Measurement and Correlation of Phase Diagram Data for Several Hydrophilic Alcohol + Citrate Aqueous Two-Phase Systems at 298.15 K

Yun Wang, Shiping Hu, Juan Han, and Yongsheng Yan*

School of Chemistry and Chemical Engineering, Jiangsu University, 301 Xuefu Road, Zhenjiang, 212013, China

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Binodal data for the ethanol + $(NH_4)_3C_6H_5O_7$ + water system and the 2-propanol + $(NH_4)_3C_6H_5O_7$/$Na_3C_6H_5O_7$/$K_3C_6H_5O_7$ + water systems were experimentally determined at 298.15 K. Three empirical equations were used to correlate binodal data. On the basis of the equation with the highest accuracy and lever rule, the liquid−liquid equilibrium data were calculated by MATLAB. The reliability of the calculation method and the corresponding tie-line data was proved by the Othmer−Tobias equation and Bancroft equation. The determined binodal data were also correlated by two theoretical equations on the basis of excluded volume theory. The calculated effective excluded volume (EEV) of salt and the binodal curves plotted in molality both indicate that the salting-out abilities of the investigated salts are in the order $Na_3C_6H_5O_7 \approx K_3C_6H_5O_7 > (NH_4)_3C_6H_5O_7$, and the phase-separation abilities of the investigated alcohols are in the order 2-propanol > ethanol.

Introduction

An aqueous two-phase system (ATPS), also known as an aqueous biphasic system, is a liquid−liquid extraction (LLE) system that has been used to separate and purify a variety of biological products, including protein,[1,2] cell,[3] and genetic materials[4] and low molecular weight products.[5,6] Aqueous two-phase extraction (ATPE) will become an efficient downstream process of bioproducts because of its biocompatibility, process-integration capability, and scale-up advantage. Reliable liquid−liquid equilibrium data are beneficial to the design of ATPE and the establishment of thermodynamic models. Recently, citrates have been investigated as a substitute for inorganic salts to form ATPS's with polymers or ionic liquids (ILs).[7−9] Citrates have the biodegradable and nontoxic advantages over the traditional phase-forming inorganic salts; nevertheless, their application in the hydrophilic alcohol−salt system is few. Zafarani-Moattar et al.[10] studied the phase diagrams of some aliphatic alcohols + $Na_3C_6H_5O_7$/$K_3C_6H_5O_7$ + water systems at 298.15 K; however, they only determined a small part of binodal data, and the phase diagrams of ethanol/2-propanol + $(NH_4)_3C_6H_5O_7$ + water systems were not reported.

The salting-out effect has been widely used in the fields of LLE and salting-out crystallization.[11,12] The salting-out abilities of salts or ions are always discussed according to lyotropic series.[7,13,14] However, in fact, there is no unique Hofmeister series,[15,16] and it depends on the type and system of the experiments. Therefore, an efficient way to evaluate the salting-out abilities of salts or ions in the investigated systems is beneficial to the design of ATPE. The effective excluded volume (EEV) of salt calculated on the basis of binodal data has been used to evaluate the salting-out abilities of salts in the polymer/IL−salt systems.[9,17,18] We extended the application of excluded volume theory to correlate binodal data of the hydrophilic alcohol−salt systems. The fitting parameter, EEV, was used to evaluate the salting-out abilities of salts and the phase-separation abilities of hydrophilic alcohols.

In this paper, binodal data for the 2-propanol−$Na_3C_6H_5O_7$/$K_3C_6H_5O_7$/$(NH_4)_3C_6H_5O_7$ systems and the ethanol−$(NH_4)_3C_6H_5O_7$ system were determined at 298.15 K. Tie-line data were calculated on the basis of the binodal data fitting equation and lever rule, which significantly simplify the traditional operations. The reliability of the calculation method and corresponding tie-line data was proved by the Othmer−Tobias equation and Bancroft equation.[19,20]

Experimental Section

Materials. Ethanol, 2-propanol, $Na_3C_6H_5O_7\cdot 2H_2O$, $K_3C_6H_5O_7\cdot H_2O$, and $(NH_4)_3C_6H_5O_7$ were supplied by the Sinopharm Chemical Reagent Co., Ltd. with minimum mass fractions of 0.997, 0.997, 0.990, 0.995, and 0.990, respectively. All chemicals were used without further purification. Double-distilled and deionized water was used throughout the entire experiment.

