Theoretical consideration and application of the SP and SP' scales in RP chromatographic systems in which Everett's equation is valid

T. J. JANJIĆ[#], G. VUČKOVIĆ[*#] and M. B. ĆELAP[#]

Faculty of Chemistry, University of Belgrade, P. O. Box 158, YU-11001 Belgrade, Yugoslavia

It is shown that in the case of ODS and less polar modifiers the log k values are a linear function of the *SP'* parameters. This findings differ from earlier investigated systems, in which a linear dependence between log k and *SP* parameters ($SP = \log SP'$) was found. Both linear relationships have been analyzed and the corresponding possible separation mechanisms have been considered. In addition, the advantages of normalization of both scales are shown and how then they can be applied in the investigation of substances congenerity.

Keywords: RP column chromatography, Everett's equation, solvent strength scales, *SP* parameter, *SP'* parameter, capacity factor.

INTRODUCTION

In previously published papers,[1,2] the influence of the stationary and mobile phase compositions on the retention factors in RP chromatographic systems in which the Everett equation is valid was studied. In all the investigated cases, a linear dependence between the log k values and the *SP* parameters was found ($SP = \log x_s/x_1$, where x_s and x_1 denote the mole fractions of a modifier in stationary and mobile phase, respectively). Continuing these investigations, it was found that in the case of ODS and less polar modifiers this relation is not valid. On the basis of preliminary investigations in those cases a linear dependence between log k values and *SP'* parameters ($SP' = 10^{SP}$) was found. Thus, the aim of this paper was to check whether this dependence has a wider importance and to analyze the linear relations log $k = f(SP)$ and log $k = f(SP')$, as well as to consider the corresponding separation mechanisms. Besides, we wanted to check if the normalized *SP* and *SP*' scales can be applied to substances congenerity investigations.

---

* Author for the correspondence: Fax +381-11-638-785, E-mails: gordanav@helix.chem.bg.ac.yu or evuckogo@kondor.etf.bg.ac.yu

\# Serbian Chemical Society active member.

Examples of the systems in which a linear dependence of the function log k = f(SP') exists

Particular problems in a previous investigation[2] were ODS/IPA–water and ODS/THF–water systems, studied earlier by Cheong and Carr,[3] over a wide modifier concentration range for a series of alkylbenzenes. They established a pronounced non-linearity between the ln k values and the volume fractions of the modifier (φ). The system ODS/THF–water was investigated over a narrow φ interval by Jandera,[4] who also established significant non-linearity of the function $\log k = f(\varphi)$ for a series of 3,5-dinitrobenzoates of aliphatic n-alcohols. Considering these two systems we found that the Everett equation could also be applied in these cases, but that the $\log k$ (ln k) values are a linear function of the quotient x_s/x_1 (*SP'* parameter), and not of its logarithm (*SP* parameter) as was found in earlier examples.[1,2] Table I and II show a good linear relationship of the function $\log k$ (ln k) $= f(x_s/x_1)$. The great difference of the best K value found for the system ODS/THF–water in Table I ($K = 14$) and Table II ($K = 30$) could be explained by the application of various types of ODS. It seems that the ODS/ACN–water system described in our last paper[2] can be used as an example when the *SP* scale ($K = 30$) is valid for ACN concentrations smaller than 75–80 % v/v, while with the higher concentrations the *SP'* scale is valid. So for $K = 30$, the following relationship was obtained:

$$P_m^N = 0.1164 \ SP' + 4.804 \times 10^{-3} \tag{1}$$

for the concentration range 75–100 % v/v, $n = 6$, $r = 0.9996$, $s = 1.15 \times 10^{-3}$ (P_m^N denotes the parameter linearly correlated with $\log k$). In this case there is a change of *SP* scale into *SP'* scale in the ACN concentration range 75–80 % v/v, caused by a change in the separation mechanism. As the differentiation possibility of K in this narrow concentration range is low, it is possible that the K value is not the same in both scales.

