin and Evans [3] reported experimental results illustrating the significant pressure dependence of the retention factors of the components of a homologous series in reversed-phase liquid chromatography. Although their interpretation of their results in terms of the unified theory of retention developed by Martire and Boehm [4] is correct, it should be noted that

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simple, general results of solution thermodynamics permit the derivation of the same conclusions using the limited set of data available.

We know from thermodynamics [5] that the change, dG , in the Gibbs free energy of 1 mol of a component is related to the changes dp and dT in the pressure and temperature, respectively, of the system by

$$dG = Vdp - SdT \quad (1)$$

where V is the molar volume and S the molar entropy. Applied to a component in equilibrium between two different phases, eqn. 1 gives

$$d(\Delta G) = \Delta V dp - \Delta S dT \quad (2)$$

where ΔG , ΔV and ΔS are the differences in the molar Gibbs free energy, the molar volume and the molar entropy, respectively, which are associated with the passage of the component from one phase to the other. We derive from eqn. 2 that

$$\frac{\partial}{\partial p} \cdot \Delta G = \Delta V \quad (3)$$

The retention factor, k' , is related to the change in the molar Gibbs free energy of phase change by

$$\Delta G = RT \ln K = RT \ln \phi k' \quad (4)$$

where R is the universal ideal gas constant, K is the thermodynamic constant of the phase equilibrium studied (based on mole fraction and activity coefficient [6]), and ϕ is the phase ratio. Combination of eqns. 3 and 4 gives

$$\frac{\partial}{\partial p} \ln k'_n = \frac{\Delta V_n}{RT} - \frac{1}{\phi} \cdot \frac{\partial \phi}{\partial p} \quad (5)$$

where k'_n is the retention factor of the homologue with n carbon atoms in its linear alkyl chain and ΔV_n is the change in partial molar volume associated with the passage of this homologue from one phase to the other.

It is reasonable to assume that, for the components of a homologous series, the molar volume, V_n , increases linearly with increasing carbon number. The unit increase in molar volume is the contribution, V_{CH_2} , to the molar volume of the addition of one CH_2 group to the molecule, hence

$$V_n = V_0 + nV_{\text{CH}_2} \quad (6a)$$

where V_0 is the contribution of the functional group to the partial volume of the homologue, and

$$\Delta V_n = \Delta V_0 + n\Delta V_{\text{CH}_2} \quad (6b)$$

where ΔV_{CH_2} represents the difference $\Delta V_{n+1} - \Delta V_n$. Then, eqns. 5 and 6b can be combined to predict the linear dependence of the logarithm of the retention factor on the pressure:

$$\frac{\partial}{\partial p} \ln k'_n = -\frac{1}{\phi} \frac{\partial \phi}{\partial p} + \frac{\Delta V_0}{RT} + \frac{\Delta V_{\text{CH}_2}}{RT} \cdot n \quad (7)$$

provided that the term $\partial \phi / \partial p$ is either negligible or constant and that ΔV_0 and ΔV_{CH_2} are independent of the pressure. The experimental results of McGuffin and Evans [3] exhibit a quadratic dependence. However, a linear dependence would be consistent with the experimental results if the data point at the highest pressure were omitted, *i.e.*, up to a pressure of *ca.* 3000 p.s.i. (Fig. 4 in ref. 3). The observed deviation from the linear dependence is easily explained by the pressure dependences of the differ-

ences between the partial molar volumes of each of the homologues in the two phases, *i.e.*, of ΔV_0 and ΔV_{CH_2} . These parameters are pressure dependent, a fact which is taken into account in the more sophisticated model derived by Martire and Boehm [4]. We also note that eqn. 6 is linear in n . The rate of variation of $\ln k'_n$ with increasing pressure increases linearly with increasing carbon number, n , again in agreement with the experimental results of McGuffin and Evans [3].

