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# Quantitative Structure–Retention Relationships for the Gas Chromatographic Retention Indices of Oxygen Containing Organic Compounds

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# Quantitative Structure–Retention Relationships for the Gas Chromatographic Retention Indices of Oxygen Containing Organic Compounds

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**Abstract**

**Motivation.** We propose a modified equation for the calculation of valence connectivity indices on the basis of summation over inverse geometric mean terms, $^n\chi^{Vm}$, instead of summation over inverse square root terms, $^n\chi^V$. Using the modified connectivity indices along with E–state and boiling points we develop quantitative structure–retention relationships (QSRR) for the gas chromatographic retention indices, I, partial molar enthalpies, ΔH, and partial molar entropies, ΔS, of oxygen containing organic compounds on seven stationary phases. The stationary phases are isosteric, one is apolar and branched alkane 19,24–dioctadecyldotetracontane, (C78), and the other six are polar resulting by replacement of one of the $-CH_3$ groups of C78 by $-OH$ (POH), $-CN$ (PCN), $-SH$ (PSH), $-CF_3$ (MTF) and four of the $-CH_2CH_3$ groups of C78 by $(-CH_2CF_3)_4$ (TTF) and $(-OCH_3)_4$ (TMO).

**Method.** Four descriptors ($^1\chi_P{}^V$, $^2\chi_P{}^{Vm}$, E–state and boiling point) are selected from a pool of several descriptors based on stepwise multiple linear regression analysis to obtain the best QSRR models for the three properties. A unified QSRR model has been proposed for each property by combining the data of all the phases and with the use of an additional descriptor, namely the property dependent phase constant (PDPC) to represent the phase. QSRR models for the three retention properties of 18 oxygen containing organic compounds are developed with multiple linear regression using ORIGIN (version 5.0).

**Results.** The QSRR model obtained with $^n\chi_P{}^{Vm}$ descriptors give slightly better predictions in some combinations than with the descriptors $^n\chi_P{}^V$. The predictive descriptors $^1\chi_P{}^V$, $^2\chi_P{}^{Vm}$, the E–state of oxygen atom and the boiling point values are give better QSRR models in all the seven independent phases as well as for the unified QSRR models. The $r_{cv}$ values are very close to $r$ in the QSRR models of seven independent phases. The correlation coefficients obtained with unified QSRR are: $r(I) = 0.995$, $r(\Delta H) = 0.973$, and $r(\Delta S) = 0.936$; and the corresponding leave–one–out cross validation correlation coefficients are $r_{cv}(I) = 0.993$, $r_{cv}(\Delta H) = 0.965$ and $r_{cv}(\Delta S) = 0.922$.

**Conclusions.** The predictive quality of the three unified QSRR equations proposed for the three properties in this study have been verified considering the retention data of two new stationary phases 1–chloro–18,23–dioctadecylhentetracontane, (PCL) and 18,23–dioctadecyl–7–hentetracontanol (SOH). The predicted results are in satisfactory agreement with the observed values in the two new phases, with maximum standard deviations $\sigma(I) = 7.6$, $\sigma(\Delta H) = 207.4$ and $\sigma(\Delta S) = 0.445$.

**Keywords.** Valence connectivity indices; Kováts retention index; partial molar enthalpy; partial molar entropy; gas chromatography; QSRR; quantitative structure–retention relationships.

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# 1 INTRODUCTION

Quantitative structure–activity relationships (QSRR) emerged in the last decades as useful tools for predicting physico–chemical, biological and pharmacological properties of molecules, especially in those cases where experimental data corresponding to such properties are not available [1,2]. Valence connectivity indices and electrotopological state indices became very popular chemical graph theoretical descriptors and have been proved to be useful in the studies of quantitative structure and retention relationships [1–4]. These descriptors are derived directly from molecular structural formula that encodes the size, branching, cyclic nature and the presence of heteroatoms in organic molecules. The application of quantitative structure–retention relationships (QSRR) models to describe Kováts retention indices and partition coefficients has been extensively reported in the literature [5–15]. In most of these studies better predictions have been observed when connectivity indices are combined with any other physico–chemical parameter such as electronic descriptor [5,6], molecular surface area [16], steric factor [11], boiling point etc. A novel valence connectivity index has been introduced here by considering the summation over inverse geometric mean terms to produce ${}^{n}\chi_{P}^{Vm}$. This modification gave no change in the values of first order connectivity indices, but significant differences are observed in higher order indices. Two sets of connectivity indices are generated one using Kier equation ${}^{n}\chi_{P}^{V}$, and another with the modified equation proposed here ${}^{n}\chi_{P}^{Vm}$. From the two sets the best combination of descriptors required in QSRR has been selected following stepwise multiple linear regression analysis (SMLR) and verified their predictive ability. The QSRR models for Kováts retention index, I, partial molar enthalpy, ΔH, and partial molar entropy, ΔS, of oxygen containing organic compounds on seven isosteric apolar and low polarity stationary phases have been developed.

In majority of QSRR studies the focus is on modeling the correlation with separate relation for each stationary phase. QSRR models for several stationary phases in one equation using an additional descriptor has been reported only in few cases [17–18]. The aim of this paper is to develop a unified QSRR that can able to predict the retention properties of oxygen containing organic compounds on any new stationary phase. By combining the data for all seven stationary phases a unified QSRR relation has been proposed using an additional descriptor, namely the property dependent phase constant to characterize the stationary phase.

# 2 MATERIALS AND METHODS

Kováts retention indices, I, partial molar enthalpies, ΔH and partial molar entropies, ΔS measured by gas chromatograph on seven isosteric stationary phases were taken from Reddy *et al.* [19–21]. The stationary phases examined are 19,24–dioctadecyldotetracontane, (C78); 18,23–dioctadecylhentetracontan–1–ol, (POH); 1–cyano–18,23–dioctadecylhentetracontane, (PCN); 18,23–dioctadecyl–1–untetracontanethiol, (PSH); 1,1,1–trifluoro–19,24–dioctadecyldotetracontane, (MTF); 19,24–bis(18,18,18–trifluoro octadecyl)–1,1,1,42,42,42–hexafluorodotetracontane, (TTF); and 17,22–bis–(16–methoxyhexa–decyl)–1,38–dimethoxyocta–triacontane, (TMO). All the stationary phases are of the same form and nearly same size. The stationary phases are used in packed columns and the details of packing and measurement of retention data was reported earlier [19].

The path type valence connectivity indices, ${}^1\chi_P^V$, ${}^2\chi_P^V$ and ${}^3\chi_P^V$ for all the solute probes were calculated using hydrogen depleted molecular graphs. According to Kier *et al.* [1] ${}^n\chi_P^V$ is given by

$$ {}^n\chi_P^V = \Sigma\,(\delta_1\,\delta_2 \ldots \delta_{(n+1)})^{-0.5} \tag{1} $$

where the summation is over the inverse square root terms of all the subgraphs of order *n*. Eq. (1) has been modified by introducing the summation over geometric mean terms as follows.

In the calculation of branching index, Randić used the product of only two vertices and the bond term is calculated as inverse square root term. In this case obviously the bond term is the inverse geometric mean term. The connectivity index is then obtained as a sum of all these bond terms. However when Kier and Hall introduced higher order connectivity indices for example in the second order connectivity indices, the bond terms are calculated as the inverse square root of the product of three vertex valences. Since this is not inverse geometric mean term as used originally by Randić, we have modified the evaluation of bond terms of 2nd order and higher orders by introducing inverse geometric mean instead of inverse square root. We have calculated a set of modified valence connectivity indices denoted as ${}^n\chi_p^{Vm}$. The ${}^n\chi_p^{Vm}$ and ${}^n\chi_p^V$ values are same for first order connectivity indices but are different in case of higher order connectivity indices. The ${}^n\chi_p^{Vm}$ values are higher than ${}^n\chi_p^V$ values for higher order indices.

Accordingly the modified equation can be written as

$$ {}^n\chi_P^{Vm} = \Sigma\,(\delta_1\,\delta_2 \ldots \delta_{(n+1)})^{-1/(n+1)} \tag{2} $$

where *n* refers to the number of bonds connecting the path and the summation goes over all the paths of that type in the molecule. $\delta_i^v$ is the valence delta of atom *i* defined by the Eq. (3):

$$ \delta_i^v = (Z_i^v - \mathrm{h}) / Z_\mathrm{i} - Z_i^v - 1) \tag{3} $$

where $Z_i$ and $Z_i^v$ are the atomic number and the number of valence electrons of atom *i* respectively and h is the number of hydrogen atoms attached to atom *i*. Eqs. (1) and (2) will give same value for ${}^1\chi_P^V$ and ${}^1\chi_P^{Vm}$ but the values of ${}^2\chi_P^V$ and ${}^3\chi_P^V$ are lower than ${}^2\chi_P^{Vm}$ and ${}^3\chi_P^{Vm}$.

Hall *et al.* [22] proposed electrotopological state, (E–state), *S* as an index of graph vertex from chemical graph theory. This new index combines both the electronic character and the topological environment of each skeletal atom in a molecule. The E–state $S_\mathrm{i}$ for atom *i* is defined as:

$$ S_\mathrm{i} = \mathrm{I}_i + \Delta\mathrm{I}_i \tag{4} $$

where $I_i$ is atom intrinsic value, given by

$$I_i = [(2/N)^2 \delta_i^V + 1]/\delta_i \tag{5}$$

where *N* is the principal quantum number $\delta_i^V$ and $\delta_i$ are the valence and simple delta values for atom *i*. For atoms in the second quantum level the equation reduces to

$$I_i = \left(\frac{\delta_i^V + 1}{\delta_i}\right) \tag{6}$$

The difference in intrinsic value, $\Delta I_i$ is given by

$$\Delta I_i = \sum \frac{I_i - I_j}{r_{ij}^2} \tag{7}$$

where $r_{ij}^2$ is the graph separation between *i* and *j* counted as the number of atoms inclusive of *i* and *j*. The E–state values calculated for oxygen atom in all the compounds are presented in Table 1.

