Solubilities of Substituted Ferrocenes in Organic Solvents

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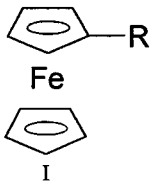
The solubilities of some ferrocenes (ferrocene, ferrocenylmethanol, and 1-ferrocenylethanol) in hexane, benzene, toluene, ethanol, 3-pentanone, and butyl methyl ether have been determined experimentally by a dynamic method at temperatures from (280 to 350) K. The results have been correlated by the Wilson and UNIQUAC equations. The average root-mean-square deviations of the solubility temperatures for all of the measured data vary from (0.4 to 4.5) K and depend on the particular system and equation.

Introduction

Ferrocenes have wide application in many fields: they are used in supramolecular chemistry, as magnetic materials and liquid crystals, in asymmetric catalysis,[1] and as oil additives.[2] Ferrocenyl compounds function as enzyme inhibitors and can act as cancer therapeutic agents.[3,4] The ferrocene molecule is a lipophilic one and can easily cross cellular membranes.[3] Recently, there has been a large increase in the number of papers dealing with solid−liquid equilibria (SLE) in new organic and organometallic systems. For substituted ferrocenes few SLE data have been reported.

The aim of the present work was to study the solubility of three selected ferrocenes (**I**) in a series of organic solvents to investigate the influence of the introduction of an organic group to ferrocene on solubility and to attempt a correlation of the experimental results with established theories of solutions.



I

R	Abbrev.
H	Fc
CH_2OH	$FcCH_2OH$
$CH(CH_3)OH$	$FcCH(CH_3)OH$

Experimental Section

Materials. Ferrocene was obtained from Aldrich and used without purification. Monosubstituted ferrocenes [ferrocenylmethanol ($FcCH_2OH$) and 1-ferrocenylethanol ($FcCH(CH_3)OH$)] were synthesized and purified as described by Misterkiewicz.[5,6] The solvents were dried over 4A molecular sieves and were fractionally distilled using a 10-plate laboratory column. Molar volumes of ferrocenes were calculated from density measurements according to a pycnometric method. Melting temperatures and enthalpies of fusion were determined by DSC (Perkin-Elmer Pyris 1). Uncertainties for these measurements were 0.1 K for melting temperature and 1% for enthalpy of fusion. The properties of the investigated ferrocenes are listed in Table 1.

Table 1. Characteristics of Ferrocenes

compound	V_m° [a]/(cm^3·mol^{-1})	$T_{m,1}$/K	$\Delta_{fus}H$/kJ·mol^{-1}
Fc	128.9	447.60	17.49
$FcCH_2OH$	156.1	351.38	23.82
$FcCH(CH_3)OH$	161.9	351.60	26.65

[a] V_m^{o} is the molar volume at 298.15 K.

Solubilities were determined according to a dynamic (synthetic) method, described by Domańska et al.[7] The reproducibility of the measurements was 0.1 K, which corresponded to a standard error in mole fraction δx_1 of 0.0005. All of the experimental data are shown in Tables 2−4.

Results and Discussion

The solubilities of each ferrocene in the solvents were lower than expected from ideal solution behavior, and the solution showed positive deviations from ideality ($\gamma_1 > 1$). All experimental activity coefficients are listed in Tables 2−4, and the SLE data are shown in comparison with the ideal solubility in Figures 1−3.

The introduction of the hydroxyalkyl group to ferrocene strongly influences the solubility, causing a decrease in the solubility in hexane, an increase in the solubility in aromatic solvents, and a large increase in the solubility in alcohol, ether, and ketone. Solubilities are similar for linear and branched alcohol groups (with the exception of hexane).