As all the cases mentioned are related to ODS and, as it is known,[5] the conformation of the alkyl chains of the bonded phase is to a great extent influenced by the concentration and the nature of the modifier, it can be assumed that the more ordered "bristle" state, appearing when the polarity of the mobile phase is low, corresponds to the *SP'* scale and the "fold up" state, occurring when the polarity of the mobile phase is high, to the *SP* scale. For this reason, with the least polar modifiers in RP chromatography THF and IPA (with solvent strength $S_{RP} = 4.4$ in both cases[6]) the *SP'* scale is valid over the whole concentration range. In the case of more polar ACN ($S_{RP} = 3.1$), this scale is valid only for high concentrations of modifier.

Analysis of the regression straight lines of log k = f(log x_s/x_1) and log k = f(x_s/x_1)

The physical meaning of the intercept and slope of the mentioned regression straight lines is easy to determine. In the case of the equation:

$$\log k = A \log x_s/x_1 + B \tag{2}$$

on the basis of the fact that in the case $x_1 = 0$ $\log x_s/x_1 = \log K$, and when $x_1 = 1$ $\log x_s/x_1 = 0$, which is a consequence of the Everett equation, it was found that:

$$A = [\log k(x_1=0) - \log k(x_1=1)]/\log K \quad\quad (3)$$

$$B = \log k(x_1=1) \quad\quad (4)$$

From the above it can be seen that the $\log x_s/x_1$ scale (*SP* scale) has values from 0 to $\log K$.

In the case of the equation:

$$\log k = A'x_s/x_1 + B' \quad\quad (5)$$

on the basis of the fact that in the case $x_1 = 0$ $x_s/x_1 = K$, and when $x_1 = 1$, $x_s/x_1 = 1$, one finds that:

$$A' = [\log k(x_1=0) - \log k(x_1=1)]/(K-1) \quad\quad (6)$$

and

$$B' = [K \log k(x_1=1) - \log k(x_1=0)]/(K-1) \quad\quad (7)$$

From the above said it can also be seen that the x_s/x_1 scale (*SP'* scale) has values from 1 to K. Both the *SP* and *SP'* scales can be normalized (giving *NSP* and *NSP'* scales) by means of the equations:

$$NSP = 1 - (SP/\log K) = \log [x_1(K-1)+1]/\log K \quad\quad (8)$$

$$NSP' = 1 - (SP'-1)/(K-1) = 1 - (K-Q)/(K-1)Q \quad\quad (9)$$

where $Q = [x_1(K-1)+1]$.

In such a way the following is achieved:

1) Both normalized scales have for $x_1 = 0$ and 1 the same values on the scale 0, or 1, respectively, regardless of the K value, which enables a comparison of scales obtained for different K values;

2) The intercepts of the corresponding regression lines $\log k = f(NSP)$ and $\log k = f(NSP')$ are equal to $\log k(x_1 = 0)$ and the slopes to $\log k(x_1 = 1) - \log k(x_1 = 0)$. Therefore, in these cases only the retention values of the chromatographed substances determine the slope and the intercept of the corresponding regression lines.

It is necessary to note that the calculation of the correlation between $\log k$ and the corresponding normalized or non-normalized scale give the same correlation coefficient, but of opposite sign.

Consideration of the separation mechanisms

In our last paper[2] many examples were given where a linear dependence between $\log k$ values and *SP* parameters exists. Only in two systems (ODS/THF–water and ODS/IPA–water) were the $\log k$ values a linear function of *SP'* parameters, as was demonstrated in this paper.

The phase equilibrium of an ideal system:

$$(\text{modif.})_1 + (\text{water})_s \longrightarrow (\text{modif.})_s + (\text{water})_1$$

has the equilibrium constant:

$$K = x_s x_1{}^w/x_1 x_s{}^w \qquad (10)$$

in which x_1 and x_s are the mole fractions of the modifier, and $x_s{}^w$ and $x_1{}^w$ mole fractions of the water in the stationary and mobile phase, respectively. From this equation, under the following conditions $x_s + x_s{}^w = 1$ and $x_1 + x_1{}^w = 1$, the Everett equation can be derived:

$$x_s/x_1 = K/[x_1(K-1)+1] \qquad (11)$$

Therefore, it is obvious that both the *SP* scale (log x_s/x_1) and the *SP'* scale (x_s/x_1) are based on the mentioned phase equilibrium. Their values can be calculated using the given equation for each x_1 when the value of the equilibrium constant K is known.