Hall *et al.* [22] have shown that the E–state values correlate with the oxygen partial charges and NMR chemical shifts in ethers, ketones and aldehydes. Guo *et al.* [17] used E–state values along with other descriptors to obtain QSRR model for Kováts retention index of saturated alcohols. The boiling points [23] used in multiple linear regression for oxygen derivatives are taken from literature and are given in Table 1. In the QSRR models developed here the modified valence connectivity indices, $^n\chi_p^{Vm}$, the E–state values of oxygen atom and the boiling points of solutes have been applied.

**Table 1.** Valence connectivity indices calculated using Eqs. (1) and (2), E–state of oxygen atom, *S*, and the boiling point, bp, values of all solutes

| No. | Solute | $^1\chi^V$ | $^2\chi_P^V$ | $^2\chi_P^{Vm}$ | $^3\chi_P^V$ | $^3\chi_P^{Vm}$ | *S* | bp/K |
|---|---|---|---|---|---|---|---|---|
| **1** | 1–Butanol | 2.0233 | 1.0772 | 1.4992 | 0.5117 | 0.9922 | 8.066 | 390.2 |
| **2** | 1–Pentanol | 2.5233 | 1.4307 | 1.9995 | 0.7617 | 1.4922 | 8.197 | 410.3 |
| **3** | 2–Pentanol | 2.4509 | 1.6377 | 2.3460 | 0.7064 | 1.4339 | 8.552 | 391.9 |
| **4** | 2–Hexanol | 2.9509 | 1.9912 | 2.8462 | 0.9755 | 1.9430 | 8.683 | 411.0 |
| **5** | 2–Heptanol | 3.4509 | 2.3448 | 3.3465 | 1.2255 | 2.4430 | 8.779 | 433.2 |
| **6** | 2–Methyl–2–propanol | 1.7236 | 2.1708 | 2.9967 | 0.0000 | 0.0000 | 8.520 | 355.3 |
| **7** | 2–Methyl–2–butanol | 2.2843 | 2.1659 | 3.1613 | 0.8652 | 1.5868 | 8.826 | 375.0 |
| **8** | 2–Methyl–2–pentanol | 2.7843 | 2.5624 | 3.6883 | 0.8618 | 1.8344 | 9.017 | 393.2 |
| **9** | 2–Methyl–2–hexanol | 3.2843 | 2.9159 | 4.1886 | 1.1421 | 2.3493 | 9.148 | 416.0 |
| **10** | 2–Butanone | 1.7648 | 1.0556 | 1.6231 | 0.4979 | 0.9745 | 9.812 | 352.6 |
| **11** | 2–Pentanone | 2.2648 | 1.452 | 2.1502 | 0.6021 | 1.3195 | 10.042 | 375.0 |
| **12** | 2–Hexanone | 2.7648 | 1.8056 | 2.6505 | 0.8824 | 1.8345 | 10.201 | 401.0 |
| **13** | 2–Heptanone | 3.2648 | 2.1592 | 3.1508 | 1.1324 | 2.3345 | 10.317 | 424.4 |
| **14** | Pentanal | 2.3511 | 1.3089 | 1.8709 | 0.6755 | 1.3897 | 9.564 | 376.0 |
| **15** | Hexanal | 2.8511 | 1.6624 | 2.3712 | 0.9255 | 1.8897 | 9.680 | 401.0 |
| **16** | Heptanal | 3.3511 | 2.0159 | 2.8715 | 1.1755 | 2.3897 | 9.764 | 425.8 |
| **17** | Dipropylether | 2.9916 | 1.6124 | 2.3015 | 0.6969 | 1.6634 | 5.132 | 364.0 |
| **18** | Dibutylether | 3.9916 | 2.3195 | 3.3021 | 1.2845 | 2.7088 | 5.314 | 415.0 |

## 2.1 Development of QSRR Models

Stepwise multiple linear regression has been performed to obtain the best QSRR for the three properties on each of the stationary phases. In this method regressions are performed with the successive addition of one independent variable to the model at a time and the statistical data obtained is compared with the data of the preceding regression. Several combinations of the independent variables are used in the regression model and the best QSRR has been selected with the criteria that the standard deviation is smaller and the correlation coefficient and F–value are higher. The results of the SMLR on I of C78 are given in Table 2 for oxygen derivatives. The statistical data obtained when ${}^{n}\chi_{P}^{V}$ descriptors are used in the regression are compared with the data obtained when ${}^{n}\chi_{P}^{Vm}$ descriptors are used. In some combinations of connectivity indices, better statistical data are obtained with ${}^{n}\chi_{P}^{Vm}$ descriptors compared to ${}^{n}\chi_{P}^{V}$ descriptors.

Similar SMLR analysis has been conducted with the three properties on all other phases and the descriptors selected for the best model are similar to that found for C78 in all the phases. E–state values along with the boiling point data are found to be necessary in the three properties to obtain better statistical performance. According to the general rule for $n$ = 18 the number of descriptors to be selected are restricted to four. Keeping this constraint in view the QSRR model for oxygen derivatives has been improved as follows: with ${}^{1}\chi_{P}^{V}$, ${}^{2}\chi_{P}^{Vm}$, ${}^{3}\chi_{P}^{Vm}$ the $\sigma$ = 31.4, with ${}^{1}\chi_{P}^{V}$, ${}^{2}\chi_{P}^{Vm}$, ${}^{3}\chi_{P}^{Vm}$, $S$ the σ = 16.8, with ${}^{1}\chi_{P}^{V}$, ${}^{2}\chi_{P}^{Vm}$, ${}^{3}\chi_{P}^{Vm}$, bp the σ = 16.3, with ${}^{1}\chi_{P}^{V}$, ${}^{3}\chi_{P}^{Vm}$, $S$, bp the σ = 14.9 and with ${}^{1}\chi_{P}^{V}$, ${}^{2}\chi_{P}^{Vm}$, $S$ , bp the σ = 5.3. The combination of $S$ and the boiling point has produced a drastic decrease in standard deviation σ. These descriptors are not correlating with each other as revealed from the correlation matrix presented in Table 3. Therefore ${}^{1}\chi_{P}^{V}$, ${}^{2}\chi_{P}^{Vm}$, $S$, bp set of descriptors has been used in the QSRR model for all stationary phases.

**Table 2.** Comparison of stepwise multiple linear regression data of oxygen derivatives; correlation coefficient, $r$, standard deviation, σ and Fisher's F values calculated using the descriptors ${}^{n}\chi_{P}^{V}$ and ${}^{n}\chi_{P}^{Vm}$ for Kováts retention index on C78

| Descriptors | | ${}^{n}\chi_{P}^{V}$ | | | ${}^{n}\chi_{P}^{Vm}$ | |
|---|---|---|---|---|---|---|
| | $r$ | σ | F | $r$ | σ | F |
| ${}^{1}\chi$ | 0.944 | 37.9 | 130 | 0.944 | 37.9 | 130 |
| ${}^{2}\chi$ | 0.491 | 100.2 | 5 | 0.497 | 99.6 | 5 |
| ${}^{3}\chi$ | 0.946 | 37.2 | 136 | 0.954 | 34.2 | 164 |
| ${}^{1}\chi\,{}^{2}\chi$ | 0.948 | 37.6 | 67 | 0.948 | 37.8 | 66 |
| ${}^{1}\chi\,{}^{3}\chi$ | 0.967 | 29.9 | 110 | 0.964 | 31.3 | 99 |
| ${}^{2}\chi\,{}^{3}\chi$ | 0.946 | 38.5 | 64 | 0.955 | 35.3 | 77 |
| ${}^{1}\chi\,{}^{2}\chi\,S$ bp | 0.999 | 5.2 | 1931 | 0.999 | 5.3 | 1881 |
| ${}^{1}\chi\,{}^{3}\chi\,S$ bp | 0.992 | 15.5 | 214 | 0.993 | 14.9 | 233 |
| ${}^{2}\chi\,{}^{3}\chi\,S$ bp | 0.972 | 29.6 | 57 | 0.984 | 22.8 | 98 |
| ${}^{1}\chi\,{}^{2}\chi\,{}^{3}\chi$ | 0.970 | 29.5 | 76 | 0.967 | 31.4 | 66 |
| ${}^{1}\chi\,{}^{2}\chi\,{}^{3}\chi\,S$ | 0.991 | 16.9 | 180 | 0.991 | 16.8 | 182 |
| ${}^{1}\chi\,{}^{2}\chi\,{}^{3}\chi$ bp | 0.991 | 17.1 | 176 | 0.992 | 16.3 | 195 |
| ${}^{1}\chi\,{}^{2}\chi\,{}^{3}\chi\,S$ bp | 0.999 | 5.1 | 1616 | 0.999 | 4.8 | 1818 |

**Table 3.** Correlation matrix for the valence connectivity indices, modified valence connectivity indices, E–state and boiling point of oxygen derivatives

| | ${}^1\chi^V$ | ${}^2\chi_P^V$ | ${}^3\chi_P^V$ | ${}^2\chi_P^{Vm}$ | ${}^3\chi_P^{Vm}$ | $S$ | bp |
|---|---|---|---|---|---|---|---|
| ${}^1\chi^V$ | 1 | | | | | | |
| ${}^2\chi_P^V$ | 0.598 | 1 | | | | | |
| ${}^3\chi_P^V$ | 0.907 | 0.519 | 1 | | | | |
| ${}^2\chi_P^{Vm}$ | 0.599 | 0.997 | 0.537 | 1 | | | |
| ${}^3\chi_P^{Vm}$ | 0.939 | 0.518 | 0.991 | 0.537 | 1 | | |
| $S$ | –0.297 | –0.061 | –0.032 | –0.030 | –0.089 | 1 | |
| bp | 0.797 | 0.482 | 0.847 | 0.477 | 0.821 | 0.098 | 1 |