The solubility of a solid nonelectrolyte 1 in a liquid solvent can be approximated by

$$-\ln x_1 = \frac{\Delta_{fus}H}{R}\left(\frac{1}{T} - \frac{1}{T_{m1}}\right) + \ln \gamma_1 \qquad (1)$$

where x_1 is the mole fraction, γ_1 the activity coefficient, $\Delta_{fus}H$ the enthalpy of fusion, T_{m1} the melting temperature, and T the equilibrium temperature of the solute. Equation 1 is the simplified version of the solubility equation, missing the term containing ΔC_p because sufficiently accurate thermodynamic data are not available for fer-

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Table 2. Experimental Mole Fraction Solubilities and Activity Coefficients of Ferrocene

x_1	T_1/K	γ_1	x_1	T_1/K	γ_1
		Benzene			
0.0720	290.75	1.100	0.1005	307.55	1.170
0.0764	293.05	1.097	0.1063	310.35	1.177
0.0806	295.65	1.109	0.1130	313.95	1.197
0.0850	298.45	1.124	0.1214	318.85	1.235
0.0898	301.95	1.154	0.1311	324.35	1.279
0.0951	304.85	1.164			
		BuOMe			
0.0179	288.45	4.178	0.0404	319.15	3.732
0.0224	296.05	4.023	0.0479	326.35	3.645
0.0250	300.15	3.972	0.0562	332.45	3.491
0.0277	302.95	3.824	0.0646	338.05	3.376
0.0296	307.05	3.934	0.0715	343.05	3.342
0.0337	311.45	3.807	0.0755	345.05	3.277
		EtOH			
0.0045	291.05	17.583	0.0106	322.15	15.074
0.0051	295.15	17.477	0.0116	325.45	14.812
0.0056	299.05	17.203	0.0124	328.55	14.713
0.0063	303.65	17.157	0.0134	331.45	14.333
0.0070	307.45	16.792	0.0152	335.55	13.741
0.0078	311.35	16.353	0.0175	340.25	12.994
0.0088	315.55	15.990	0.0186	342.75	12.802
0.0096	318.05	15.295			
		Hexane			
0.0211	287.95	3.508	0.0458	327.15	3.874
0.0259	298.95	3.732	0.0476	329.15	3.871
0.0315	308.35	3.808	0.0491	331.55	3.934
0.0349	313.15	3.815	0.0510	333.15	3.902
0.0362	315.15	3.829	0.0528	335.15	3.913
0.0408	320.25	3.785	0.0544	336.75	3.912
0.0436	323.75	3.801	0.0579	339.35	3.857
		3-Pentanone			
0.0391	292.45	2.113	0.0882	327.05	2.006
0.0436	297.35	2.135	0.0910	329.45	2.038
0.0485	302.15	2.148	0.1123	339.35	1.989
0.0537	306.55	2.143	0.1243	345.15	1.994
0.0594	310.05	2.092	0.1363	350.65	2.000
0.0666	314.95	2.074	0.1625	360.95	1.992
0.0732	318.05	2.014	0.1625	360.95	1.992
0.0790	322.35	2.040			
		Toluene			
0.0682	282.95	0.952	0.1186	317.65	1.233
0.0782	292.55	1.059	0.1293	322.45	1.248
0.0857	299.75	1.148	0.1411	330.95	1.353
0.0941	305.85	1.203	0.1605	341.35	1.443
0.1014	309.75	1.218	0.1858	355.35	1.589
0.1101	313.35	1.213			

rocenes. Two methods were chosen to represent the solute activity coefficients (γ_1) from the so-called correlation equations describing the excess Gibbs free energy of mixing (G^E): the Wilson and the UNIQUAC equations. The exact mathematical forms of the equations are given in refs 8 and 9. On the basis of the results for similar systems, a modified version of the Wilson equation was applied.[10] The parameters of the equations were found by an optimization technique using the maximum neighborhood method for minimization

$$\Omega = \sum_{i=1}^{n} [T_i^{\text{exptl}} - T_i^{\text{calcd}}(x_1, P_1, P_2)]^2 \qquad (2)$$

where T_i^{exptl} denotes an experimental value of the temperature for a given concentration x_{1i}, T_i^{calcd} is the temperature calculated for a given concentration x_{1i}, and parameters P_1 and P_2 were obtained by solving the nonlinear eq 1 and the expression for the logarithm of the activity according to the assumed model. The nonlinear equations