Finally, if k'_n and k'_{n+1} are the retention factors of two successive homologues, and $\alpha_{n+1/n} = k'_{n+1}/k'_n$, we have

$$\frac{\partial}{\partial p} \ln \alpha_{n+1/n} = \frac{\Delta V_{\text{CH}_2}}{RT} \quad (8)$$

As the molar volumes of homologues increase linearly with increasing carbon number of the chain, the difference between the molar volumes of two successive homologues is constant and equal to the contribution of one CH_2 group. Hence it is expected that the increase in the separation factor for a given increase in the column average pressure will be constant. This is confirmed by the experimental results, and the value reported by McGuffin and Evans [3] for two successive homologues with an even carbon number is $\Delta \alpha / \alpha = 0.026 (\pm 0.0083)$ for $\delta p = 3500$ p.s.i. or $\partial \ln \alpha / \partial p \approx 1.04 \cdot 10^{-4}$. Obviously, as $\ln k'$ actually increases as a quadratic function of the pressure, so does $\ln \alpha$. The precision of the experimental data [3] does not permit the investigation of this dependence, however.

If we introduce the numerical result of McGuffin and Evans [3] into eqn. 8, and note that what they call α is what we have defined above as $\alpha_{n+2/n} = \alpha_{n+1/n}^2$, we obtain

$$\Delta(\Delta V_{\text{CH}_2}) = 0.0001 RT = 2.5 (\pm 0.8) \text{ ml} \quad (9)$$

(with $RT = 22\,400T/273$), assuming the measurements were made at 20°C . Hence the experiments of McGuffin and Evans permit the direct determination of the difference between the partial molar volumes of the CH_2 group in solution in methanol and adsorbed on the surface of the C_{18} -bonded silica. This difference is significant and of the order of 6%, as the volume occupied by a CH_2 group in a pure alkane is *ca.* $14/0.7 = 20$ ml (assuming a density of 0.7 for the liquid alkane). It is noteworthy that the partial molar volume of a CH_2 group is larger when

adsorbed in the chemically bonded C₁₈ phase than in solution in methanol. This probably reflects a lower density of the bonded phase and some hindrance of the immobilized alkyl chains, more than any peculiarity of the methanol solution.

From the results obtained, it could further be expected that the pressure dependence of $\ln k'$ for the components of other homologous series will be very similar. As the volume occupied by a CH₂ group is relatively independent of the chemical structure of the functional end-group, we can predict that the slope of the plot of $\partial \ln k' / \partial p$ versus n will be very close for all homologous series studied in a given phase system, and that the value of $\alpha_{n+1/n}$ will be nearly the same for all successive couples of all these series. These values should depend only on the nature of the phase system selected, through the values of ϕ and ΔV_0 , and their pressure dependences.

As expected, these relationships are similar to and consistent with those which have been abundantly demonstrated previously, and which are commonly found in gas or liquid chromatography [7,8] between the number of carbon atoms and the retention indices or $\ln k'$ in homologous series. Likewise, the additivity of group contributions to the Gibbs free energy of phase equilibria should not cause any surprises: those relationships are the application to a new experimental problem of the classical Martin principle of linear contributions to phase equilibrium constants [1,7–9].

The changes in the partial molar volumes of the solutes may result from the compressibility of either phases, from variations in the energy of molecular

interactions or from the energy density of interactions. As always with a purely thermodynamic approach, no information is available regarding the mechanism(s) or the interaction(s) involved at the microscopic or molecular level. Studies of the possible mechanisms can be made only through the use of microscopic models, such as that provided by the unified theory of retention [4]. These studies will require more abundant, and probably more precise, experimental data.

In conclusion, the paper by McGuffin and Evans [3] provides both a warning to analysts that the influence of the pressure (and hence of the flow-rate) on the retention factors, and therefore on the resolution of mixtures, is far from negligible, and reminds us of a useful tool for the study of the thermodynamics of solutions and of phase equilibria [1,2].

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