Apparatus and Procedures. The binodal curves were determined by the titration method (cloud point method). A $Na_3C_6H_5O_7$, $K_3C_6H_5O_7$, or $(NH_4)_3C_6H_5O_7$ solution of known concentration was titrated with 2-propanol or ethanol until the clear solution turned turbid. The compositions of the mixture were determined by a Sartorious analytical balance (model BS 124S) with a precision of 0.0001 g. A conical flask (50 cm^3) was used to carry out the experiment, and the temperature was maintained within ± 0.1 K in a water bath.

The phase equilibrium experiments were carried out in a separating funnel (60 mL). The feed samples were prepared by mixing an appropriate mass of 2-propanol/ethanol (m_1), $Na_3C_6H_5O_7$/$K_3C_6H_5O_7$/$(NH_4)_3C_6H_5O_7$ (m_2), and water (m_3) in a vessel (50 mL), and the mass of each composition was determined by the same Sartorious analytical balance mentioned above. After sufficient mixing, the samples were placed in a water bath (298.15 K) for more than 6 h until it separated into two clear phases. After the phase separation, the masses of the bottom phase (m_b) and top phase (m_t) were determined, respectively.

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* Corresponding author. E-mail: gaojian-wy@163.com.

10.1021/je9007348

Table 1. Binodal Data for the Hydrophilic Alcohol (1) + Citrate (2) + Water (3) Systems at 298.15 K

100 w_1	100 w_2	100 w_1	100 w_2	100 w_1	100 w_2	100 w_1	100 w_2	100 w_1	100 w_2	100 w_1	100 w_2
2-Propanol (1) + $(NH_4)_3C_6H_5O_7$ (2)				6.01	25.58	35.27	5.05	7.94	25.19	49.30	2.36
3.62	43.65	41.24	6.53	7.18	23.86	37.30	4.35	9.99	22.48	51.93	1.86
4.33	40.29	43.91	5.55	8.29	22.12	39.00	3.82	11.78	20.54	54.47	1.45
4.65	39.06	46.71	4.64	8.77	21.66	42.21	2.98	16.83	16.20	57.40	1.06
6.01	34.77	50.35	3.60	10.66	19.32	45.13	2.32	21.72	13.15	59.52	0.84
7.67	30.81	52.24	3.15	13.20	16.90	46.32	2.08	25.96	10.94	60.84	0.71
9.55	27.14	54.69	2.57	15.11	15.44	47.43	1.89				
11.49	24.36	57.74	1.99	15.78	14.96	49.90	1.49	Ethanol (1) + $(NH_4)_3C_6H_5O_7$ (2)			
12.56	23.01	59.99	1.63	18.13	13.36	52.52	1.14	9.35	43.24	45.57	9.67
15.71	19.8	60.58	1.54	19.89	12.36	54.43	0.93	9.81	41.91	46.60	8.98
18.47	17.63	62.17	1.32	23.67	10.33	56.07	0.77	13.22	36.36	48.45	8.01
19.23	17.09	64.00	1.09	26.43	8.91	57.76	0.63	16.21	32.81	52.69	5.93
25.18	13.59	65.20	0.96					17.64	31.05	53.59	5.45
30.56	11.01	65.92	0.89	2-Propanol (1) + $K_3C_6H_5O_7$ (2)				18.04	30.52	57.02	4.20
32.82	10.03	68.80	0.63	0.53	57.10	29.43	9.28	24.97	24.18	62.92	2.56
34.57	9.19	71.86	0.43	0.79	52.30	31.92	8.10	30.37	19.83	68.09	1.52
				1.19	44.27	36.00	6.38	32.39	18.32	70.86	1.13
2-Propanol (1) + $Na_3C_6H_5O_7$ (2)				1.80	40.87	39.34	5.12	34.73	16.63	73.40	0.84
2.52	35.13	28.78	7.77	2.38	37.97	41.92	4.27	37.85	14.42	75.37	0.67
3.48	31.83	30.70	6.90	4.25	32.69	44.03	3.65	41.43	12.35		
4.49	28.90	32.75	6.02	5.99	28.51	45.68	3.21				