Table 3. Experimental Mole Fraction Solubilities and Activity Coefficients of Ferrocenylmethanol

x_1	T_1/K	γ_1	x_1	T_1/K	γ_1
		Benzene			
0.0427	285.05	3.487	0.1269	303.95	2.191
0.0495	287.25	3.249	0.1406	305.15	2.053
0.0580	290.35	3.083	0.1494	306.45	2.010
0.0675	292.85	2.884	0.1629	307.95	1.930
0.0778	295.55	2.734	0.1796	309.85	1.853
0.0902	298.75	2.618	0.1998	312.45	1.799
0.1007	300.55	2.483	0.2223	315.25	1.754
0.1110	301.95	2.355	0.2518	318.95	1.721
0.1214	303.15	2.234			
		BuOMe			
0.0444	285.05	3.356	0.1088	308.05	2.899
0.0495	287.95	3.330	0.1138	309.25	2.873
0.0551	290.65	3.277	0.1206	310.95	2.851
0.0603	293.05	3.251	0.1274	312.35	2.812
0.0657	294.95	3.173	0.1360	314.15	2.776
0.0703	297.45	3.221	0.1429	315.35	2.736
0.0751	299.75	3.246	0.1515	316.95	2.702
0.0854	303.05	3.166	0.1622	318.35	2.626
0.0970	306.05	3.058			
		Hexane			
0.0015	286.95	107.510	0.0107	324.85	47.890
0.0025	299.35	95.482	0.0114	325.15	45.224
0.0026	300.95	99.284	0.0120	326.35	44.371
0.0032	304.95	89.361	0.0125	326.15	42.398
0.0035	306.85	86.127	0.0130	326.75	41.234
0.0038	307.65	81.120	0.0137	327.15	39.726
0.0045	310.65	75.736	0.0143	328.05	39.007
0.0051	313.15	72.215	0.0152	328.95	37.453
0.0052	313.15	70.413	0.0157	329.15	36.453
0.0059	315.35	65.941	0.0160	329.95	36.487
0.0065	316.65	62.929	0.0166	330.85	36.140
0.0069	317.95	61.308	0.0168	331.05	35.747
0.0075	319.15	58.171	0.0176	332.95	35.975
0.0082	321.15	56.052	0.0182	334.35	35.925
0.0091	322.75	53.214	0.0184	334.15	35.469
0.0098	323.65	50.472			
		EtOH			
0.0599	279.15	2.009	0.1991	305.25	1.454
0.0692	283.05	2.003	0.2112	306.35	1.418
0.0792	285.95	1.939	0.2195	307.05	1.394
0.0898	288.95	1.898	0.2346	309.05	1.385
0.1008	291.65	1.854	0.2522	310.35	1.339
0.1111	293.55	1.793	0.2607	311.15	1.327
0.1203	295.35	1.757	0.2736	312.15	1.302
0.1297	296.95	1.717	0.2859	313.25	1.287
0.1409	298.95	1.686	0.2978	314.15	1.268
0.1461	299.35	1.647	0.3121	314.85	1.235
0.1525	300.35	1.629	0.3288	315.35	1.189
0.1608	301.25	1.589	0.3464	317.15	1.189
0.1702	302.95	1.584	0.3644	318.95	1.189
0.1799	303.55	1.527	0.3807	320.15	1.177
0.1883	304.45	1.500	0.4049	322.25	1.173
		3-Pentanone			
0.0741	283.65	1.913	0.2743	313.95	1.369
0.0957	289.55	1.818	0.2945	315.45	1.332
0.1226	294.75	1.690	0.3091	316.85	1.320
0.1533	298.75	1.540	0.3314	318.15	1.278
0.1794	303.05	1.507	0.3561	319.95	1.251
0.2012	307.25	1.530	0.3813	321.45	1.219
0.2221	309.55	1.485	0.4130	324.25	1.215
0.2318	310.65	1.470	0.4596	328.35	1.219
0.2461	311.25	1.410	0.5086	330.85	1.177
0.2600	312.75	1.395			
		Toluene			
0.0416	297.15	5.387	0.2281	319.05	1.905
0.0708	302.75	3.783	0.2637	321.15	1.747
0.0888	306.25	3.362	0.3155	323.35	1.552
0.1121	309.15	2.908	0.3584	326.25	1.478
0.1349	312.45	2.664	0.4100	329.15	1.396
0.1616	314.35	2.351	0.4876	332.75	1.290
0.1939	316.65	2.093			