The general QSRR for the three properties on the seven phases can be represented as follows

$$X = b_0 + b_1 {}^1\chi_P^V + b_2 {}^2\chi_P^{Vm} + b_S.S + b_T.bp. \tag{8}$$

QSRR for Kováts retention indices for the seven phases are given below

$$\mathrm{I(C78)} = -290.8(\pm 28.4) + 162.4(\pm 5.0)\,{}^1\chi_P^V - 23.8(\pm 2.3)\,{}^2\chi_P^{Vm} + 16.06(\pm 1.17)S + 1.187(\pm 0.107)\mathrm{bp} \tag{9}$$
$$r = 0.9991 \quad r_{cv} = 0.9989 \quad \sigma = 5.3 \quad F = 1881 \quad n = 18$$

$$\mathrm{I(POH)} = -475.6(\pm 34.2) + 115.4(\pm 6.0)\,{}^1\chi_P^V - 14.8(\pm 2.7)\,{}^2\chi_P^{Vm} + 13.90(\pm 1.41)S + 2.092(\pm 0.129)\mathrm{bp} \tag{10}$$
$$r = 0.9987 \quad r_{cv} = 0.9985 \quad \sigma = 6.3 \quad F = 1241 \ n = 18$$

$$\mathrm{I(PCN)} = -447.4(\pm 33.4) + 132.9(\pm 5.9)\,{}^1\chi_P^V - 24.2(\pm 2.7)\,{}^2\chi_P^{Vm} + 19.16(\pm 1.37)S + 1.848(\pm 0.126)\mathrm{bp} \tag{11}$$
$$r = 0.9987 \quad r_{cv} = 0.9986 \quad \sigma = 6.2 \quad F = 1324 \ n = 18$$

$$\mathrm{I(PSH)} = -329.7(\pm 29.9) + 156.9(\pm 5.3)\,{}^1\chi_P^V - 25.6(\pm 2.4)\,{}^2\chi_P^{Vm} + 17.48(\pm 1.23)S + 1.341(\pm 0.113)\mathrm{bp} \tag{12}$$
$$r = 0.9990 \quad r_{cv} = 0.9988 \quad \sigma = 5.5 \quad F = 1690 \ n = 18$$

$$\mathrm{I(MTF)} = -297.1(\pm 26.3) + 162.8(\pm 4.6)\,{}^1\chi_P^V - 26.1(\pm 2.1)\,{}^2\chi_P^{Vm} + 19.34(\pm 1.08)S + 1.183(\pm 0.099)\mathrm{bp} \tag{13}$$
$$r = 0.9992 \quad r_{cv} = 0.9990 \quad \sigma = 4.9 \quad F = 2160 \quad n = 18$$

$$\mathrm{I(TTF)} = -261.8(\pm 32.3) + 182.1(\pm 5.7)\,{}^1\chi_P^V - 34.6(\pm 2.6)\,{}^2\chi_P^{Vm} + 30.28(\pm 1.33)S + 0.862(\pm 0.122)\mathrm{bp} \tag{14}$$
$$r = 0.9985 \quad r_{cv} = 0.9983 \quad \sigma = 6.0 \quad F = 1479 \quad n = 18$$

$$\mathrm{I(TMO)} = -633.9(\pm 52.4) + 79.4(\pm 9.2)\,{}^1\chi_P^V - 10.2(\pm 4.2)\,{}^2\chi_P^{Vm} + 8.78(\pm 2.16)S + 2.857(\pm 0.198)\mathrm{bp} \tag{15}$$
$$r = 0.9969 \quad r_{cv} = 0.9965 \quad \sigma = 9.7 \quad F = 526 \quad n = 18$$

The constant values are generally related to the interaction between the solute probes with different polar phases. The solute probes of this series being hydrogen accepting or hydrogen donating can form hydrogen bonding in POH and TMO phases and interact through dipolar forces in the other polar phases. In the above QSRR models the algebraic sum of both $b_0$ and $b_T$ (bp) values are to be considered to understand the interactions of solutes with different stationary phases. Boiling point of any one solute has been used in the calculation of the algebraic sum of $b_0$ and $b_T$ (bp) for different phases, which are positively correlating with the McReynolds phase polarity. The values of $b_1$, $b_2$ and $b_S$ coefficients indicate the sensitivity of retention indices with respect to ${}^1\chi_P^V$, ${}^2\chi_P^{Vm}$ and $S$.

In all the phases the coefficients of ${}^{1}\chi_{P}^{V}$ are positive and large representing the effect of size of the molecule on retention index. The coefficients of ${}^{2}\chi_{P}^{Vm}$ are negative which are expected to encode the extent of branching and cluster in the molecular structure. With increase of branching ${}^{2}\chi_{P}^{Vm}$ increases but at the same time the retention indices decreases with increase of branching. The negative coefficients for ${}^{2}\chi_{P}^{Vm}$ indicate that this descriptor is representing the branching effects correctly on retention index. The coefficients for *S* are positive but smaller for oxygen containing phases and larger for fluorine containing phases compared to the non polar C78. The coefficients of bp are positive in all the phases but the values are higher in oxygen containing phases than in the other phases. In all the relations the correlation coefficients are greater than 0.997, the F values are higher and the errors in the coefficients are small.

QSRR for partial molar enthalpy of oxygen derivatives on the seven phases are given below:

$$\Delta\text{H(C78)} = 2136.6(\pm 242.7) - 1652.4(\pm 42.9)\,{}^{1}\chi_{P}^{V} + 241.1(\pm 19.4)\,{}^{2}\chi_{P}^{Vm} - 121.24(\pm 10.01)S - 11.481(\pm 0.920)\text{bp} \tag{16}$$
$$r = 0.9993 \qquad r_{cv} = 0.9991 \qquad \sigma = 45.2 \quad F = 2622 \qquad n = 18$$

$$\Delta\text{H(POH)} = 9922.9(\pm 948.4) + 614.8(\pm 167.6)\,{}^{1}\chi_{P}^{V} - 301.1(\pm 75.7)\,{}^{2}\chi_{P}^{Vm} + 175.00(\pm 39.09)S - 52.242(\pm 3.596)\text{bp} \tag{17}$$
$$r = 0.9900 \qquad r_{cv} = 0.9896 \qquad \sigma = 176.5 \qquad F = 161 \quad n = 18$$

$$\Delta\text{H(PCN)} = 5384.9(\pm 458.5) - 802.1(\pm 81.0)\,{}^{1}\chi_{P}^{V} + 130.4(\pm 36.6)\,{}^{2}\chi_{P}^{Vm} - 69.38(\pm 18.89)S - 27.605(\pm 1.738)\text{bp} \tag{18}$$
$$r = 0.9975 \qquad r_{cv} = 0.9972 \qquad \sigma = 85.3 \quad F = 649 \quad n = 18$$

$$\Delta\text{H(PSH)} = 1889.7(\pm 460.9) - 1561.6(\pm 81.4)\,{}^{1}\chi_{P}^{V} + 232.5(\pm 36.8)\,{}^{2}\chi_{P}^{Vm} - 139.25(\pm 19.00)S - 11.247(\pm 1.748)\text{bp} \tag{19}$$
$$r = 0.9975 \qquad r_{cv} = 0.9973 \qquad \sigma = 85.8 \quad F = 655 \quad n = 18$$

$$\Delta\text{H(MTF)} = 1457.6(\pm 371.9) - 1671.7(\pm 65.7)\,{}^{1}\chi_{P}^{V} + 250.8(\pm 29.7)\,{}^{2}\chi_{P}^{Vm} - 176.07(\pm 15.33)S - 9.251(\pm 1.410)\text{bp} \tag{20}$$
$$r = 0.9984 \qquad r_{cv} = 0.9981 \qquad \sigma = 69.2 \quad F = 1027 \qquad n = 18$$

$$\Delta\text{H(TTF)} = 1087.2(\pm 535.4) - 1836.2(\pm 94.6)\,{}^{1}\chi_{P}^{V} + 325.5(\pm 42.7)\,{}^{2}\chi_{P}^{Vm} - 272.94(\pm 22.07)S - 6.081(\pm 2.030)\text{bp} \tag{21}$$
$$r = 0.9967 \qquad r_{cv} = 0.9964 \qquad \sigma = 99.6 \quad F = 497 \quad n = 18$$

$$\Delta\text{H(TMO)} = 9118.8(\pm 1005.2) + 213.7(\pm 177.6)\,{}^{1}\chi_{P}^{V} - 164.6(\pm 80.3)\,{}^{2}\chi_{P}^{Vm} + 114.9(\pm 41.4)S - 47.053(\pm 3.812)\text{bp} \tag{22}$$
$$r = 0.9891 \qquad r_{cv} = 0.9886 \qquad \sigma = 187.1 \qquad F = 147 \quad n = 18$$