Table 2. Values of Parameters of Equations 1 and 2 for the Hydrophilic Alcohol + Citrate + Water Systems at 298.15 K

alcohol−salt system	a	b	c	R^2	100 SD
2-propanol−$(NH_4)_3C_6H_5O_7$	0.89354[a]	−3.13566[a]	27.89398[a]	0.9968	1.30
	0.84971[b]	−2.09353[b]	1.27719[b]	0.9986	0.86
2-propanol−$Na_3C_6H_5O_7$	0.76673[a]	−3.49781[a]	50.79759[a]	0.9987	0.64
	0.71878[b]	−1.92114[b]	1.23944[b]	0.9992	0.49
2-propanol−$K_3C_6H_5O_7$	0.80516[a]	−3.21823[a]	43.28929[a]	0.9986	0.78
	0.77522[b]	−2.02297[b]	1.31381[b]	0.9986	0.78
ethanol−$(NH_4)_3C_6H_5O_7$	0.89786[a]	−2.19218[a]	12.15435[a]	0.9993	0.56
	0.85451[b]	−1.41099[b]	0.36939[b]	0.9990	0.66

[a] Values of parameters of eq 1. [b] Values of parameters of eq 2. SD = $(\sum_{i=1}^{n}(w_1^{\mathrm{cal}} - w_1^{\mathrm{exp}})^2/N)^{0.5}$, where w_1 and N represent the mass fraction of alcohol and the number of binodal data, respectively. w_1^{exp} is experimental mass fraction of ethanol/2-propanol listed in Table 1, and w_1^{cal} is the corresponding data calculated using eq 1 or 2.

Table 3. Values of Parameters of Equation 3 for the Hydrophilic Alcohol + Citrate + Water Systems at 298.15 K

alcohol−salt system	a	b	c	d	R^2	100 SD
2-propanol−$(NH_4)_3C_6H_5O_7$	−0.20056	−2.06044	−2.35194	−5.41593	0.9994	0.59
2-propanol−$Na_3C_6H_5O_7$	−0.30119	−3.21503	0.36096	−15.0122	0.9997	0.28
2-propanol−$K_3C_6H_5O_7$	−0.27628	−2.61121	−0.72207	−11.7248	0.9998	0.30
ethanol−$(NH_4)_3C_6H_5O_7$	−0.08576	−2.60471	1.80722	−7.66674	0.9998	0.29

Results and Discussion

Binodal Data and Correlation. For the ethanol (1) + $(NH_4)_3C_6H_5O_7$ (2) + water (3) system and the 2-propanol (1) + $Na_3C_6H_5O_7/K_3C_6H_5O_7/(NH_4)_3C_6H_5O_7$ (2) + water (3) systems, the binodal data determined at 298.15 K are given in Table 1, and the binodal curves are plotted in Figure 1. The binodal data were correlated by the following equations

$$w_1 = a \exp(b{w_2}^{0.5} - c{w_2}^{3}) \tag{1}$$

$$w_1 = a + b{w_2}^{0.5} + c w_2 \tag{2}$$

$$w_1 = \exp(a + b{w_2}^{0.5} + c w_2 + d{w_2}^{2}) \tag{3}$$

where w_2 is the mass fraction of salts, w_1 is the mass fraction of hydrophilic alcohols, and a, b, c, and d are fitting parameters. Equation 1 has been widely used in correlating binodal data of IL−salt systems,[7] and eq 2 has been widely used in correlating binodal data of polymer−salt systems.[9] For the hydrophilic alcohol−salt systems, the application of empirical equations in binodal data fitting is much less than the polymer/IL−salt systems. Equation 3 was used in the binodal data fitting of ethanol−K_2HPO_4/NaH_2PO_4 and methanol−K_2HPO_4 systems.[21] The fitting parameters, correlation coefficients (R), and standard deviations (SD) of eqs 1 and 2 as well eq 3 are given in Tables 2 and 3, respectively. On the basis of the obtained R and SD, it can be concluded that eq 3 shows satisfactory accuracy in binodal data fitting for the investigated systems, which can also be proved by the binodal curves reproduced by eq 3 in Figure 2.

