J. Chem. Eng. Data **2008,** *53,* 331–334

Prediction of pK_a Values of Extractant Using Novel Quantitative Structure–Property Relationship Models

Xinchang Shan, Wei Qin,* Zhiyong Zhou, and Youyuan Dai

State Key Laboratory of Chemical Engineering, Department of Chemical Engineering, Tsinghua University,
Beijing 100084, China

The dissociation equilibrium constant (pK_a) of an extractant is one of the main factors determining the reactive extraction behavior. A quantitative structure–property relationship (QSPR) was investigated for predicting the pK_a of some pure extractants and the apparent basicity (p$K_{a,B}$) of three typical mixture solvents, trioctylamine (TOA)/hexane, TOA/1-octanol, and TOA/methyl isobutyl ketone (MIBK). Novel QSPR models for the pK_a of a pure extractant and the p$K_{a,B}$ of a mixture solvent were set up. The novel QSPR models include the concentration of extractant in the solvent and three kinds of molecular connectivity indices of extractant and diluent. The calculated values from the models of the pure extractant and mixture solvents show good consistency with experimental values.

Introduction

Liquid–liquid extraction based on reversible chemical complexation is a novel separation technique that is highly effective and selective for separating polar organic solutes from aqueous solutions.[1–5] Recently, on the basis of carboxylic acid extraction behavior from aqueous solutions, three factors have been found to influence extraction equilibrium characteristics. They are the dissociation equilibrium constant of the acid (pK_a),[6] the hydrophobicity of the acid (log P),[7] and the apparent basicity of the extractant (p$K_{a,B}$),[8–10] where the pK_a and log P are related to the nature of the solute and the p$K_{a,B}$ is related to the nature of the solvent. Shan[9] studied the extraction equilibria of monocarboxylic acids with trioctylamine (TOA) and trialkyl phosphine oxide (TRPO), where a correlative equation including the above three parameters, pK_a, log P, and p$K_{a,B}$, was obtained. It was shown that the correlative equation could be used to predict the extraction behavior very well and could also be used to evaluate the extraction equilibria of other extraction systems such as water/phenol/tributyl phosphate (TBP)–kerosene, water/aniline/di-(2-ethylhexyl)phosphate (D2EHPA)–kerosene, and water/amphoteric organics/alamine 336–1-octanol.[11]

Values for the pK_a and log P, can be found in chemistry handbooks easily, e.g., "Lange's Handbook of Chemistry", while almost no reports on p$K_{a,B}$ values can be found. A correlation to estimate the p$K_{a,B}$ value is required.

Since the 1970s, many publications have reported the application of quantitative structure–property relationships (QSPR) in describing the physical properties and biological activity of chemicals,[12–16] and all results have shown that the QSPR models can clearly indicate the molecular structure of the related chemicals. The common method used in QSPR is the molecular connectivity index (MCI),[17,18] and many research papers can be found relating properties of organic compounds using the QSPR model in recent years. For most compounds, the QSPR model can predict accurate properties of the compounds, e.g., hydrophobicity, solubility, and toxicity. However, as the model can become very complicated when there are heteroatoms or multiple functional groups in the compound, very few research results using the QSPR model can be found for the calculation of the pK_a of chemicals, especially acidity or basicity of extractants.[19,20]

The long-chain aliphatic tertiary amine, trioctylamine (TOA) or alamine 336, is a popular extractant and is used to extract Lewis acid organic compounds, e.g., phenols, organic acids, alcohols, and amphoteric functional compounds (e.g., amino benzoic acid). In the present study, the pK_a values of some extractants and the p$K_{a,B}$ values for three typical TOA mixture solvents, TOA/hexane, TOA/1-octanol, and TOA/methyl isobutyl ketone (MIBK), were collected. A novel QSPR model for the pK_a of the pure extractant and the p$K_{a,B}$ of the mixture solvents was set up.

Methodology

For a given molecule, a simple molecular connectivity index (${}^i\chi_p$), can be calculated on the basis of the method outlined by Kier and Hall,[17] and the molecular connectivity valent index (${}^i\chi^v{}_p$) can be obtained by using the method described in ref 21. Moreover, the deference in the molecular connectivity valent indices is available through the deference of ${}^i\chi_p$ and ${}^i\chi^v{}_p$, i.e., $\Delta^i\chi = {}^i\chi_p - {}^i\chi_p{}^v$.