For the above QSRR models r > 0.989, σ < 86 and F values are higher in all phases except in POH and TMO. In these two phases the higher σ and lower r values may be due to stronger interactions involving both hydrogen accepting and hydrogen donating with the solutes. In the regression equations of ΔH the signs of the coefficients are opposite to the corresponding coefficients in the regression equations of retention index in all the phases except in POH and TMO. The coefficients of ${}^{1}\chi_{P}^{V}$ and *S* are positive and the coefficients of ${}^{2}\chi_{P}^{Vm}$ are negative for POH and TMO solvents. This may be due to the formation of hydrogen bond by some of the solutes with these two polar phases. Unlike the coefficients of I, the coefficients of ΔH are able to distinguish between the solvents. The coefficients of bp are negative for all the phases and become more negative in POH and TMO phases. If the solute is more volatile then its contribution is small to ΔH in less polar solvents than in more polar solvents like POH and TMO. The QSRR for partial molar entropy of oxygen derivatives on the seven phases are as follows:

$$\Delta S(C78) = -7.382(\pm0.682) - 1.980(\pm0.121)\,{}^{1}\chi_P^V + 0.275(\pm0.054)\,{}^{2}\chi_P^{Vm} - 0.0936(\pm0.0281)S - 0.01274(\pm0.00259)\mathrm{bp} \quad (23)$$

$r = 0.9965$ $r_{cv} = 0.9963$ $\sigma = 0.127$ $F = 470$ $n = 18$

$$\Delta S\ (POH) = 9.585\ (\pm2.008) + 3.001\ (\pm0.355)\ {}^{1}\chi_P^V - 0.944\ (\pm0.160)\ {}^{2}\chi_P^{Vm} + 0.6085\ (\pm0.0828)\ S - 0.10260\ (\pm0.00762)\ \mathrm{bp} \quad (24)$$

$r = 0.9781$ $r_{cv} = 0.9778$ $\sigma = 0.374$ $F = 72$ $n = 18$

$$\Delta S\ (PCN) = -1.226\ (\pm0.875) - 0.237\ (\pm0.154)\ {}^{1}\chi_P^V - 0.013\ (\pm0.069)\ {}^{2}\chi_P^{Vm} + 0.0815\ (\pm0.0361)\ S - 0.04541\ (\pm0.00332)\ \mathrm{bp} \quad (25)$$

$r = 0.9934$ $r_{cv} = 0.9931$ $\sigma = 0.163$ $F = 244$ $n = 18$

$$\Delta S\ (PSH) = -\ 8.526\ (\pm1.165) - 1.836\ (\pm0.206)\ {}^{1}\chi_P^V + 0.229\ (\pm0.093)\ {}^{2}\chi_P^{Vm} - 0.1180\ (\pm0.0480)\ S - 0.01069\ (\pm0.00442)\ \mathrm{bp} \quad (26)$$

$r = 0.9881$ $r_{cv} = 0.9880$ $\sigma = 0.217$ $F = 134$ $n = 18$

$$\Delta S\ (MTF) = -\ 8.971\ (\pm0.738) - 2.046\ (\pm0.130)\ {}^{1}\chi_P^V + 0.272\ (\pm0.058)\ {}^{2}\chi_P^{Vm} - 0.1897\ (\pm0.0304)\ S - 0.00742\ (\pm0.00280)\ \mathrm{bp} \quad (27)$$

$r = 0.9954$ $r_{cv} = 0.9951$ $\sigma = 0.137$ $F = 350$ $n = 18$

$$\Delta S\ (TTF) = -\ 9.273\ (\pm1.128) - 2.237\ (\pm0.199)\ {}^{1}\chi_P^V + 0.358\ (\pm0.090)\ {}^{2}\chi_P^{Vm} - 0.2939\ (\pm0.0465)\ S - 0.00449\ (\pm0.00428)\ \mathrm{bp} \quad (28)$$

$r = 0.9895$ $r_{cv} = 0.9890$ $\sigma = 0.210$ $F = 152$ $n = 18$

$$\Delta S\ (TMO) = 5.749\ (\pm1.898) + 1.563\ (\pm0.335)\ {}^{1}\chi_P^V - 0.557\ (\pm0.151)\ {}^{2}\chi_P^{Vm} + 0.4003\ (\pm0.0782)\ S - 0.08043\ (\pm0.00720)\ \mathrm{bp} \quad (29)$$

$r = 0.9775$ $r_{cv} = 0.9769$ $\sigma = 0.353$ $F = 70$ $n = 18$

In the regression equations of ΔS the signs of the coefficients for POH and TMO are same as those observed in the regression equations of ΔH. In other phases, apart from the sign of the constant, the signs of the coefficients in ΔS equations are similar to the signs of the coefficients observed in ΔH equations. In ΔH and ΔS the descriptors are contributing in the same direction supporting the generally observed positive correlation between these two properties. The r values in ΔS relations are smaller than in ΔH relations in all phases indicating that the QSRR models are better for ΔH than for ΔS. The calculated and observed values of I, ΔH and ΔS at 403.15K are presented in Table 4 for the seven phases.

## 2.2 Validation of QSRR Models

The predictive quality of the QSRR models for I, ΔH and ΔS have been verified by leave–one–out cross validation method. In this method one compound is deleted at a time from the regression and the prediction of retention of the deleted compound is made based on the QSRR model. The procedure has been repeated for all compounds and the prediction of the retention properties have been made for all compounds. The cross validated correlation coefficient $r_{cv}$ values evaluated by leave–one–out method are very close to regression correlation coefficient r values in all the phases except in the more polar TMO stationary phase. This suggests that the QSRR models are stable and useful for prediction of retention properties [24].

**Table 4.** Comparison of observed and calculated retention properties; Kováts retention indices, I, partial molar enthalpies, ΔH, and partial molar entropies, ΔS for oxygen derivatives at 403.15 K