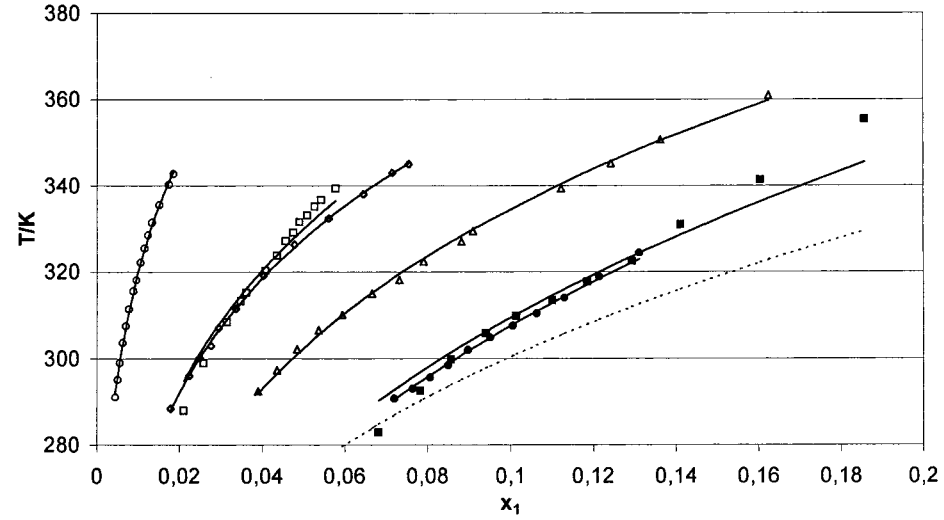

Figure 1. Solubility of ferrocene: □, in hexane; ●, in benzene; ■, in toluene; ○, in ethanol; △, in 3-pentanone; ◇, in *n*-butyl methyl ether. The dotted line represents the ideal solubility.

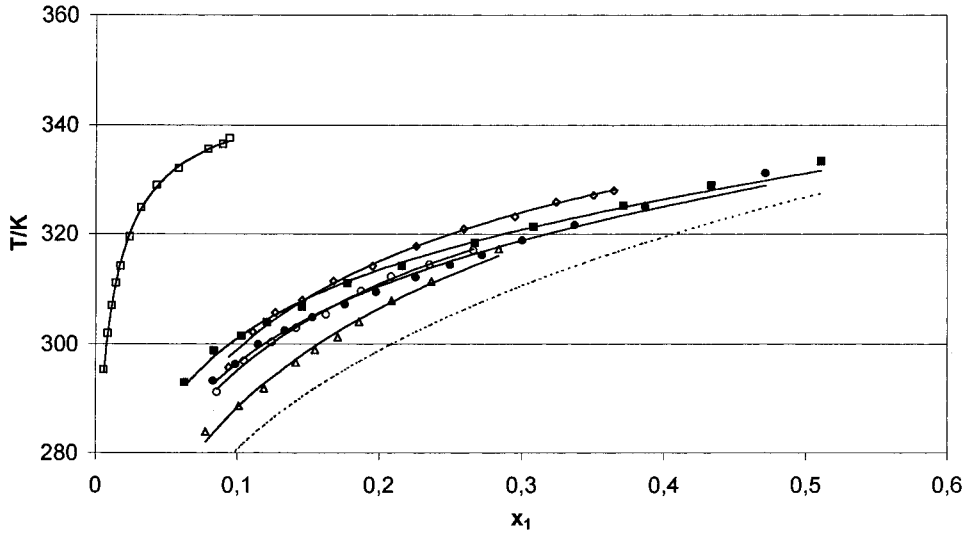

Figure 2. Solubility of ferrocenylmethanol: □, in hexane; ●, in benzene; ■, in toluene; ○, in ethanol; △, in 3-pentanone; ◇, in *n*-butyl methyl ether. The dotted line represents the ideal solubility.

