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Liquid−Liquid Equilibrium in the System Poly(ethylene glycol) + $MgSO_4$ + H_2O at 298 K

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The liquid−liquid equilibrium for the ternary systems PEG1000 + $MgSO_4$ + H_2O, PEG3350 + $MgSO_4$ + H_2O and PEG8000 + $MgSO_4$ + H_2O has been obtained experimentally. The results are fitted to a three-parameter equation which fits the results to within ±2%. Tie lines have also been measured, along with the viscosity and density in both phases. The tie-line compositions have been fitted to Bancroft's potential equation.

Introduction

The extraction of biomolecules and cell particles using two-phase systems allows the separation and purification of these substances in biocompatible surroundings under nondenaturation conditions (Mattiason and Ling, 1987; Albertsson *et al.*, 1990). The degree of separation obtained depends upon the surface properties of the solute (size, electric charge, hydrophobicity, etc.) and on the characteristics of the two-phase system formed (density, viscosity, pH, etc.). Among the polymers most widely used are poly(ethylene glycol) (PEG), dextran, and starch derivatives. Salts such as $MgSO_4$, Na_2SO_4, $(NH_4)_2SO_4$, and KH_2PO_2 are also added.

The density and refraction-index values of both phases are very similar due to their high water content (above 85 mass %). The surface tension between the phases is small, with values between 0.1 and 100 μN/m. Equilibrium between the aqueous phases is slow, taking between 15 min and several hours, due to the small difference in densities and the high viscosity of the phases. The time to reach equilibrium may be reduced by using conventional centrifugal separators.

Extraction using the two aqueous phases can be made where contact is either continuous (packed columns) or intermittent (separation by means of equilibrium stages). In both cases it is essential to know the density and the rheological characteristics of the fluid phases in order to design the contactor. In a previous paper (González-Tello *et al.*, 1994) these properties were determined for different aqueous poly(ethylene glycol) (PEG) solutions of three average molecular weights (1000, 3350, and 8000), the concentrations of which were between 10 and 50 mass %. In all cases the PEG solutions show Newtonian behavior.

Empirical equations have been proposed to model the equilibrium results of traditional liquid−liquid extraction, the most used being those of Othmer and Tobias (eq 1) and Bancroft (eq 2) where w_{CA} is the mass fraction of H_2O in

$$\left(\frac{1 - w_{AA}}{w_{AA}}\right) = k_1\left(\frac{1 - w_{BB}}{w_{BB}}\right)^{k_2} \tag{1}$$

$$\frac{w_{CB}}{w_{BB}} = k\left(\frac{w_{CA}}{w_{AA}}\right)^{r} \tag{2}$$

the PEG-rich phase, w_{AA} is the weight fraction of PEG in the PEG-rich phase, w_{CB} is the mass fraction of H_2O in the $MgSO_4$-rich phase, w_{BB} is the mass fraction of Mg SO_4 in the $MgSO_4$-rich phase, and k_1, k_2, k, and r are parameters.

King *et al.* (1988) used the thermodynamic model involving the virial equation to predict the binodal curve in PEG + dextran + water and PEG + salt (KCl, KH_2PO_4, or K_2SO_4) + water systems and obtained a good fitting to the experimental results.

Currently, methods based on group-contribution models are used to determine activity coefficients of substances (UNIQUAC, UNIFAC), although sometimes it is difficult to find the values of the parameters required, which have then to be estimated. Gao et *al.* (1991) used the UNIQUAC and UNIFAC methods to reproduce the binodal curve of PEG + $(NH_4)_2SO_4$ + H_2O systems.

Materials and Methods

Materials. Milli-Q quality distilled water was used. Poly(ethylene glycol) (PEG) was provided by Sigma Chemical Co. and has three average molecular weights, 1000, 3350, and 8000, designed as PEG1000, PEG3350, and PEG8000. Ultrapure $MgSO_4{\cdot}7H_2O$ was provided by PANREAC (Spain).