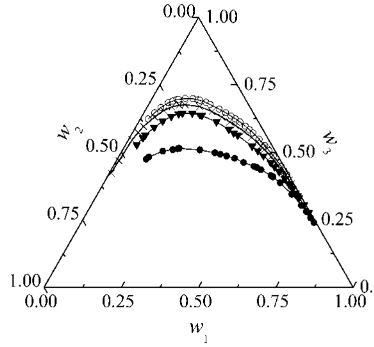

Figure 1. Binodal curves for the hydrophilic alcohol (1) + citrate (2) + water (3) systems at 298.15 K. ○, 2-propanol (1) + $Na_3C_6H_5O_7$ (2) + water (3); ×, 2-propanol (1) + $K_3C_6H_5O_7$ (2) + water (3); ▼, 2-propanol (1) + $(NH_4)_3C_6H_5O_7$ (2) + water (3); ●, ethanol (1) + $(NH_4)_3C_6H_5O_7$ (2) + water (3); solid line, obtained by connecting experimental binodal data.

Table 4. Phase Equilibrium Compositions for the Hydrophilic Alcohol (1) + Citrate (2) + Water (3) Systems at 298.15 K

	total composition		alcohol-rich phase		salt-rich phase	
no.	100 w_1	100 w_2	100 w_1^t	100 w_2^t	100 w_1^b	100 w_2^b
			2-Propanol (1) + $(NH_4)_3C_6H_5O_7$ (2)			
①	23.98	17.99	54.04	2.80	12.68	23.70
②	32.88	21.99	72.28	0.32	4.43	37.64
③	33.01	20.03	70.14	0.48	5.58	34.74
④	24.00	16.01	46.53	4.64	16.74	19.68
			2-Propanol (1) + $Na_3C_6H_5O_7$ (2)			
①	23.97	15.99	53.68	1.01	6.46	24.83
②	24.00	17.99	58.90	0.51	4.69	27.83
③	24.01	12.99	44.68	2.46	10.48	19.88
④	26.97	12.71	48.81	1.69	8.58	21.99
⑤	28.04	13.41	52.37	1.17	7.06	23.97
			2-Propanol (1) + $K_3C_6H_5O_7$ (2)			
①	24.02	14.03	45.43	3.32	13.63	19.22
②	24.00	15.99	52.72	1.77	9.90	22.98
③	24.01	18.00	58.27	0.96	7.31	26.30
④	26.01	16.04	55.90	1.27	8.46	24.72
			Ethanol (1) + $(NH_4)_3C_6H_5O_7$ (2)			
①	33.00	22.00	56.30	4.54	12.68	37.24
②	33.00	23.96	61.29	3.00	10.00	41.02
③	31.01	24.03	57.86	4.01	11.88	38.30
④	31.03	22.02	51.37	6.53	15.34	33.97

Liquid−Liquid Equilibrium Data and Correlation. On the basis of eq 3 and lever rule, the equilibrium compositions were calculated by MATLAB, using eqs 4, 5, 6, and 7 as follows

$$w_1^t = \exp(a + b(w_2^t)^{0.5} + cw_2^t + d(w_2^t)^2) \tag{4}$$

$$w_1^b = \exp(a + b(w_2^b)^{0.5} + cw_2^b + d(w_2^b)^2) \tag{5}$$

$$\frac{w_1^t - w_1}{w_1 - w_1^b} = \frac{m_b}{m_t} \tag{6}$$

$$\frac{w_2 - w_2^t}{w_2^b - w_2} = \frac{m_b}{m_t} \tag{7}$$

where w_1^t, w_1^b, w_2^t, and w_2^b represent the equilibrium compositions (in mass fraction) of alcohol (1) and salt (2), in the top, t, and bottom, b, phases, respectively. w_1 and w_2 represent the total compositions (in mass fraction) of alcohol (1) and salt (2), respectively. The results are given in Table 4.

The Othmer−Tobias equation (eq 8) and Bancroft equation (eq 9) have been successfully used in correlating tie-line data of poly(ethylene glycol (PEG)−salt system,[9] ionic liquid−salt system,[22,23] and hydrophilic alcohol−salt system.[19] In this paper, these two equations were used to evaluate the reliability of the calculation method and the corresponding tie-line data.