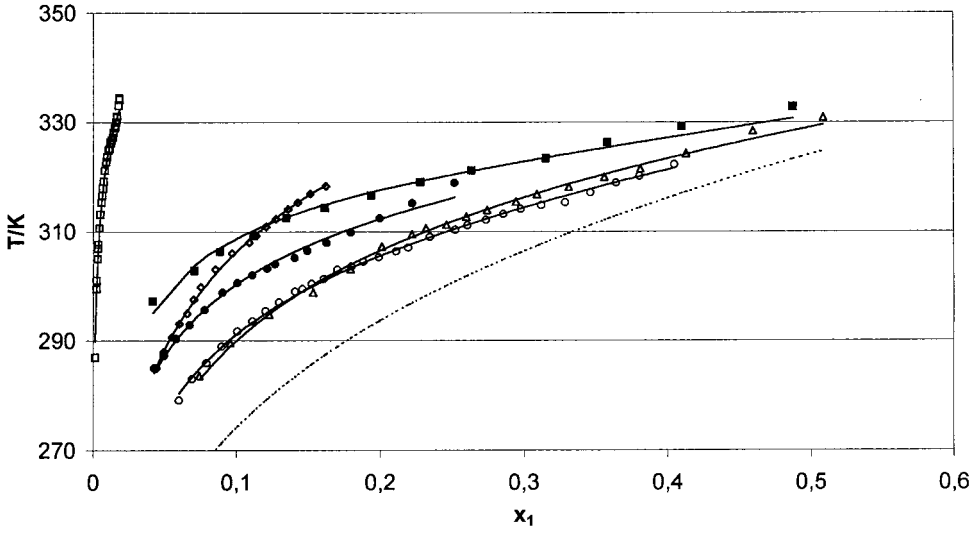

Figure 3. Solubility of 1-ferrocenylethanol: □, in hexane; ●, benzene; ■, in toluene; ○, in ethanol; △, in 3-pentanone; ◇, in *n*-butyl methyl ether. The dotted line represents the ideal solubility.

Table 4. Experimental Mole Fraction Solubilities and Activity Coefficients of 1-Ferrocenylethanol

x_1	T_1/K	γ_1	x_1	T_1/K	γ_1
		Benzene			
0.0830	293.25	1.965	0.2257	312.15	1.400
0.0986	296.35	1.854	0.2500	314.35	1.359
0.1148	299.95	1.813	0.2721	316.15	1.323
0.1335	302.45	1.704	0.3006	318.85	1.304
0.1531	304.85	1.614	0.3375	321.65	1.268
0.1758	307.25	1.526	0.3869	325.05	1.228
0.1979	309.45	1.460	0.4718	331.15	1.207
		BuOMe			
0.0940	295.75	1.904	0.2261	317.75	1.675
0.1110	302.15	2.027	0.2596	320.95	1.613
0.1267	305.75	2.011	0.2955	323.15	1.517
0.1456	307.95	1.887	0.3246	325.85	1.499
0.1679	311.45	1.839	0.3507	327.05	1.439
0.1954	314.15	1.726	0.3649	327.95	1.420
		EtOH			
0.0858	291.15	1.756	0.1872	309.65	1.554
0.1047	296.95	1.785	0.2082	312.25	1.523
0.1242	300.35	1.700	0.2353	314.45	1.448
0.1414	302.95	1.637	0.2660	317.05	1.393
0.1626	305.35	1.546			
		Hexane			
0.0059	295.25	29.609	0.0322	324.85	14.650
0.0086	301.95	25.978	0.0431	328.95	12.400
0.0113	306.95	23.420	0.0586	332.05	9.988
0.0143	311.05	21.253	0.0794	335.55	8.141
0.0175	314.15	19.236	0.0897	336.45	7.395
0.0241	319.45	16.568	0.0944	337.55	7.254
		3-Pentanone			
0.0778	283.85	1.459	0.1707	301.25	1.277
0.1011	288.55	1.350	0.1858	304.05	1.294
0.1190	291.85	1.300	0.2086	307.85	1.312
0.1412	296.65	1.309	0.2366	311.35	1.301
0.1548	298.95	1.297	0.2840	317.25	1.313
		Toluene			
0.0630	292.95	2.558	0.2672	318.35	1.445
0.0837	298.75	2.381	0.3086	321.35	1.374
0.1030	301.45	2.132	0.3717	325.15	1.282
0.1210	303.95	1.981	0.4336	328.95	1.231
0.1458	306.75	1.809	0.5109	333.35	1.189
0.1778	311.05	1.714			
0.2162	314.15	1.561			