Apparatus and Procedures. Binodal Curve. The binodal curve was obtained by adding a $MgSO_4{\cdot}7H_2O$ solution to a PEG solution until turbidity appeared, indicating the beginning of the formation of a two-phase system. This corresponds to a point on the so-called binodal curve. Although other methods have been proposed in the literature (King *et al.*, 1988; Pathak *et al.*, 1991; Eiteman and Gainer, 1990; Lei *et al.*, 1990; Hartounian and Sandler, 1991; Mukataka *et al.*, 1992; Park and Wang, 1991), our procedure seems to be simple and accurate.

The experimental device consisted of a jacketed cylindrical vessel (internal diameter, 5 cm; height, 10 cm), connected to a thermostated bath. The mixture was stirred mechanically and $MgSO_4{\cdot}7H_2O$ was added from a 10 cm^3 buret, with ±0.1 cm^3 accuracy.

PEG solutions of known concentrations and density (ρ) were used to obtain the binodal curve. After equilibration of the initial PEG + H_2O solution at 298 K, a $MgSO_4{\cdot}7H_2O$ solution of known concentration and density was added slowly from a buret until the appearance of turbidity. The composition of one point on the binodal curve could be calculated from the initial concentrations of PEG and the quantity of $MgSO_4{\cdot}7H_2O$ added.

Tie Lines. Solutions of PEG and $MgSO_4{\cdot}7H_2O$, at concentrations that form a mixture of a composition above the binodal curve, were prepared to obtain the tie lines. These solutions were put into 50 cm^3 decanters and

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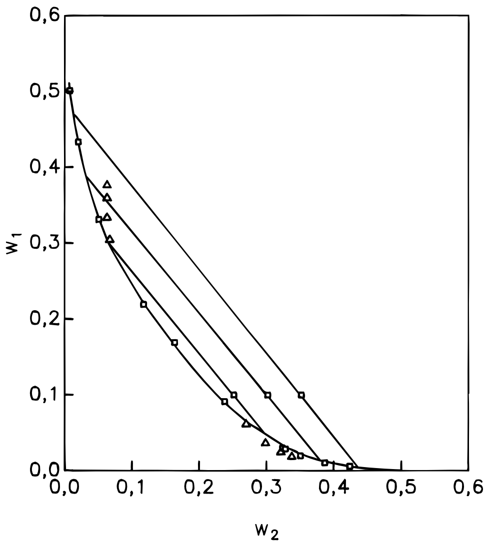

Figure 1. Plot of the binodal curve together with the tie lines for the PEG1000 + $MgSO_4 \cdot 7H_2O$ + H_2O system, at 298 K: (□) this paper; (△) Snyder *et al.* (1992).

Table 1. Binodal Curve Data of the PEG (1) + $MgSO_4 \cdot 7H_2O$ (2) + H_2O (3) Systems at Various Mass Fractions (*w*) of the Components at 298 K

PEG1000		PEG3350		PEG8000	
w_1	w_2	w_1	w_2	w_1	w_2
0.5012	0.0077	0.4617	0.0075	0.5206	0.0055
0.4334	0.0205	0.2446	0.0609	0.4066	0.0126
0.3314	0.0512	0.1467	0.1136	0.2477	0.0477
0.2192	0.1175	0.0698	0.1739	0.1946	0.0683
0.1691	0.1636	0.0277	0.2092	0.1461	0.0889
0.0912	0.2381	0.0319	0.2116	0.0969	0.1194
0.0300	0.3239	0.0296	0.2132	0.0563	0.1481
0.0287	0.3281	0.0158	0.2350	0.0240	0.1743
0.0197	0.3506	0.0095	0.2496	0.0242	0.1762
0.0106	0.3868	0.0041	0.2704	0.0109	0.1930
0.0059	0.4241			0.0044	0.2158
				0.0038	0.2164
				0.0020	0.2265
				0.0016	0.2298
				0.0008	0.2388
				0.0006	0.2514
				0.0005	0.2594

thermostated at 298 K. The time needed to reach a clear separation between phases never exceeded 48 h. After this time the phases were separated and the density, sulfate concentration, and viscosity (μ) of each phase were determined. Density and dynamic viscosity were measured using procedures described elsewhere (González-Tello *et al.*, 1994) and the sulfate concentration was determined using a turbidimetric method based on SO_4^{2-} precipitation in excess $CaCl_2$ and subsequent measurement of absorbance at 420 nm, as described in *Standard Methods for the Examination of Water and Wastewater* (1992). The PEG concentration was obtained by the binodal curve data obtained before.