| No. | Solute | I | | | ΔH (cal mol$^{-1}$) | | | ΔS (cal mol$^{-1}$ K$^{-1}$) | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | obs | calc | res | obs | calc | δ | obs | calc | res |
| | | | | | **C78** | | | | | |
| **1** | 1–Butanol | 594.8 | 594.8 | 0.0 | –6259 | –6303 | 44 | –16.592 | –16.702 | 0.110 |
| **2** | 1–Pentanol | 698.8 | 690.1 | 8.7 | –7319 | –7255 | –64 | –17.865 | –17.823 | –0.042 |
| **3** | 2–Pentanol | 643.8 | 653.9 | –10.1 | –6858 | –6884 | 26 | –17.438 | –17.383 | –0.055 |
| **4** | 2–Hexanol | 744.7 | 748.0 | –3.3 | –7839 | –7825 | –14 | –18.568 | –18.491 | –0.077 |
| **5** | 2–Heptanol | 845.0 | 845.2 | –0.2 | –8828 | –8797 | –31 | –19.744 | –19.635 | –0.109 |
| **6** | 2–Methyl–2–propanol | 471.0 | 476.4 | –5.4 | –5078 | –5101 | 23 | –15.379 | –15.295 | –0.084 |
| **7** | 2–Methyl–2–butanol | 597.9 | 591.8 | 6.1 | –6225 | –6251 | 26 | –16.464 | –16.639 | 0.175 |
| **8** | 2–Methyl–2–pentanol | 690.9 | 685.1 | 5.8 | –7209 | –7182 | –27 | –17.696 | –17.734 | 0.038 |
| **9** | 2–Methyl–2–hexanol | 786.1 | 783.6 | 2.5 | –8158 | –8166 | 8 | –18.829 | –18.889 | 0.060 |
| **10** | 2–Butanone | 537.5 | 533.3 | 4.2 | –5708 | –5626 | –82 | –16.031 | –15.84 | –0.191 |
| **11** | 2–Pentanone | 629.6 | 632.2 | –2.6 | –6628 | –6610 | –18 | –17.063 | –16.992 | –0.071 |
| **12** | 2–Hexanone | 731.4 | 734.9 | –3.5 | –7649 | –7634 | –15 | –18.273 | –18.191 | –0.082 |
| **13** | 2–Heptanone | 831.4 | 833.9 | –2.5 | –8643 | –8622 | –21 | –19.462 | –19.352 | –0.110 |
| **14** | Pentanal | 647.8 | 646.4 | 1.4 | –6700 | –6774 | 74 | –16.998 | –17.208 | 0.210 |
| **15** | Hexanal | 749.5 | 747.2 | 2.3 | –7738 | –7780 | 42 | –18.258 | –18.39 | 0.132 |
| **16** | Heptanal | 851.0 | 847.3 | 3.7 | –8746 | –8781 | 35 | –19.469 | –19.566 | 0.097 |
| **17** | Dipropylether | 656.8 | 654.7 | 2.1 | –7074 | –7053 | –21 | –17.803 | –17.79 | –0.013 |
| **18** | Dibutylether | 854.9 | 856.8 | –1.9 | –9061 | –9072 | 11 | –20.196 | –20.162 | –0.034 |
| | | | | | **POH** | | | | | |
| **1** | 1–Butanol | 661.1 | 664.1 | –3.0 | –8145 | –8258 | 113 | –20.641 | –20.885 | 0.244 |
| **2** | 1–Pentanol | 766.7 | 758.3 | 8.4 | –9162 | –9128 | –34 | –21.809 | –21.839 | 0.030 |
| **3** | 2–Pentanol | 704.1 | 711.2 | –7.1 | –8294 | –8254 | –40 | –20.459 | –20.28 | –0.179 |
| **4** | 2–Hexanol | 805.5 | 803.3 | 2.2 | –9272 | –9072 | –200 | –21.589 | –21.131 | –0.458 |
| **5** | 2–Heptanol | 906.6 | 901.4 | 5.2 | –10288 | –10058 | –230 | –22.845 | –22.322 | –0.523 |
| **6** | 2–Methyl–2–propanol | 530.6 | 540.7 | –10.1 | –6792 | –6990 | 198 | –19.03 | –19.341 | 0.311 |
| **7** | 2–Methyl–2–butanol | 653.7 | 648.4 | 5.3 | –7671 | –7671 | 0 | –19.562 | –19.648 | 0.086 |
| **8** | 2–Methyl–2–pentanol | 746.1 | 739.0 | 7.1 | –8587 | –8439 | –148 | –20.647 | –20.397 | –0.250 |
| **9** | 2–Methyl–2–hexanol | 842.2 | 838.8 | 3.4 | –9535 | –9451 | –84 | –21.784 | –21.628 | –0.156 |
| **10** | 2–Butanone | 583.6 | 578.1 | 5.5 | –6223 | –6184 | –39 | –16.897 | –16.857 | –0.040 |
| **11** | 2–Pentanone | 676.3 | 678.0 | –1.7 | –7121 | –7166 | 45 | –17.913 | –18.013 | 0.100 |
| **12** | 2–Hexanone | 779.3 | 784.9 | –5.6 | –8117 | –8339 | 222 | –19.067 | –19.555 | 0.488 |
| **13** | 2–Heptanone | 880.3 | 885.8 | –5.5 | –9119 | –9385 | 266 | –20.286 | –20.857 | 0.571 |
| **14** | Pentanal | 689.7 | 687.6 | 2.1 | –7345 | –7164 | –181 | –18.304 | –17.883 | –0.421 |
| **15** | Hexanal | 792.3 | 791.8 | 0.5 | –8356 | –8293 | –63 | –19.501 | –19.35 | –0.151 |
| **16** | Heptanal | 894.2 | 895.1 | –0.9 | –9372 | –9417 | 45 | –20.741 | –20.815 | 0.074 |
| **17** | Dipropylether | 673.1 | 668.4 | 4.7 | –7153 | –7049 | –104 | –18.026 | –17.833 | –0.193 |
| **18** | Dibutylether | 871.1 | 878.2 | –7.1 | –9132 | –9368 | 236 | –20.417 | –20.899 | 0.482 |
| | | | | | **PCN** | | | | | |
| **1** | 1–Butanol | 659.6 | 660.9 | –1.3 | –7329 | –7374 | 45 | –18.694 | –18.787 | 0.093 |
| **2** | 1–Pentanol | 765.3 | 754.8 | 10.5 | –8356 | –8273 | –83 | –19.889 | –19.814 | –0.075 |
| **3** | 2–Pentanol | 699.1 | 709.6 | –10.5 | –7619 | –7687 | 68 | –18.894 | –18.937 | 0.043 |
| **4** | 2–Hexanol | 801.0 | 801.8 | –0.8 | –8619 | –8559 | –60 | –20.076 | –19.918 | –0.158 |
| **5** | 2–Heptanol | 901.9 | 899.0 | 2.9 | –9629 | –9514 | –115 | –21.315 | –21.043 | –0.272 |
| **6** | 2–Methyl–2–propanol | 520.8 | 529.0 | –8.2 | –5883 | –6006 | 123 | –16.965 | –17.113 | 0.148 |
| **7** | 2–Methyl–2–butanol | 647.1 | 641.8 | 5.3 | –6992 | –6999 | 7 | –18.014 | –18.118 | 0.104 |
| **8** | 2–Methyl–2–pentanol | 740.2 | 732.8 | 7.4 | –7918 | –7847 | –71 | –19.117 | –19.054 | –0.063 |
| **9** | 2–Methyl–2–hexanol | 835.7 | 831.8 | 3.9 | –8863 | –8822 | –41 | –20.247 | –20.204 | –0.043 |
| **10** | 2–Butanone | 594.2 | 587.5 | 6.7 | –6363 | –6233 | –130 | –17.140 | –16.877 | –0.263 |
| **11** | 2–Pentanone | 685.7 | 687.0 | –1.3 | –7226 | –7200 | –26 | –18.095 | –18.001 | –0.094 |
| **12** | 2–Hexanone | 788.5 | 792.4 | –3.9 | –8230 | –8264 | 34 | –19.267 | –19.294 | 0.027 |
| **13** | 2–Heptanone | 889.0 | 892.2 | –3.2 | –9225 | –9254 | 29 | –20.471 | –20.472 | 0.001 |
| **14** | Pentanal | 698.3 | 697.9 | 0.4 | –7256 | –7300 | 44 | –17.957 | –18.102 | 0.145 |
| **15** | Hexanal | 801.4 | 800.6 | 0.8 | –8280 | –8334 | 54 | –19.213 | –19.353 | 0.140 |
| **16** | Heptanal | 903.6 | 902.4 | 1.2 | –9261 | –9360 | 99 | –20.366 | –20.597 | 0.231 |
| **17** | Dipropylether | 669.7 | 665.5 | 4.2 | –7174 | –7119 | –55 | –18.166 | –18.076 | –0.090 |
| **18** | Dibutylether | 867.5 | 871.9 | –4.4 | –9138 | –9211 | 73 | –20.523 | –20.627 | 0.104 |

**Table 4.** (Continued)

| No. | Solute | I | | | ΔH (cal mol $^{-1}$) | | | ΔS (cal mol $^{-1}$ K $^{-1}$) | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | obs | calc | res | obs | calc | δ | obs | calc | res |
| | | | | | **PSH** | | | | | |
| **1** | 1–Butanol | 613.8 | 613.6 | 0.2 | –6440 | –6433 | –7 | –17.028 | –17.020 | –0.008 |
| **2** | 1–Pentanol | 717.1 | 708.5 | 8.6 | –7411 | –7342 | –69 | –18.110 | –18.054 | –0.056 |
| **3** | 2–Pentanol | 659.1 | 669.8 | –10.7 | –6869 | –6991 | 122 | –17.512 | –17.687 | 0.175 |
| **4** | 2–Hexanol | 760.2 | 763.4 | –3.2 | –7865 | –7888 | 23 | –18.694 | –18.710 | 0.016 |
| **5** | 2–Heptanol | 860.7 | 860.5 | 0.2 | –8855 | –8816 | –39 | –19.882 | –19.762 | –0.120 |
| **6** | 2–Methyl–2–propanol | 483.0 | 489.4 | –6.4 | –5271 | –5288 | 17 | –15.903 | –15.808 | –0.095 |
| **7** | 2–Methyl–2–butanol | 610.6 | 604.9 | 5.7 | –6346 | –6389 | 43 | –16.834 | –17.046 | 0.212 |
| **8** | 2–Methyl–2–pentanol | 704.0 | 697.6 | 6.4 | –7290 | –7279 | –11 | –17.985 | –18.061 | 0.076 |
| **9** | 2–Methyl–2–hexanol | 798.8 | 796.1 | 2.7 | –8222 | –8218 | –4 | –19.088 | –19.123 | 0.035 |
| **10** | 2–Butanone | 555.1 | 550.0 | 5.1 | –5980 | –5821 | –159 | –16.688 | –16.322 | –0.366 |
| **11** | 2–Pentanone | 646.2 | 649.0 | –2.8 | –6804 | –6763 | –41 | –17.524 | –17.385 | –0.139 |
| **12** | 2–Hexanone | 748.3 | 752.3 | –4.0 | –7790 | –7742 | –48 | –18.611 | –18.486 | –0.125 |
| **13** | 2–Heptanone | 848.5 | 851.3 | –2.8 | –8769 | –8686 | –83 | –19.827 | –19.553 | –0.274 |
| **14** | Pentanal | 663.5 | 662.7 | 0.8 | –6762 | –6907 | 145 | –17.184 | –17.562 | 0.378 |
| **15** | Hexanal | 765.7 | 763.9 | 1.8 | –7765 | –7869 | 104 | –18.370 | –18.647 | 0.277 |
| **16** | Heptanal | 867.5 | 864.2 | 3.3 | –8774 | –8824 | 50 | –19.577 | –19.725 | 0.148 |
| **17** | Dipropylether | 660.9 | 658.6 | 2.3 | –7069 | –7055 | –14 | –17.976 | –17.988 | 0.012 |
| **18** | Dibutylether | 858.9 | 861.5 | –2.6 | –9011 | –8983 | –28 | –20.290 | –20.162 | –0.128 |
| | | | | | **MTF** | | | | | |
| **1** | 1–Butanol | 610.7 | 610.8 | –0.1 | –6603 | –6579 | –24 | –17.184 | –17.128 | –0.056 |
| **2** | 1–Pentanol | 714.1 | 705.4 | 8.7 | –7575 | –7498 | –77 | –18.267 | –18.189 | –0.078 |
| **3** | 2–Pentanol | 659.2 | 669.7 | –10.5 | –7057 | –7182 | 125 | –17.690 | –17.878 | 0.188 |
| **4** | 2–Hexanol | 759.9 | 763.2 | –3.3 | –8049 | –8093 | 44 | –18.868 | –18.931 | 0.063 |
| **5** | 2–Heptanol | 859.9 | 859.6 | 0.3 | –9049 | –9025 | –24 | –20.086 | –20.001 | –0.085 |
| **6** | 2–Methyl–2–propanol | 486.0 | 490.4 | –4.4 | –5384 | –5459 | 75 | –15.874 | –15.935 | 0.061 |
| **7** | 2–Methyl–2–butanol | 611.0 | 606.6 | 4.4 | –6610 | –6591 | –19 | –17.202 | –17.242 | 0.040 |
| **8** | 2–Methyl–2–pentanol | 704.0 | 699.5 | 4.5 | –7521 | –7497 | –24 | –18.263 | –18.293 | 0.030 |
| **9** | 2–Methyl–2–hexanol | 799.9 | 797.3 | 2.6 | –8495 | –8441 | –54 | –19.460 | –19.373 | –0.087 |
| **10** | 2–Butanone | 560.4 | 554.7 | 5.7 | –6184 | –6075 | –109 | –16.840 | –16.618 | –0.222 |
| **11** | 2–Pentanone | 651.3 | 653.3 | –2.0 | –7061 | –7026 | –35 | –17.815 | –17.707 | –0.108 |
| **12** | 2–Hexanone | 752.8 | 755.5 | –2.7 | –8023 | –8005 | –18 | –18.899 | –18.817 | –0.082 |
| **13** | 2–Heptanone | 852.9 | 853.8 | –0.9 | –8974 | –8953 | –21 | –19.987 | –19.900 | –0.087 |
| **14** | Pentanal | 666.6 | 666.6 | 0.0 | –7117 | –7166 | 49 | –17.750 | –17.877 | 0.127 |
| **15** | Hexanal | 768.2 | 766.8 | 1.4 | –8093 | –8128 | 35 | –18.873 | –18.971 | 0.098 |
| **16** | Heptanal | 868.0 | 866.1 | 1.9 | –8989 | –9082 | 93 | –19.831 | –20.058 | 0.227 |
| **17** | Dipropylether | 661.3 | 659.7 | 1.6 | –7218 | –7237 | 19 | –18.068 | –18.140 | 0.072 |
| **18** | Dibutylether | 859.4 | 860.3 | –0.9 | –9202 | –9162 | –40 | –20.463 | –20.327 | –0.136 |
| | | | | | **TTF** | | | | | |
| **1** | 1–Butanol | 635.8 | 635.4 | 0.4 | –6732 | –6714 | –18 | –17.421 | –17.385 | –0.036 |
| **2** | 1–Pentanol | 740.5 | 730.4 | 10.1 | –7723 | –7628 | –95 | –18.555 | –18.453 | –0.102 |
| **3** | 2–Pentanol | 685.5 | 700.1 | –14.6 | –7192 | –7367 | 175 | –17.93 | –18.189 | 0.259 |
| **4** | 2–Hexanol | 786.7 | 794.3 | –7.6 | –8176 | –8274 | 98 | –19.102 | –19.253 | 0.151 |
| **5** | 2–Heptanol | 887.1 | 890.1 | –3.0 | –9177 | –9190 | 13 | –20.341 | –20.320 | –0.021 |
| **6** | 2–Methyl–2–propanol | 513.2 | 512.6 | 0.6 | –5655 | –5588 | –67 | –16.374 | –16.155 | –0.219 |
| **7** | 2–Methyl–2–butanol | 637.8 | 635.3 | 2.5 | –6720 | –6768 | 48 | –17.353 | –17.529 | 0.176 |
| **8** | 2–Methyl–2–pentanol | 731.6 | 729.6 | 2.0 | –7646 | –7677 | 31 | –18.465 | –18.597 | 0.132 |
| **9** | 2–Methyl–2–hexanol | 827.5 | 826.9 | 0.6 | –8600 | –8607 | 7 | –19.635 | –19.677 | 0.042 |
| **10** | 2–Butanone | 610.2 | 604.5 | 5.7 | –6577 | –6447 | –130 | –17.368 | –17.107 | –0.261 |
| **11** | 2–Pentanone | 701.8 | 703.5 | –1.7 | –7428 | –7393 | –35 | –18.313 | –18.205 | –0.108 |
| **12** | 2–Hexanone | 804.6 | 804.5 | 0.1 | –8409 | –8350 | –59 | –19.452 | –19.308 | –0.144 |
| **13** | 2–Heptanone | 905.3 | 901.9 | 3.4 | –9412 | –9279 | –133 | –20.701 | –20.386 | –0.315 |
| **14** | Pentanal | 711.7 | 715.3 | –3.6 | –7383 | –7518 | 135 | –18.065 | –18.362 | 0.297 |
| **15** | Hexanal | 814.0 | 814.1 | –0.1 | –8375 | –8457 | 82 | –19.246 | –19.447 | 0.201 |
| **16** | Heptanal | 915.5 | 911.8 | 3.7 | –9373 | –9386 | 13 | –20.470 | –20.523 | 0.053 |
| **17** | Dipropylether | 672.9 | 672.5 | 0.4 | –7254 | –7271 | 17 | –18.232 | –18.284 | 0.052 |
| **18** | Dibutylether | 871.4 | 869.5 | 1.9 | –9225 | –9141 | –84 | –20.646 | –20.445 | –0.201 |