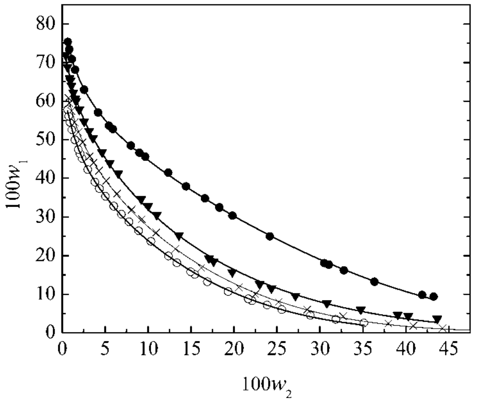

Figure 2. Binodal curves for the hydrophilic alcohol (1) + citrate (2) + water (3) systems at 298.15 K. ○, 2-propanol (1) + $Na_3C_6H_5O_7$ (2); ×, 2-propanol (1) + $K_3C_6H_5O_7$ (2); ▼, 2-propanol (1) + $(NH_4)_3C_6H_5O_7$ (2); ●, ethanol (1) + $(NH_4)_3C_6H_5O_7$ (2); solid line, obtained by eq 3.

Table 5. Values of Parameters of Equation 8 for the Hydrophilic Alcohol (1) + Citrate (2) + Water (3) Systems at 298.15 K

alcohol−salt system	k_1	n	R	100 SD[a]
2-propanol−$(NH_4)_3C_6H_5O_7$	0.19975	1.2411	0.9994	0.38
2-propanol−$Na_3C_6H_5O_7$	0.20450	1.2928	0.9998	0.10
2-propanol−$K_3C_6H_5O_7$	0.18989	1.2838	0.9998	0.09
ethanol−$(NH_4)_3C_6H_5O_7$	0.38534	1.3470	0.9996	0.11

[a] SD = $(\sum_{i=1}^{N}(w_1^{t,cal} - w_1^{t,exp})^2/N)^{0.5}$, where w_1^t and N represent the mass fraction of alcohol in the top phase and the number of tie-lines, respectively. $w_1^{t,exp}$ is the experimental mass fraction of alcohol in the top phase listed in Table 4, and $w_1^{t,cal}$ is corresponding data calculated using eq 8.

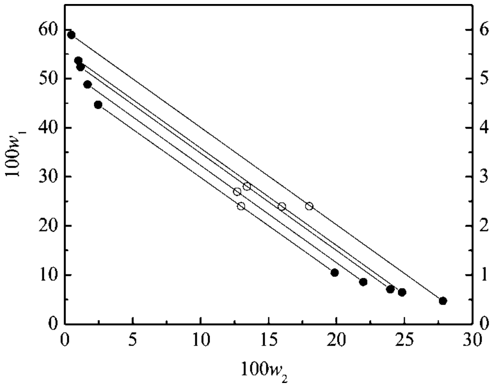

Figure 3. Liquid−liquid equilibria of the 2-propanol (1) + $Na_3C_6H_5O_7$ (2) + water (3) systems at 298.15 K. ○, total compositions of tie line; ●, LLE compositions of tie-line; solid line, tie-lines.

$$\frac{1 - w_1^t}{w_1^t} = k_1\left(\frac{1 - w_2^b}{w_2^b}\right)^n \tag{8}$$

$$\frac{w_3^b}{w_2^b} = k_2\left(\frac{w_3^t}{w_1^t}\right)^r \tag{9}$$

where w_1^t, w_1^b, w_2^t, w_2^b, w_3^t, and w_3^b represent the equilibrium compositions (in mass fraction) of alcohol (1), salt (2), and water (3) in the top, t, and bottom, b, phases, respectively. k_1, k_2, n, and r are fitting parameters. The fitting parameters of eq 8 are given in Table 5. A linear dependence of $\log((1 - w_1^t)/w_1^t)$ against $\log((1 - w_2^b)/w_2^b)$ as well as $\log(w_3^b/w_2^b)$ against $\log(w_3^t/w_1^t)$ also indicate a good fitting property of the experimental results to eqs 8 and 9. The linear correlation coefficients of eq 9 for the 2-propanol−$Na_3C_6H_5O_7$ system, 2-propanol−$K_3C_6H_5O_7$ system, 2-propanol−$(NH_4)_3C_6H_5O_7$ system, and ethanol−$(NH_4)_3C_6H_5O_7$ system are 0.9998, 0.9997, 0.9989, and 0.9996, respectively. The results show a good reliability of the calculation method and the corresponding tie-line data.