Results and Discussion

Binodal Curves. The binodal curves of the three systems, PEG1000 + $MgSO_4$ + H_2O, PEG3350 + $MgSO_4$ + H_2O and PEG8000 + $MgSO_4$ + H_2O, are shown in Table 1 and are plotted in Figures 1−3, together with values to be found in the literature. Our experimental values are lower than those published by Snyder *et al.* (1992). The difference may be due to the distribution of the molecular mass in the PEG batches and its variation from the nominal value.

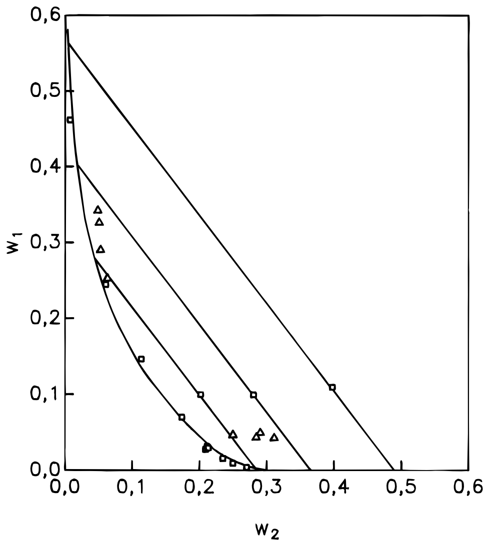

Figure 2. Plot of the binodal curve together with the tie lines for the PEG3350 + $MgSO_4 \cdot 7H_2O$ + H_2O system, at 298 K: (□) this paper; (△) Snyder *et al.* (1992).

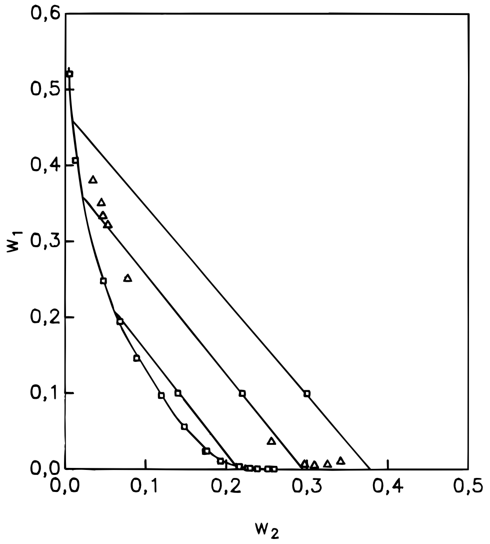

Figure 3. Plot of the binodal curve together with the tie lines for the PEG8000 + $MgSO_4 \cdot 7H_2O$ + H_2O system, at 298 K: (□) this paper; (△) Snyder *et al.* (1992).

Table 2. Constants of Eq 3 for Various Systems at 298 K unless Cited

	b	*a*	*c*
PEG1000 + $MgSO_4$[a]	−0.1588	−0.1874	0.0215
PEG3350 + $MgSO_4$	−0.2066	−0.1602	0.0069
PEG8000 + $MgSO_4$	−0.2333	−0.1592	0.0039
PEG1000 + $(NH_4)SO_4$[b]	−0.3534	−0.2472	0.0042
PEG1540 + $(NH_4)SO_4$	−0.3871	−0.2432	0.0040
PEG2000 + $(NH_4)SO_4$	−0.3443	−0.2035	−0.0100
PEG4000 + $(NH_4)SO_4$	−0.2742	−0.1334	−0.0350
PEG4000 + $FeSO_4$ (20 °C)[c]	−0.1138	−0.1475	0.0120
PEG4000 + Na_2SO_4 (20 °C)	−0.2713	−0.1485	−0.0100
PEG3350 + dextran T-70[d]	−0.0224	−0.0301	0.0005

[a] This paper. [b] Gao *et al.* (1991). [c] Pathak *et al.* (1991). [d] Diamond *et al.* (1989).