**Table 4.** (Continued)

| No. | Solute | I | | | ΔH (cal mol $^{-1}$) | | | ΔS (cal mol $^{-1}$ K $^{-1}$) | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | obs | calc | res | obs | calc | δ | obs | calc | res |
| | | | | | **TMO** | | | | | |
| **1** | 1–Butanol | 692.6 | 697.1 | –4.5 | –8018 | –8128 | 110 | –19.855 | –20.079 | 0.224 |
| **2** | 1–Pentanol | 798.4 | 790.3 | 8.1 | –9056 | –9035 | –21 | –21.087 | –21.14 | 0.053 |
| **3** | 2–Pentanol | 726.8 | 731.5 | –4.7 | –8285 | –8201 | –84 | –20.085 | –19.824 | –0.261 |
| **4** | 2–Hexanol | 829.0 | 821.8 | 7.2 | –9314 | –9060 | –254 | –21.344 | –20.805 | –0.539 |
| **5** | 2–Heptanol | 930.3 | 920.7 | 9.6 | –10330 | –10069 | –261 | –22.596 | –22.049 | –0.547 |
| **6** | 2–Methyl–2–propanol | 545.2 | 562.3 | –17.1 | –6461 | –6745 | 284 | –17.941 | –18.392 | 0.451 |
| **7** | 2–Methyl–2–butanol | 670.2 | 664.1 | 6.1 | –7551 | –7544 | –7 | –18.987 | –19.070 | 0.083 |
| **8** | 2–Methyl–2–pentanol | 763.0 | 752.1 | 10.9 | –8503 | –8358 | –145 | –20.164 | –19.969 | –0.195 |
| **9** | 2–Methyl–2–hexanol | 858.8 | 853.0 | 5.8 | –9488 | –9391 | –97 | –21.402 | –21.248 | –0.154 |
| **10** | 2–Butanone | 590.1 | 583.2 | 6.9 | –6354 | –6234 | –120 | –17.070 | –16.829 | –0.241 |
| **11** | 2–Pentanone | 681.7 | 683.5 | –1.8 | –7234 | –7242 | 8 | –18.064 | –18.050 | –0.014 |
| **12** | 2–Hexanone | 784.2 | 793.8 | –9.6 | –8258 | –8422 | 164 | –19.291 | –19.575 | 0.284 |
| **13** | 2–Heptanone | 884.7 | 896.3 | –11.6 | –9277 | –9485 | 208 | –20.555 | –20.908 | 0.353 |
| **14** | Pentanal | 697.0 | 691.9 | 5.1 | –7375 | –7279 | –96 | –18.161 | –18.032 | –0.129 |
| **15** | Hexanal | 799.8 | 798.9 | 0.9 | –8408 | –8418 | 10 | –19.453 | –19.493 | 0.040 |
| **16** | Heptanal | 901.8 | 905.1 | –3.3 | –9370 | –9551 | 181 | –20.558 | –20.951 | 0.393 |
| **17** | Dipropylether | 671.9 | 665.2 | 6.7 | –7270 | –7158 | –112 | –18.272 | –18.079 | –0.193 |
| **18** | Dibutylether | 869.7 | 881.7 | –12 | –9259 | –9488 | 229 | –20.695 | –21.103 | 0.408 |

## 2.3 Unified QSRR

The retention indices of oxygen derivatives (*n* = 18) on the seven stationary phases are combined to obtain 126 data points that are applied as dependent variables in the Unified QSRR. Two sets of descriptors characterizing solute properties and solvent polarity are used as independent variables in the development of unified QSRR for retention index, partial molar enthalpy and partial molar entropy. The descriptors characterizing solute properties are selected from SMLR analysis following the criteria that the selected combination should give lower σ, higher r and higher F. Therefore from Table 2 the descriptors $^{1}\chi_{P}^{V}$ , $^{2}\chi_{P}^{Vm}$ along with *S* and bp have been selected. The descriptors used to characterize the solvent polarity are defined as the property dependent phase constants (PDPC), which have been calculated as follows

$$\text{PDPC} = \text{X}_{\text{j}}\ (\text{polar}) - \text{X}_{\text{j}}\ (\text{C78}) \tag{30}$$

where $X_j$ is the retention property of solute *j*. Solute *j* has been selected in such a way that it should represent the congener series of solutes. The interactions of *j* with the solvents should be similar to the interactions of solutes in that series. PDPC of j is the difference in retention property between polar solvent and the non polar C78. PDPC values of two solutes, 2–methyl–2–pentanol ($H'$) and 2–pentanone ($Z'$) representing oxygen derivatives have been used. McReynolds [25] used the symbols H and Z for the solutes 2–Methyl–2–pentanol and 2–Pentanone to represent the retention index difference between polar phase and the squalane. We have followed the similar notations and used the symbols $H'$ and $Z'$ to represent the difference in the property between polar phase and the non polar C78. The PDPC values for the three properties and on the seven phases are given in Table 5.