A. Consideration of linear dependence of log k = f(SP)

It is assumed that the chromatographed substance is in competitive equilibrium with the modifier in the stationary phase:

$$A(modif.)_s + (solute)_1 \longrightarrow A(modif)_1 + (solute)_s$$

Taking into account that the mole fraction of solute is very low in both phases ($x_s{}^*$ and $x_1{}^*$) in comparison with mole fraction of the other constituents (modifier and water), the presence of the solute has no significant effect on the quotient x_s/x_1 and, therefore, it follows

$$K_1 = x_s{}^*/x_1{}^* \, (x_1/x_s)^A \qquad (12)$$

After exchanging the value $x_s{}^*/x_1{}^*$ with capacity factor (k) and putting in the logarithmic form, the following is obtained:

$$\log k = A \log x_s/x_1 + \log K_1 \qquad (13)$$

The slope of the obtained straight line corresponds to the average number of modifier molecules exchanged by one solute molecule, while the intercept is equal to $\log K_1$. Equation (13) is applicable in most cases. The exceptions appear only in the case of ODS with a less polar mobile phase, where the log k values are a linear function of *SP'* parameters. We call the corresponding Combined phase equilibrium-displacement model the SP mechanism.

B. Consideration of the linear dependence log k = f(SP')

As already stated, the linear correlation log $k = f(SP')$ is observed only in the case of ODS when a less polar mobile phase is used, which favours the "bristle" state conformation of the chains of the bonded phase compared to "fold up" one, thus setting the conditions for the distribution of the investigated substances between the stationary and mobile phases.

The condition for this dependence is that the distribution coefficient K_D (defined as $k \, \varphi^{-1}$, where φ is the phase ratio) is the exponential function of the x_s/x_1 value:

$$K_D = k \, \varphi^{-1} = K_{D_0}{}^{(x_s/x_1)}$$

or in the logarithmic form:

$$\log k = x_s/x_1 \log K_{D_0} + \log \varphi \qquad (14)$$

where K_{D_0} denotes the distribution coefficient when $x_s/x_1 = 1$. In accordance with this equation, the slope of the straight line is equal to $\log K_{D_0}$, and the intercept to $\log \varphi$, *i.e.,* for a given column and modifier they should be almost constant. This is confirmed by the results given in Tables I and II. For instance, in Table I (left) for the system ODS/IPA–water the average value of the intercept and the corresponding standard deviation is –2.37±0.12, and for the system ODF/THF–water it is –2.83±0.14 (Table I, right). From Table II it can be seen that for the system ODS/THF–water the average $\log \varphi$ equals –1.32±0.04. Only in the case of compound No. 1 in Table I (right) was the corresponding intercept value rejected on the basis of the $Q_{0.95}$ test. We call this Combining phase equilibrium-distribution model the SP' mechanism.

TABLE I. Linear dependence of the function: $\ln k = f(x_s/x_1)$ for the series of alkylbenzenes in the systems: ODS/IPA–water ($K = 15$) (A) and ODS/THF–water ($K = 14$) (B). The $\ln k$ values were taken from Fig. 1 and 2 from the literature.[3] Concentration range of modifier: 100–30 % v/v for IPA and 90–30 % v/v for THF

No.	Compound	A					B				
		–Intercept	Slope	r	n	$s\times10^2$	–Intercept	Slope	r	n	$s\times10^2$
1	Benzene	2.2309	0.6579	0.9993	8	4.74	2.2601	0.7316	0.9985	7	5.70
2	Toluene	2.2690	0.7710	0.9999	8	2.10	2.5849	0.8072	0.9988	7	7.27
3	Ethylbenzene	2.3174	0.8555	0.9998	8	3.30	2.6564	0.9044	0.9997	7	4.07
4	Propylbenzene	2.3865	0.9682	0.9996	8	5.28	2.8236	1.0113	0.9998	7	3.72
5	Butylbenzene	2.4778	1.0740	0.9993	8	7.74	2.9321	1.1021	0.9997	6	3.82
6	Pentylbenzene	2.3378	1.1030	0.9998	7	3.29	2.9556	1.1674	0.9998	6	3.30
7	Hexylbenzene	2.3540	1.1807	0.9997	7	4.31	2.9222	1.2064	0.9992	5	5.18
8	Octylbenzene	2.3335	1.3325	0.9991	6	6.51	2.9216	1.2992	0.9991	4	4.41
9	Dodecylbenzene	2.6336	1.8085	0.9980	4	10.8	2.8503	1.4455	0.9972	4	8.63

The derived equations explain the linear correlation between the log k values (or parameters linearly related to them) and the *SP* and *SP'* parameters. They indicate the probable separation mechanism in the cases where the mentioned linearities exist.