Effect of Salts and Hydrophilic Alcohols on Liquid−Liquid Equilibrium. As shown in Figures 3, 4, 5, and 6, the additions of salts and alcohols both increase the tie-line length, which indicate that the increasing amount of salts and alcohols is beneficial to phase separation. The addition of salts to the aqueous ethanol/2-propanol solutions leads to the migration of water molecules away from alcohols to the ions of salts. Then more alcohol molecules will be excluded from the salt-rich phase to the alcohol-rich phase. In comparison with tie-lines with the same total compositions for the 2-propanol−$Na_3C_6H_5O_7$/$K_3C_6H_5O_7$/$(NH_4)_3C_6H_5O_7$ ATPS's, it can be seen that the mass fraction of 2-propanol in the top phase is in the order $Na_3C_6H_5O_7$

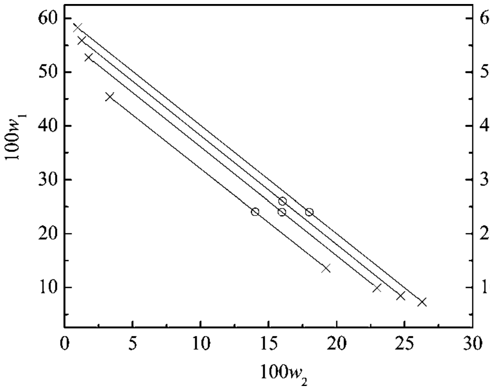

Figure 4. Liquid−liquid equilibria of the 2-propanol (1) + $K_3C_6H_5O_7$ (2) + water (3) systems at 298.15 K. ○, total compositions of tie line; ×, LLE compositions of tie-line; solid line, tie-lines.

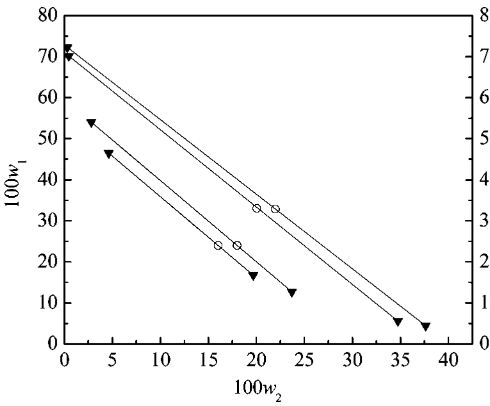

Figure 5. Liquid−liquid equilibria of the 2-propanol (1) + $(NH_4)_3C_6H_5O_7$ (2) + water (3) systems at 298.15 K. ○, total compositions of tie line; ▼, LLE compositions of tie-line; solid line, tie-lines.

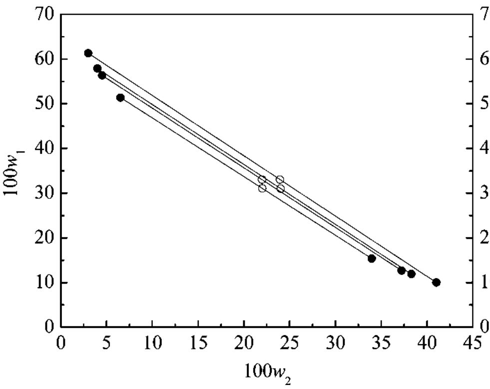

Figure 6. Liquid−liquid equilibria of the ethanol (1) + $(NH_4)_3C_6H_5O_7$ (2) + water (3) systems at 298.15 K. ○, total compositions of tie line; ●, LLE compositions of tie-line; solid line, tie-lines.

≈ $K_3C_6H_5O_7$ > $(NH_4)_3C_6H_5O_7$. For the ethanol/2-propanol−$(NH_4)_3C_6H_5O_7$ systems, the mass fraction of 2-propanol is much higher than that of ethanol in the alcohol-rich phase. In the next section, the determined binodal data were correlated by two theoretical equations obtained on the basis of excluded volume theory.