Generally, ${}^i\chi_p$ and ${}^i\chi^v{}_p$ represent specific molecular information, e.g., the relative degree of branching, the molecular size, the molecular volume, the molecular surface area, and topology of unsaturation and heteroatoms, etc. The first-order molecular connectivity valent index (${}^1\chi^v{}_p$) especially can reflect atomic charge, π electrons, electron number, and nonhydrogen σ electron number on the lone-pair electronic orbit, when there are heteroatoms in a molecule. The deference in the first-order molecular connectivity valent indices ($\Delta^1\chi$) is an index that encodes information about nonsigma electrons on an atom, the branching pattern of all atoms, and the influence of the atoms on a heteroatom or double bond. With increasing numbers of nonsigma electrons in a molecule in the series in which ${}^1\chi_p$ is constant, the values of ${}^1\chi_p{}^v$ decrease, then the $\Delta^1\chi$ values also increase as the molecule increases in polarity. For a molecule

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* To whom correspondence should be addressed. E-mail: qinwei@tsinghua.edu.cn. Fax: +86 10 62782748. Tel.: +86 10 62782748.

10.1021/je7002034 CCC: $40.75

Table 1. pK_a of Pure Extractants

extractant	$^1\chi^v_{ext}$	$\Delta^1\chi_{ext}$	pK_a^{22-24}	$pK_{a,calcd}$
di-(2-ethylhexyl) phosphate (D2EHPA)	8.293	1.382	2.35	2.16
2-ethylhexyl hydrogen 2-ethylhexyl phosphonate (HEHEHP)	8.448	1.037	3.30	3.36
bis(2,4,4-trimethylpentyl)phosphinic acid (Cyanex272)	7.510	0.692	3.93	5.32
bis(2,4,4-trimethylpentyl)dithiophosphinic acid (Cyanex301)	7.855	0.892	3.16	4.32
bis(2,4,4-trimethylpentyl)monothiophosphinic acid (Cyanex302)	8.510	0.892	3.52	3.86
iso-propyl phosphonic acid mono(1-hexyl-4-ethyl) octyl ester	11.270	0.030	5.49	5.17
sec-octylphenoxy acetic acid (CA-12)	12.080	0.627	3.53	2.34
di-(2-ethylhexyl)-phosphinic acid	8.293	0.692	4.58	4.77
trioctylamine (TOA)	12.070	0.276	3.32	3.68
octylamine	4.115	0.092	9.95	9.99
di-*iso*-butylamine	3.833	0.293	10.50	9.42
cis-cinnamic acid	1.766	2.239	3.88	3.52
trans-2-bromocinnamic acid	4.589	1.539	4.41	4.18
benzylamine	2.199	0.692	9.35	9.07
triethylenediamine	1.321	0.890	8.19	8.94

in a homologous series, the polarity decreases with increasing molecular size, where the $\Delta^1\chi$ values are constant. If $\Delta^1\chi$ is used as the index related to the polarity of a molecule, another index is required to modify the effect of molecular size. Thus, the polarity of a molecule can be expressed as $f(^1\chi^v_p, \Delta^1\chi)$.

It is known that, for a mixture solvent, a polar diluent increases the dissociating ability of relatively low polar extractants. On the other hand, a nonpolar diluent does not affect the extractant dissociation.[10] On the basis of the above, the $pK_{a,B}$ value for a mixture solvent should depend on the polarity of the extractant and diluent, $^1\chi^v_{ext}$, $\Delta^1\chi_{ext}$, and $\Delta^1\chi_{dilu}$, and the basicity of the mixture solvent can be expressed by an equation depending on the three MCIs as follows

$$pK_{a,B} = C_0 + \varphi(C_1{}^1\chi^v_{ext} + C_2\Delta^1\chi_{ext}) + C_3(1-\varphi)^m(\Delta^1\chi_{dilu} + C_4) \quad (1)$$

where subscript ext and dilu represent the extractant and diluent molecules, respectively. φ is the volume fraction of extractant in the solvent. C_i and m are constants.

For a pure extractant system, $\varphi = 1$ and the pK_a of the extractant can be written as

$$pK_a = C_0 + C_1{}^1\chi^v_{ext} + C_2\Delta^1\chi_{ext} \quad (2)$$

Then, substitution of eq 2 into eq 1 gives

$$pK_{a,B} = C_0(1-\varphi) + \varphi pK_a + C_3(1-\varphi)^m(\Delta^1\chi_{dilu} + C_4) \quad (3)$$

Thus, if a QSPR model for the pK_a of pure extractant is available, the $pK_{a,B}$ can be predicted easily using eq 3.