It is quite clear that the log k values are linear functions of the *SP* or *SP'* parameters only if the described equilibria prevail over the other possible interactions between the compounds to be separated and the stationary and mobile phases. Thus in examples

2 and 3 described in our last paper[2] the log k values corresponding to 1 % v/v of modifier deviate relatively often from the regression straight line, and in example 4 this point could not be used. In these examples the phase equilibrium constant is very small (less than 2) and consequently in the case of 1 % v/v of modifier the values $x_s < 0.0089$ (for MeOH) or 0.0068 (for ACN) are also very small, making the conditions for the substitution of the modifier in the stationary phase by chromatographed substances very unfavourable. This causes a considerably strong effect for some other interactions.

TABLE II. Linear dependence of the function log $k = f(x_s/x_1)$ for the series of 3,5-dinitrobenzoates of aliphatic n-alcohols. System ODS/THF–water ($K = 30$). Concentration range of THF 45–65 % v/v. The log k values were taken from Fig. 3 from the paper by Jandera[4]

Number of C atoms in n-alcohol	–Intercept	Slope	r	n	$s \times 10^2$
1	1.2756	0.3302	0.9992	5	1.22
2	1.2857	0.3662	0.9995	5	1.35
3	1.3050	0.4033	0.9995	5	1.17
4	1.3570	0.4472	0.9986	5	2.18
5	1.3797	0.4778	0.9989	5	2.06
6	1.3462	0.4911	0.9987	4	1.74

TABLE III. Functional dependence log $k = f(NSP)$ using $K = 3.4$ for 1–100 % v/v of methanol. System CN–silica/methanol–water. The log k values were taken from the literature[7,8]

No.	Compound	–Intercept	Slope	$-r$	$s \times 10^2$
1	Naphthalene	1.7500	2.5348	0.9977	5.78
2	2-Hexanone	0.4392	1.0374	0.9956	3.28
3	Benzaldehyde	0.7543	1.5455	0.9950	5.20
4	Anisole	0.9566	1.6471	0.9994	1.92
5	Benzonitrile	0.8051	1.4882	0.9992	2.00
6	Bromobenzene	1.3424	2.1170	0.9989	3.33
7	Chlorobenzene	1.2068	1.9736	0.9976	4.60
8	Benzyl alcohol	0.4056	1.1711	0.9976	2.73
9	2-Chlorophenol	0.9516	1.8413	0.9994	2.14
10	n-Propylbenzene	1.5905	2.4523	0.9987	5.21
11	Acetophenone	0.8907	1.6413	0.9952	5.41
12	1,2-Dichlorbenzene	1.5937	2.4269	0.9990	3.64
13	2-Phenylethanol	0.5701	1.3477	0.9971	3.43
14	4-Cresol	0.7875	1.6528	0.9989	2.60
15	Phenol	0.5312	1.3255	0.9963	3.84
16	Benzamide	0.4014	1.2024	0.9956	3.80
17	Acetanilide	0.6230	1.4084	0.9989	2.22
18	Nitrobenzene	0.9995	1.6448	0.9996	1.56

Application of NSP and NSP' scales in the investigation of the congenerity of substances

The fact that linearity between log k values and *NSP* or *NSP'* scales exists, as well as that the intercept of this straight line in both cases is equal to log k (x_1=0), offers a possibility for their application in the investigation of congenerity, even in cases when there is no corresponding scale for such an investigation. The intercept and slope of the functions log $k = A_N(NSP) + B_N$ and log $k = A_{N'}(NSP') + B_{N'}$ can be determined directly or calculated from the intercept and slope obtained in *SP* or *SP'* scales.

$$A_N = - A \,(\log K) \quad ; \quad A_{N'} = A'(1-K)$$

$$B_N = A \log K + B \quad ; \quad B_{N'} = A'K + B'$$

The following systems have been studied:

1) CN–silica/methanol–water for 1–100 % v/v of methanol (Table III). Regression data of the function $B_N = f(-A_N)$:

$n = 18$, $r = 0.9837$, $s = 7.6 \times 10^{-2}$, intercept = –0.6862, slope = 0.9561.