The binodal curves (Figures 1−3) were fitted by a logarithmic expression which relates the concentration of PEG (w_1) to the concentration of $MgSO_4 \cdot 7H_2O$ (w_2).

$$w_1 = a \ln(w_2 + c) + b \tag{3}$$

To obtain the parameters of eq 3 (*a*, *b*, and *c*) by

Table 3. Tie Lines for the PEG (1) + $MgSO_4 \cdot 7H_2O$ (2) + H_2O (3) Systems at Various Initial Mass Fractions of the Components at 298 K

initial.comp		top phase			bottom phase		
w_1	w_2	ρ/g·cm^{-3}	μ/mPa·s	w_2	ρ/g·cm^{-3}	μ/mPa·s	w_2
			PEG1000 (1) + $MgSO_4$ (2) + H_2O (3)				
0.0998	0.2511	1.0827	7.2037	0.0672	1.1674	3.4517	0.2661
0.0997	0.3011	1.0834	12.0254	0.0356	1.2077	4.2016	0.3808
0.0998	0.3510	1.0843	15.1037	0.0174	1.2428	5.1003	0.4349
			PEG3350 (1) + $MgSO_4$ (2) + H_2O (3)				
0.0998	0.2019	1.0663	15.5996	0.0509	1.1465	2.2046	0.2830
0.0993	0.2807	1.0706	31.3988	0.0153	1.1966	3.0224	0.3657
0.1095	0.3975	1.0784	74.9330	0.0043	1.2744	5.8356	0.4897
			PEG8000 (1) + $MgSO_4$ (2) + H_2O (3)				
0.1000	0.1400	1.0658	17.7774	0.0649	1.1057	1.7713	0.2124
0.1000	0.2200	1.0677	64.0164	0.0239	1.1540	2.1627	0.2951
0.1000	0.3000	1.0764	153.2471	0.0108	1.2058	2.9701	0.3788

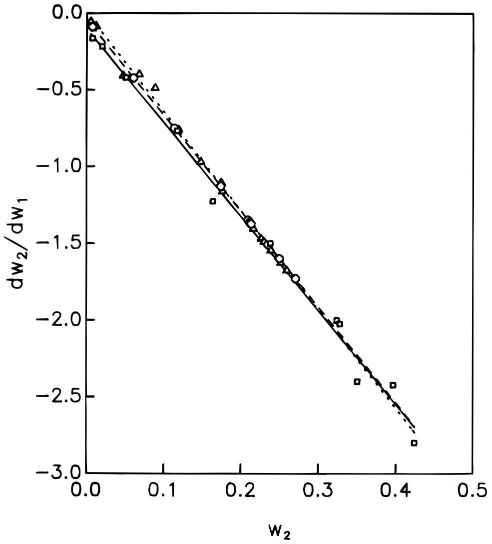

Figure 4. Plot of the inverse from the derivative (dw_2/dw_1) against $MgSO_4 \cdot 7H_2O$ concentration (w_2). (□) PEG1000; (○) PEG3350; (△) PEG8000.