Results And Discussion

pK_a Values of Pure Extractants. Available pK_a data for several typical pure extractants used in the chemical industry and hydrometallurgy, which are listed in Table 1, are retrieved from the published literature.[22–24] The $^1\chi^v_{ext}$ and $\Delta^1\chi_{ext}$ values calculated according to the method in refs 17 and 21 also can be found in Table 1.

The constants C_0, C_1, and C_2 can be obtained by fitting the set of 15 pK_a values given in Table 1 to eq 2 using a least-squares regression method. Equation 3 then becomes

$$pK_a = 13.1929 - 0.7042{}^1\chi^v_{ext} - 3.7912\Delta^1\chi_{ext} \quad (r = 0.9662, n = 15) \quad (4)$$

where n is the number of pK_a data and r is the correlation coefficient.

According to the correlation coefficient, $r = 0.9662$, the calculated pK_a values of pure extractant fit the measured data very well as shown in Figure 1. This result illustrates that eq 4 can be used to predict the pK_a values of pure extractants.

$pK_{a,B}$ Values for Mixture Solvent. As shown in Figure 2 and Table 2, $pK_{a,B}$ decreases with increasing TOA concentration for the protic and polar diluent 1-octanol, and increases with increasing TOA concentration for the nonpolar diluent hexane, whereas $pK_{a,B}$ is apparently not dependent on the TOA concentration for the diluent MIBK. For a fixed TOA concen-

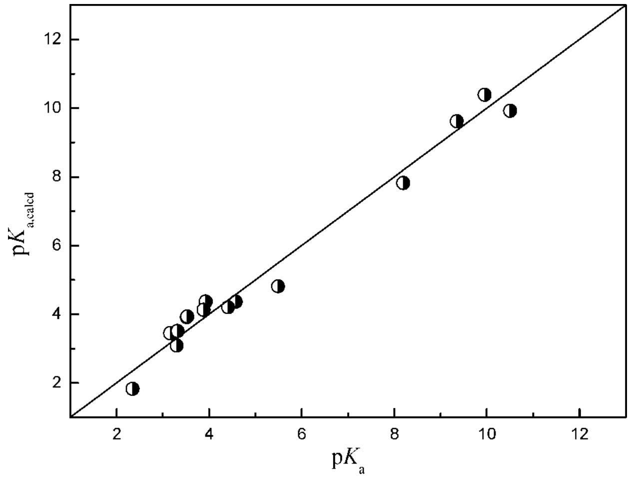

Figure 1. pK_a vs $pK_{a,calcd}$.

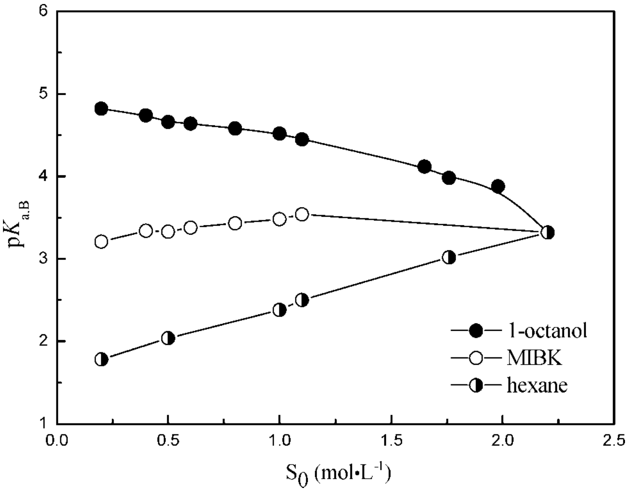

Figure 2. Effect of extractant concentration on the apparent basicity of extractant (TOA).

Table 2. $pK_{a,B}$ for TOA−Diluent Systems

diluent	$pK_{a,B}$[21]	φ_{TOA}	$pK_{a,B,calcd}$	deviation/%
hexane	1.78	0.09	1.76	−1.41
($\Delta^1\chi_{dilu} = 0$)	2.04	0.23	2.01	−1.80
	2.38	0.45	2.37	−0.25
	2.50	0.50	2.46	−1.60
	3.02	0.80	2.98	−1.46
1-octanol	4.82	0.09	4.82	0.03
($\Delta^1\chi_{dilu} = 0.3909$)	4.74	0.18	4.75	0.13
	4.66	0.23	4.70	0.89
	4.64	0.27	4.66	0.52
	4.58	0.36	4.57	−0.12
	4.52	0.45	4.48	−0.97
	4.45	0.50	4.42	−0.74
	4.12	0.75	4.05	−1.61
	3.98	0.80	3.96	−0.49
	3.88	0.90	3.73	−3.78
MIBK	3.21	0.09	3.30	2.92
($\Delta^1\chi_{dilu} = 0.5052$)	3.34	0.19	3.35	0.18
	3.33	0.23	3.36	0.96
	3.38	0.27	3.38	−0.08
	3.43	0.36	3.41	−0.62
	3.48	0.45	3.44	−1.27
	3.54	0.5	3.45	−2.59

tration, $pK_{a,B}$ decreases in the order 1-ocatnol > MIBK > hexane. Thus, $pK_{a,B}$ depends on both diluent type and TOA concentration.