2) ODS/IPA–water for 30–100 % v/v of IPA (Table I, left). Regression data of the function $B_{N'} = f(-A_{N'})$:

$n = 9$, $r = 0.9999$, $s = 6.38 \times 10^{-2}$, intercept = –2.0487, slope = 1.0502.

3) ODS/THF–water for 30–90 % v/v of THF (Table I, right). Regression data of the function $B_{N'} = f(-A_{N'})$:

$n = 9$, $r = 0.9990$, $s = 1.38 \times 10^{-2}$, intercept = –1.9165, slope = 1.0160.

4) ODS/THF–water for 45–65 % v/v of THF (Table II). Regression data of the function $B_{N'} = f(-A_{N'})$:

$n = 6$, $r = 0.99996$, $s = 1.60 \times 10^{-2}$, intercept = –1.0713, slope = 1.0136.

The values of the intercepts and slopes calculated in the cited examples correspond to the ordinate or abscissa of the section point, respectively. The ordinates are expressed in log k units in the examples 1 and 4, and in ln k units in the examples 2 and 3. As expected, excellent correlation was found in the examples 2–4, because homologous series of compounds were considered. Unexpectedly, a relatively high correlation coefficient was also found in the first example where substances with considerably different solute descriptors were used. In order to illustrate the mentioned linearity, the fact that the r_{test} value for $n = 18$, with a certainty of 99.9 %, amounts to 0.708 could be cited. The investigation of the congenerity of the substances in the given examples (by using *NSP* or *NSP'* scales) was performed for the first time, as till now no corresponding scale for such investigations existed.

И З В О Д

ТЕОРИЈСКО РАЗМАТРАЊЕ И ПРИМЕНА SP И SP' СКАЛА У RP ХРОМАТОГРАФСКИМ
СИСТЕМИМА У КОЈИМА ВАЖИ ЕВЕРЕТОВА ЈЕДНАЧИНА

ТОМИСЛАВ Ј. ЈАЊИЋ, ГОРДАНА ВУЧКОВИЋ и МИЛЕНКО Б. ЋЕЛАП

Хемијски факулȓеȓ, Универзиȓеȓ у Беоīраду, ȕ. ȕр. 158, 11001 Беоīрад

Показано је да су у случају ОДС и мање поларних модификатора log k вредности линеарна функција *SP'* параметара. Ово се разликује од раније изучаваних система у којима је нађена линеарна зависност између log k и *SP* параметара (*SP* = log *SP'*). Обе линеарне зависности су анализиране и разматрани су могући механизми одвајања. Такође је показано које су предности нормализације обе скале и како се оне могу применити за изучавање конгенеричности супстанци.

(Примљено 18. септембра 2001)

REFERENCES

1. T. J. Janjić, G. Vučković, M. B. Ćelap, *J. Serb. Chem. Soc.* **65** (2000) 725
2. T. J. Janjić, G. Vučković, M. B. Ćelap, *J. Serb. Chem. Soc.* **66** (2001) 671
3. W. J. Cheong, P. W. Carr, *Anal. Chem.* **61** (1989) 1524
4. P. Jandera, *J. Chromatogr.* **314** (1984) 13
5. M. T. Gilbert, *High Performance Liquid Chromatography*, Wright, Bristol, 1987, p. 169 and papers cited therein
6. F. Geiss, *Fundamentals of Thin Layer Chromatography (Planar Chromatography),* Hüttig, Heidelberg, 1987, p. 288
7. D. S. Seibert, C. F. Pool, *Chromatographia* **41** (1995) 51
8. D. S. Seibert, C. F. Pool, *J. High Resol. Chromatogr.* **18** (1995) 226.