Table 6. Values of Parameters of Equations 10 and 11 for the Hydrophilic Alcohol + $(NH_4)_3C_6H_5O_7$ + Water Systems at 298.15 K

alcohol	$10^2\ v^*_{213}/(\mathrm{g \cdot mol^{-1}})$	$10^{-2}\ f_{213}$	R	100 SD[a]
2-propanol	3.6391	0.45370	0.9939	3.17
	3.7855		0.9886	3.55
ethanol	2.4232	1.1599	0.9913	3.11
	2.6449		0.9753	4.95

[a] SD = $(\sum_{i=1}^{N}(w_1^{\mathrm{cal}} - w_1^{\mathrm{exp}})^2/N)^{0.5}$, where N represent the number of binodal data. w_1^{exp} is experimental mass fraction of ethanol listed in Table 1, and w_1^{cal} is corresponding data calculated using eqs 10 or 11.

EEV and Salting-Out Ability of Salts. In the paper, the excluded volume theory developed by Guan et al.[24] was used to correlate the binodal curve and calculate the EEV of salts. It is based on the concept that macroscopically any molecule species in a solution is distributed at random and every system composition on the binodal is a geometrically saturated solution of one solute in the presence of another. The binodal model developed by Guan et al. was originally used in the polymer−polymer ATPS's, while we extended the application of this model in the hydrophilic alcohol−salt systems. As for the hydrophilic alcohol (1) + salt (2) + water (3) ternary system, two equations can be obtained from the excluded volume theory

$$\ln\left(V^*_{213}\frac{w_2}{M_2} + f_{213}\right) + V^*_{213}\frac{w_1}{M_1} = 0 \qquad (10)$$

$$\ln\left(V^*_{213}\frac{w_2}{M_2}\right) + V^*_{213}\frac{w_1}{M_1} = 0 \qquad (11)$$

where V^*_{213}, f_{213}, M_1, and M_2 are the scaled EEV of salts, the volume fraction of unfilled effective available volume after tight packing of salt into the network of alcohol molecules in aqueous alcohol solution, and the molar mass of the alcohol and salt, respectively. In the original application, eq 11 was used to correlate binodal data of polymer−polymer systems because of the marked difference in size between the two components. The f_{213} value will be very small and consequently can be neglected. The f_{213} value depends on the relative geometric shape, size, and interaction of unlike molecules.

The EEV represents the smallest spacing of hydrophilic alcohol which will accept an individual salt, so it reflects the compatibility of components in the same system. It has been used to evaluate the salting-out abilities of salts in the polymer−salt systems.[9,18,25] In this paper, the scaled EEV was used to evaluate the salting-out abilities of salts in the hydrophilic alcohol−salt systems. For different salts in a same hydrophilic alcohol−water component solvent, the salting-out abilities of salts increase with the increase of EEV. As for the $Na_3C_6H_5O_7$−2-propanol systems, the standard deviations of eqs 10 and 11 are both 0.029; meanwhile, as for $K_3C_6H_5O_7$−2-propanol systems, the standard deviations of eqs 10 and 11 are both 0.038. There is no significant difference between these two equations in binodal data fitting, so a simplified equation (eq 11) can be used. The scaled EEV of $Na_3C_6H_5O_7$ and $K_3C_6H_5O_7$ are 450.69 g·mol^{-1} and 439.42 g·mol^{-1}, respectively. Nevertheless, as for the $Na_3C_6H_5O_7$−ethanol system and the $(NH_4)_3C_6H_5O_7$−2-propanol system, f_{213} is not so small as to be neglected, and thus eq 10 should be used to correlate binodal data, as given in Table 6. The scaled EEV of investigated citrates in the 2-propanol−water component solvent is in the order $Na_3C_6H_5O_7$ (450.69 g·mol^{-1}) > $K_3C_6H_5O_7$ (439.42 g·mol^{-1}) > $(NH_4)_3C_6H_5O_7$ (363.91 g·mol^{-1}), which indicates that the salting-out abilities of $Na_3C_6H_5O_7$ and $K_3C_6H_5O_7$ are higher than $(NH_4)_3C_6H_5O_7$.