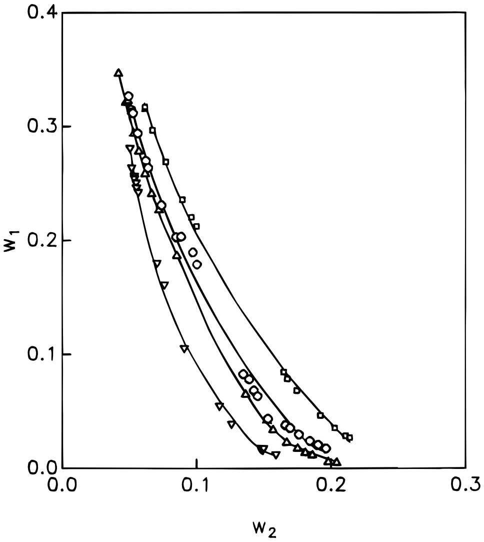

Figure 5. Plot of the experimental data together with those calculated by the eq 3 for three PEG + $(NH_4)_2SO_4$ + H_2O systems, collected in the literature, (Gao *et al.* (1991)): (□) PEG1000; (○) PEG1540; (△) PEG2000; (▽) PEG4000; (—) calculated data.

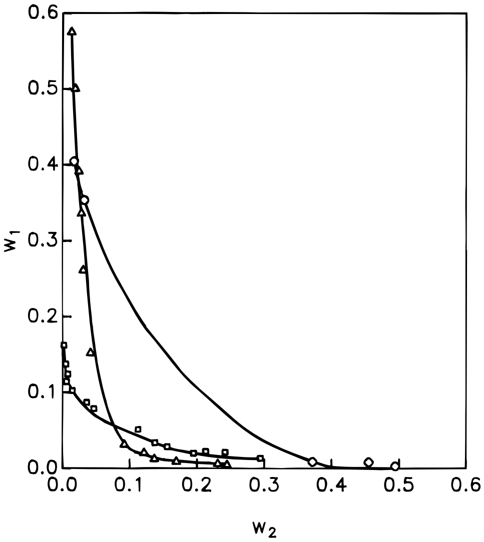

Figure 6. Plot of the experimental data together with those calculated by eq 3 for three systems, collected in the literature (Pathak *et al.* (1991); Diamond and Hsu (1989)). (□) PEG3350 + dextran T-70; (○) PEG4000 + $FeSO_4$ (20 °C); (△) PEG4000 + Na_2SO_4 (20 °C); (—) calculated data. w_2 is the dextran or salt mass fraction.

nonlinear regression, a previous estimation of these values is necessary.

From eq 3

$$\frac{dw_1}{dw_2} = \frac{a}{c + w_2} \tag{4}$$

Eq 4 can be transformed to

$$\frac{dw_2}{dw_1} = \frac{c}{a} + \frac{w_2}{a} \tag{5}$$

A plot of dw_2/dw_1 against w_2 will give a straight line (Figure 4) and thus the initial values of *a* and *c* can be calculated.

To obtain the slopes, dw_1/dw_2, the results were fitted to cubic-spline functions to give the slope at each point, with the condition that the variation of these must be continuous from one to the next.

Once the initial values of *a* and *c* are determined, *b* is estimated from eq 3. The nonlinear regression is started with these initial parameters and the results obtained for *a*, *b*, and *c* are shown in Table 2.

Our experimental data are reproduced with a maximum absolute deviation (MAD) of less than ±2%. Equation 3 was also used to fit the results of some aqueous two-phase systems found in the literature. When the treatment described above was used to fit the results published by Gao *et al.* (1991), Pathak *et al.* (1991), and Diamond *et al.* (1989), the values of the *a*, *b*, and *c* parameters shown in Table 2 were obtained. With these constants for eq 3, the

Table 4. Values of the Parameters of Eq 2

PEG	*k*	*r*	$R^{2\,a}$
1000	0.855	0.97	0.996
3350	0.316	1.15	0.991
8000	0.074	1.26	0.993

[a] Linear regression index.

results of these authors can be reproduced with a MAD of ±2% (Figures 5 and 6).

Tie Lines. The tie line compositions are given in Table 3 and are in Figures 1−3. Among the various literature expressions, the best fitting was obtained using eq 2, proposed by Bancroft. The values of *k* and *r* are given in Table 4.

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