**Table 5.** Property dependent phase constant (PDPC) values calculated as Kováts retention index difference, partial molar enthalpy difference and partial molar entropy difference between polar stationary phase and C78 for 2–Pentanone ($Z'$), 2–Methyl–2–pentanol ($H'$)

| Column | $Z'$ (I) | $H'$ (I) | $Z'$ (ΔH) | $H'$ (ΔH) | $Z'$ (ΔS) | $H'$ (ΔS) |
|---|---|---|---|---|---|---|
| C78 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| POH | 46.7 | 55.2 | –493 | –1378 | –0.85 | –2.951 |
| PCN | 56.1 | 49.3 | –598 | –709 | –1.032 | –1.421 |
| PSH | 16.6 | 13.1 | –176 | –81 | –0.461 | –0.289 |
| MTF | 52.1 | 72.1 | –433 | –312 | –0.752 | –0.567 |
| TTF | 21.7 | 13.1 | –800 | –437 | –1.25 | –0.769 |
| TMO | 72.2 | 40.7 | –606 | –1294 | –1.001 | –2.468 |
| PCL | 19.5 | 13.3 | –142 | 12 | –0.26 | 0.037 |
| SOH | 18.9 | 13.3 | –462 | –858 | –0.773 | –1.734 |

The unified QSRR for I, ΔH and ΔS are given below along with the statistical data

$$I = -425.2\,(\pm 23.3) + 141.7\,(\pm 4.1)\ {}^{1}\chi_P^{V} - 22.7\,(\pm 1.8)\ {}^{2}\chi_P^{Vm} + 17.85\,(\pm 0.95)\ S + 1.625\,(\pm 0.088)\ \mathrm{bp} + 0.331\,(\pm 0.073)\ Z' + 0.626\,(\pm 0.071)\ H' \tag{31}$$

$r = 0.9948$ $r_{cv} = 0.9933$ $\sigma = 11.4$ $F = 1903$ $n = 126$

$$\Delta H = 4949.5\,(\pm 546.7) - 956.5\,(\pm 96.3)\ {}^{1}\chi_P^{V} + 102.1\,(\pm 43.5)\ {}^{2}\chi_P^{Vm} - 69.85\,(\pm 22.46)\ S - 23.566\,(\pm 2.067)\ \mathrm{bp} + 0.627\,(\pm 0.056)\ Z' + 0.323\,(\pm 0.115)\ H' \tag{32}$$

$r = 0.9725$ $r_{cv} = 0.9650$ $\sigma = 268.4$ $F = 347$ $n = 126$

$$\Delta S = -1.867\,(\pm 0.959) - 0.543\,(\pm 0.169)\ {}^{1}\chi_P^{V} - 0.041\,(\pm 0.076)\ {}^{2}\chi_P^{Vm} + 0.0614\,(\pm 0.0394)\ S - 0.03792\,(\pm 0.00366)\ \mathrm{bp} + 0.306\,(\pm 0.140)\ Z' + 0.622\,(\pm 0.051)\ H' \tag{33}$$

– $r = 0.9365$ $r_{cv} = 0.9217$ $\sigma = 0.533$ $F = 183$ $n = 126$

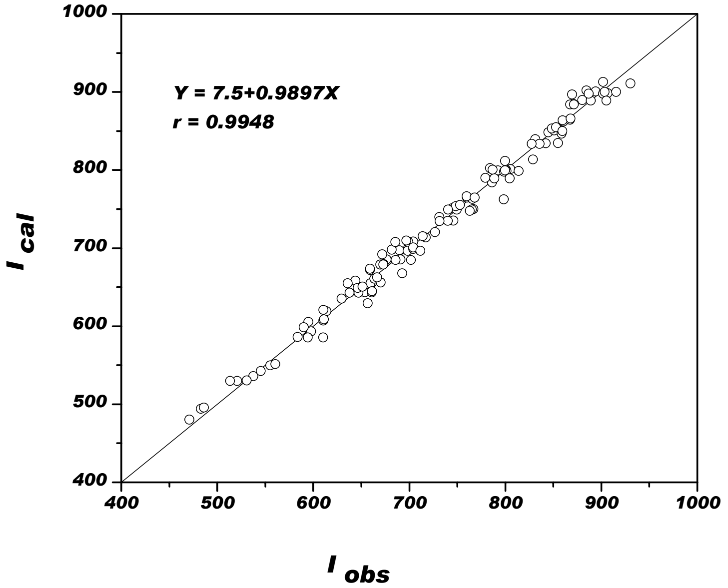

**Figure 1.** Plot of calculated Kováts retention indices, using unified QSRR Eq. (31), *versus* observed values of oxygen derivatives for the seven stationary phases.

# 3 RESULTS AND DISCUSSION

In the three unified QSRR models the *r* values are high and the errors in the coefficients are small. These factors indicate that the proposed QSRR models are statistically significant. The I, ΔH, ΔS values calculated using Eqs. (31)–(33) are plotted as a function of observed values (Table 4) in Figures 1–3, respectively. The lines drawn in these figures represent an ideal fit where the differences between observed and calculated values are zero. The standard deviations of linear fit between calculated and observed retention properties are: σ(I) = 11.1, σ(ΔH) = 255.7, σ(ΔS) = 0.5031. Eqs. (31)–(33) can be used to predict the retention properties for a new solute on any new stationary phase provided $Z'$ and $H'$ values of the phase are known.

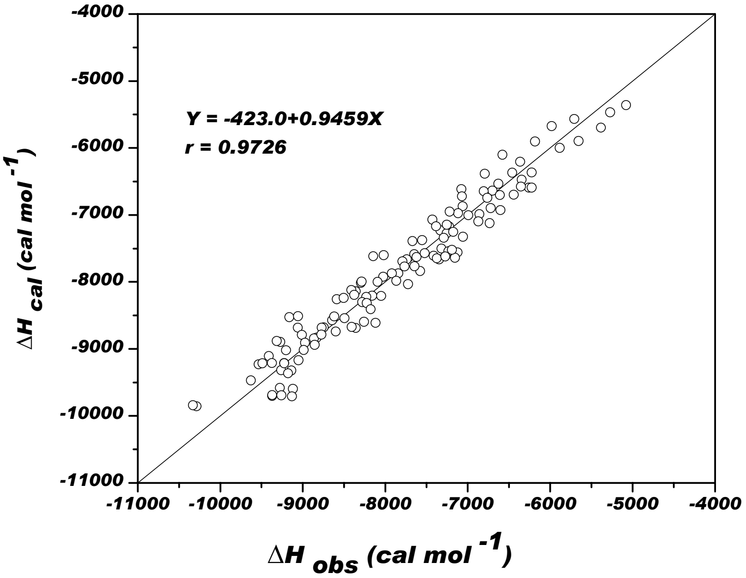

**Figure 2.** Plot of calculated partial molar enthalpy, using unified QSRR Eq. (32), *versus* observed values of oxygen derivatives for the seven stationary phases.

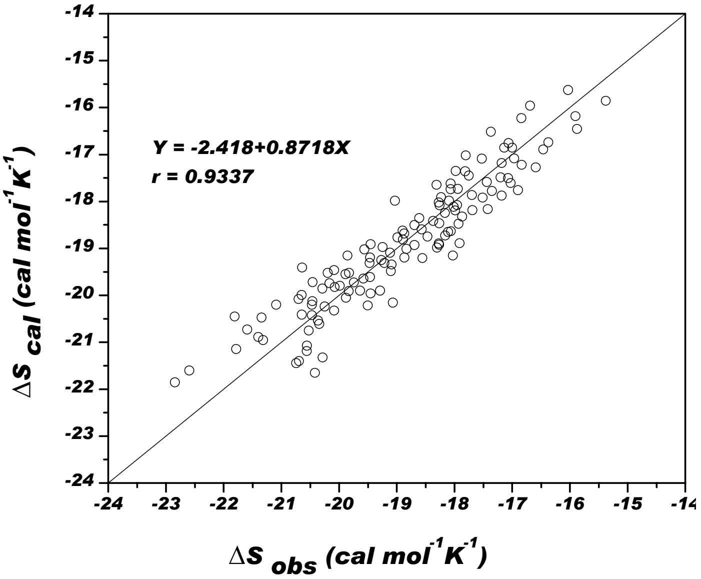

**Figure 3.** Plot of calculated partial molar entropy, using unified QSRR Eq. (33), *versus* observed values of oxygen derivatives for the seven stationary phases.

The predictive ability of the unified QSRR models has been validated by leave–one–out cross validation method. The predicted I, ΔH and ΔS values for 126 solutes by cross validation are plotted as a function of observed values in the Figures 4–6. The cross validated correlation coefficients $r_{cv}$ are close to regression r values in the three properties as shown in Eqs. (31)–(33).