Generally, for a mixture solvent, a polar diluent increases the dissociating ability of relatively low polar extractants. On the other hand, a nonpolar diluent does not affect the extractant dissociation.[10] The interactions between the extractant and diluent can, somewhat arbitrarily, be divided into "general solvation" and "specific interaction" of the diluent with the extractant. Active diluents, such as 1-octanol, have functional groups that enable greater solvation of the extractant. In particular, protic halogenated hydrocarbons and alcoholic diluents give unusually high degrees of dissociation, higher than would be expected from polarity arguments alone. Specific hydrogen bonding between the proton of the diluent and the amine is thought to explain the extra solvation provided by the diluent. Therefore, the constant C_4 in eq 3 is the specific constant to modify the "specific interaction" of the diluent with the extractant, so for TOA/hexane and TOA/MIBK, $C_4 = 0$. Moreover, the C_0 in eq 2 (for the pure extractant system) is different from that in eq 3 (for the mixture solvent).

By regression, using 23 sets of $pK_{a,B}$ data, the constants m, C_0, C_3, and C_4 in eq 3 were determined, and the equation obtained is

$$pK_{a,B} = 1.60(1-\varphi) + 3.29(\Delta^1\chi_{dilu} + 0.61)(1-\varphi)^{0.75} + \varphi pK_a \quad (r^2 = 0.9971, n = 23) \quad (5)$$

Figure 3 shows that the calculated values of $pK_{a,B}$ well approach the experimental values within an error of ± 4 %.

Conclusion

Novel QSPR models, including the concentration of extractant in the solvent and three kinds of molecular connectivity indices of extractant and diluent (${}^1\chi^v{}_{ext}$, $\Delta^1\chi_{ext}$, and $\Delta^1\chi_{dilu}$), were set up to predict the pK_a of a pure extractant and the $pK_{a,B}$ of a mixture solvent. The calculated values from the model of pK_a and $pK_{a,B}$ well approach the experimental values.

Nomenclature. $pK_{a,B}$, the apparent basicity of extractant ($mol\cdot L^{-1}$); pK_a, dissociation equilibrium constant of the Lewis acid ($mol\cdot L^{-1}$); log P, hydrophobicity parameter of the acid; S_0, initial concentration of extractant in the organic phase ($mol\cdot L^{-1}$); φ, volume fraction of extractant; ${}^1\chi_p$, simple molecular connectivity index; ${}^1\chi^v{}_p$, the first-order molecular connectivity valent index; $\Delta^1\chi$, the difference in the first-order molecular connectivity valent index.

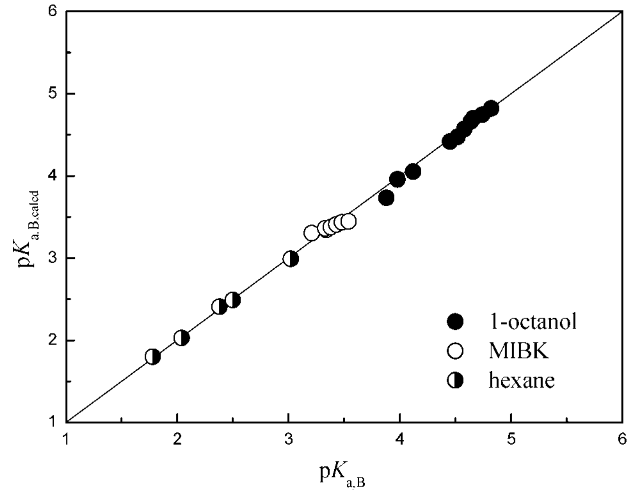

Figure 3. $pK_{a,B,calcd}$ vs $pK_{a,B}$.

Note Added after ASAP Publication: This paper was published ASAP on January 31, 2008. Equation 3 was changed. The revised paper was reposted on February 14, 2008.

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Received for review April 17, 2007. Accepted December 28, 2007. This work was supported by the National Natural Science Foundation of China, Grant No. 29836130.

JE7002034