In many previous papers, the salting-out abilities of salts or ions are always compared by the binodal curves plotted in mass fraction. In fact, it cannot exactly reflect the nature of interaction between molecules in the system. In this paper, the binodal curves of the investigated systems are plotted in molality, as can be seen in Figure 7. The increase in EEV is reflected by a decrease in the concentration of salt required for the formation of ATPS's, which indicates a higher salting-

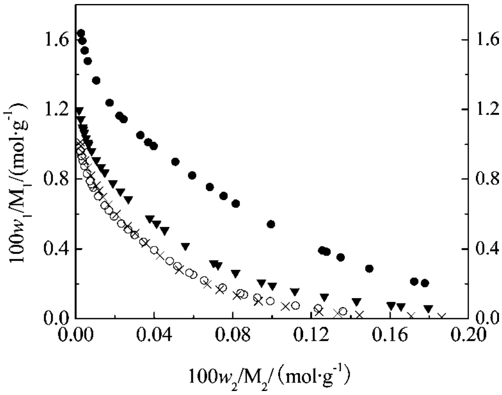

Figure 7. Binodal curves plotted in molality for the hydrophilic alcohol (1) + citrate (2) + water (3) systems at 298.15 K. ○, 2-propanol (1) + $Na_3C_6H_5O_7$ (2); ×, 2-propanol (1) + $K_3C_6H_5O_7$ (2); ▼, 2-propanol (1) + $(NH_4)_3C_6H_5O_7$ (2); ●, ethanol (1) + $(NH_4)_3C_6H_5O_7$ (2).

out ability of phase-forming salt. This relationship can also be deduced from eq 10 or 11. As shown in Figure 7, the salting-out abilities of salts are also in the same order as EEV, $Na_3C_6H_5O_7 \approx K_3C_6H_5O_7 > (NH_4)_3C_6H_5O_7$. When the concentration of salts is below 0.038 $\mathrm{mol \cdot g^{-1}}$, the salting-out ability of $Na_3C_6H_5O_7$ is slightly higher than $K_3C_6H_5O_7$; when the concentration of salts exceeds 0.038 $\mathrm{mol \cdot g^{-1}}$, the salting-out ability of $K_3C_6H_5O_7$ become slightly higher than $(NH_4)_3C_6H_5O_7$. In conclusion, there's no significant difference in the salting-out abilities between $K_3C_6H_5O_7$ and $Na_3C_6H_5O_7$ under the concentration of $Na_3C_6H_5O_7$ that can form an ATPS with 2-propanol. However, the area of an ATPS of $K_3C_6H_5O_7$−2-propanol system is larger than that of the $Na_3C_6H_5O_7$−2-propanol system because of a higher solubility of $K_3C_6H_5O_7$ than $Na_3C_6H_5O_7$. Therefore, $K_3C_6H_5O_7$ is more suitable to be a phase-separation salt under a high concentration of salt.

EEV and Phase-Separation Abilities of Alcohols. The scaled EEV of a same salt varies in different solvents because of the difference in size, shape, and interaction of molecules. The scaled EEV of $(NH_4)_3C_6H_5O_7$ in a 2-propanol−water solvent is much higher than that in ethanol−water solvent, which indicates that 2-propanol is easier to be excluded from the salt-rich phase to the alcohol-rich phase. For a same salt in different component solvents, the phase-separation abilities of alcohols increase with increasing EEV. So the phase-separation abilities of the investigated alcohols are in the order 2-propanol > ethanol, which is also proved by the locations of binodal curves in Figure 7. The increase in EEV is reflected by a decrease in the concentration of alcohol required for the formation of ATPS. Although the phase-separation ability of 2-propanol is higher than ethanol, the stability of bioproducts in hydrophilic solvents is in the order ethanol > 2-propanol. So the selection of appropriate phase-forming alcohols must take these factors into consideration.

Conclusion

Binodal data of the ethanol−$(NH_4)_3C_6H_5O_7$−water systems and the 2-propanol−$(NH_4)_3C_6H_5O_7$/$Na_3C_6H_5O_7$/$K_3C_6H_5O_7$−water systems were determined at 298.15 K. On the basis of a binodal data fitting equation with the highest accuracy and lever rule, the liquid−liquid equilibrium data were directly calculated by MATLAB. The reliability of the calculation method and the corresponding LLE data was proved by the Othmer−Tobias equation and the Bancroft equation.

The excluded volume theory was applied to correlate binodal data of the investigated hydrophilic alcohol−salt systems. The parameter, EEV, can be taken as a criterion to evaluate the salting-out abilities of different salts and the phase-separation abilities of different hydrophilic solvents. The obtained series will be very useful for the design of ATPE, the crystallization of salts and the recovery of hydrophilic solvents.

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Received for review September 8, 2009. Accepted November 12, 2009. Financial support from the National Natural Science Foundation of China (20777029; 2097607) is gratefully acknowledged.

JE9007348