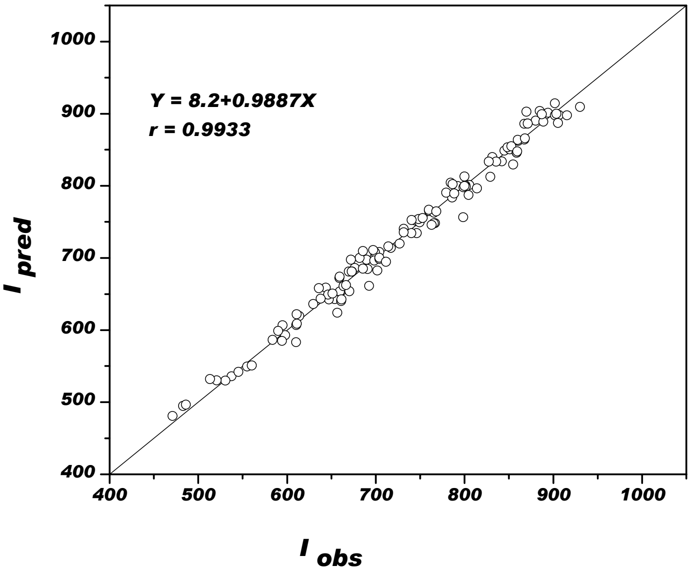

**Figure 4**. Plot of predicted Kováts retention index by cross validation using Eq. (31), *versus* observed values.

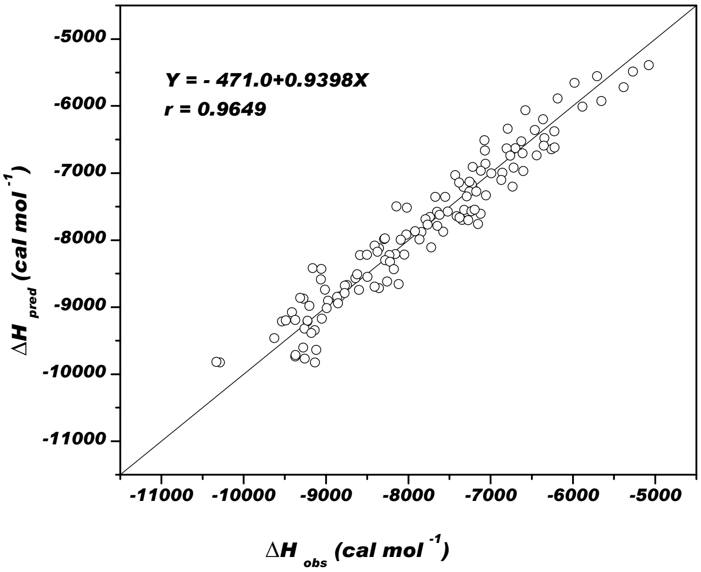

**Figure 5**. Plot of predicted partial molar enthalpy by cross validation using Eq. (32), *versus* observed values.

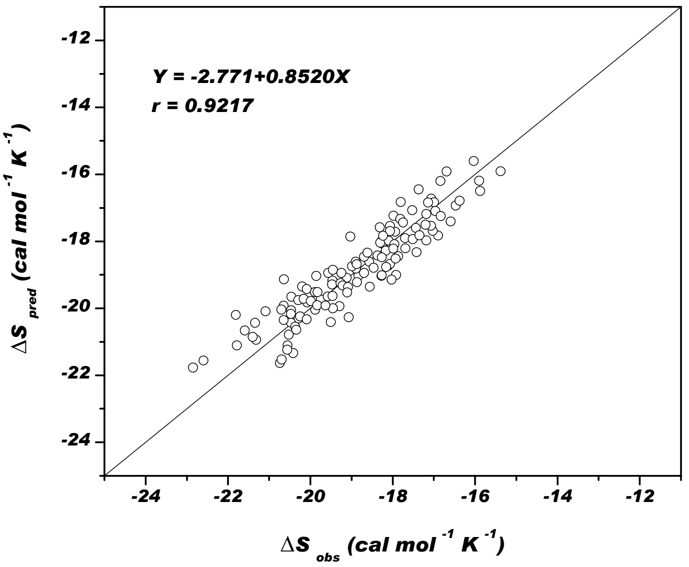

**Figure 6**. Plot of predicted partial molar entropy by cross validation using Eq. (33), *versus* observed values.

The applicability of the unified QSRR has been verified by predicting the three properties on two new stationary phases 1–chloro–18,23–dioctadecylhentetracontane (PCL) and 18,23–dioctadecyl–7–hentetracontanol (SOH) and compared with the observed values [26–27]. Such a comparison has been shown in Figures 7–9 by plotting predicted data *versus* observed data. There is a close agreement between the two sets of data with a maximum standard deviations, σ(I) = 7.6, σ(ΔH) = 207.4, and σ(ΔS) = 0.4448 has been observed in the two phases. The smaller σ values are expected in this comparison as the stationary phases used in training set and in the test set have the same structure and nearly same molar volume but differ in polarity.

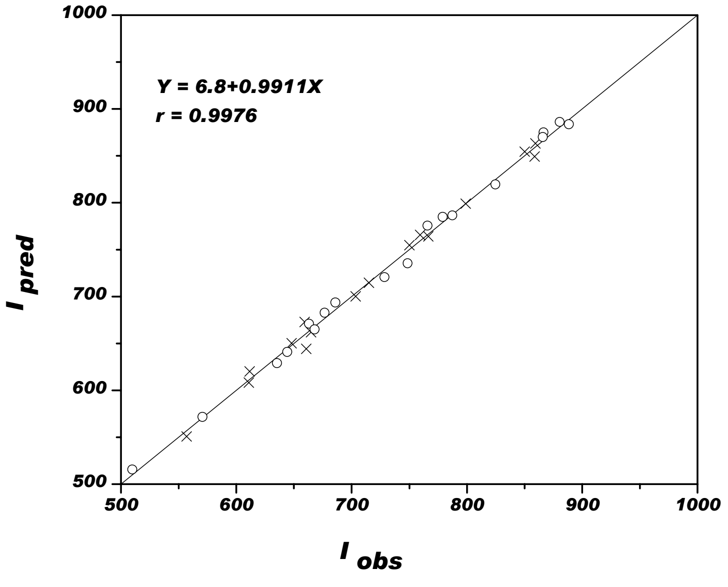

**Figure 7.** Plot of predicted Kováts retention indices, using unified QSRR Eq. (31) *versus* observed values of oxygen derivatives for the two new phases PCL (×) and SOH (o).

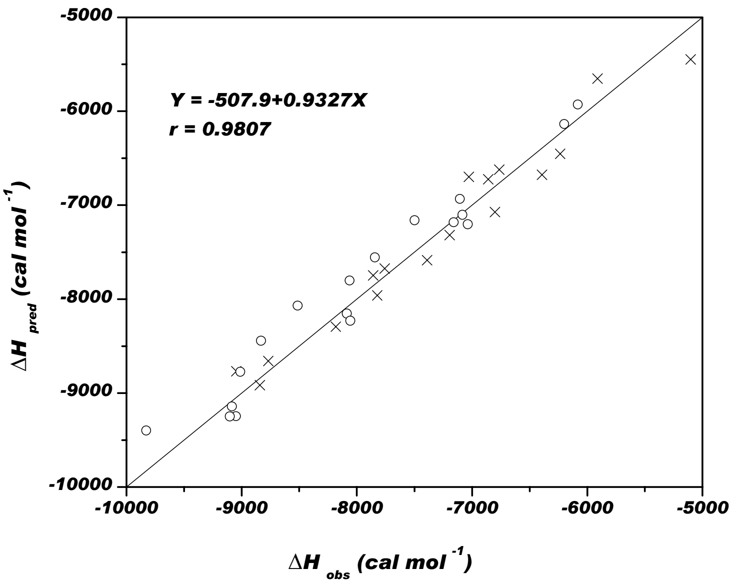

**Figure 8.** Plot of predicted partial molar enthalpy, using unified QSRR Eq. (32) *versus* observed values of oxygen derivatives for the two new phases PCL (×) and SOH (o)

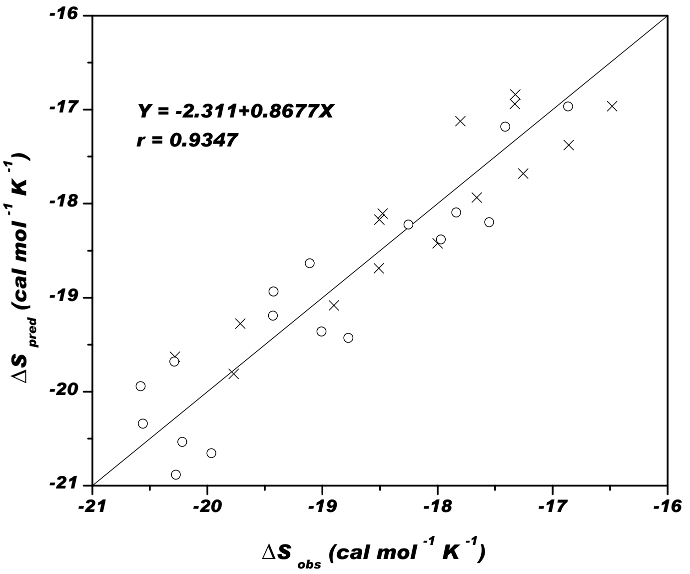

**Figure 9.** Plot of predicted partial molar entropy, using unified QSRR Eq. (33) *versus* observed values of oxygen derivatives for the two new phases PCL (×) and SOH (o)

# 4 CONCLUSIONS

Modified valence connectivity index, ${}^{n}\chi^{Vm}$, based on the summation over inverse geometric mean terms have been evaluated and used in the development of QSRR for oxygen derivatives. To obtain the best predictive models for retention index, partial molar enthalpy and partial molar entropy it is found to be necessary to use the E–state value of the oxygen atom and boiling point of oxygen derivatives along with the valence connectivity indices. SMLR analysis shows that in certain combinations with ${}^{n}\chi^{Vm}$ descriptors produced better predictions than with ${}^{n}\chi^{V}$ descriptors. The predictive descriptors ${}^{1}\chi_{P}^{V}$, ${}^{2}\chi_{P}^{Vm}$ ,$S$ and bp are found to yield a better QSRR model in all the seven phases. The same set of descriptors applied for all phases has been explained due to the isosteric nature of the seven stationary phases. Further combining the data of the seven phases a unified QSRR has been proposed for each property. The proposed unified QSRR model is expected to predict the retention property of a new solute belongs to the congener series of oxygen derivatives on any new stationary phase. In this study the unified QSRR has been applied to predict satisfactorily the I, ΔH and ΔS values of oxygen derivatives on two new stationary phases. The maximum standard deviations of the fit between calculated and observed property are as follows: σ(I) = 7.6, σ(ΔH) = 207.4 and σ(ΔS) = 0.4448. The predictive ability of the unified QSRR models have been validated by leave–one–out cross validation, which shows that the models are satisfactory.

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