Table 5. Analyses of the Solubility Data of Ferrocenes by the Wilson Equation: Values of the Parameters and Measures of Deviations

	solvent					
	benzene	BuOMe	EtOH	hexane	3-pentanone	toluene
			Ferrocene			
σ/K	0.59	0.47	0.63	2.90	0.93	4.54
$10^{-3}\,a_{12}$/(kJ·mol^{-1})	−3.1162	1.1076	2.9050	1.2085	−0.9272	−2.5600
$10^{-3}\,a_{21}$/(kJ·mol^{-1})	113.5473	6.4138	10.8449	114.3930	7.9817	125.6193
			Ferrocenylmethanol			
σ/K	0.92	0.42	0.99	0.50	0.74	1.14
$10^{-3}\,a_{12}$/(kJ·mol^{-1})	2.1677	0.3234	9.3327	0.3372	0.4448	3.9287
$10^{-3}\,a_{21}$/(kJ·mol^{-1})	1.3092	6.2104	5.7239	1.8969	1.3704	1.1053
			1-Ferrocenylethanol			
σ/K	0.84	0.74	0.50	0.37	0.92	0.83
$10^{-3}\,a_{12}$/(kJ·mol^{-1})	0.9433	−0.0331	−1.4395	6.1826	−1.7359	2.0771
$10^{-3}\,a_{21}$/(kJ·mol^{-1})	1.2091	2.7437	3.2815	4.5501	3.4555	0.8212

were solved using the secant method. The root-mean-square deviation of the temperatures defined by eq 3 was used as a measure of the goodness of fit

$$\sigma = \left[\sum_{i=1}^{n} \frac{(T_i^{\text{exptl}} - T_i^{\text{calcd}})^2}{(n-l)}\right]^{1/2} \tag{3}$$

where n is the number of experimental points (including the melting point) and l is the number of adjustable parameters.

The Wilson equation has been tested with a parameter Λ_{ij} in the form

$$\Lambda_{12} = (V_2/V_1)\exp[-(g_{12} - g_{11})/RT]$$

$$\Lambda_{21} = (V_1/V_2)\exp[-(g_{12} - g_{22})/RT] \tag{4}$$

Table 6. Analyses of the Solubility Data of Ferrocenes by the UNIQUAC Equation: Values of the Parameters and Measures of Deviations

	solvent					
	benzene	BuOMe	EtOH	hexane	3-pentanone	toluene
			Ferrocene			
σ/K	0.54	0.47	0.65	2.98	1.06	1.79
Δg_{12}/(J·mol^{-1})	4420.40	2258.33	4633.30	3808.56	3154.02	7084.58
Δg_{21}/(J·mol^{-1})	−1944.77	−334.43	501.48	−832.69	−1177.10	−2297.57
			Ferrocenylmethanol			
σ/K	0.98	0.41	1.21	0.49	0.75	1.51
Δg_{12}/(J·mol^{-1})	354.38	2333.29	−2075.24	1125.19	586.14	−268.86
Δg_{21}/(J·mol^{-1})	718.74	−646.29	6443.37	27.31	−18.86	1609.16
			1-Ferrocenylethanol			
σ/K	0.85	0.73	0.50	0.63	0.95	0.89
Δg_{12}/(J·mol^{-1})	680.08	1445.41	2216.36	−776.67	1817.86	−262.77
Δg_{21}/(J·mol^{-1})	100.29	−544.58	−652.77	3138.94	−1033.53	1047.45

where

$$(g_{12} - g_{11}) = a_{12}/T; \qquad a_{12} \neq f(T)$$

$$(g_{12} - g_{22}) = a_{21}/T; \qquad a_{21} \neq f(T) \qquad (5)$$

V_2 and V_1 are the molar volumes of pure solute and solvent in the liquid phase, respectively, g_{ij} is the molar energy of interaction between the i and j components, and a_{ij} is the binary interaction parameter.

The pure component structural parameters r (volume parameter) and q (surface parameter) in UNIQUAC were obtained in accordance with the methods suggested by Vera et al.[11] and relationships from Hofman and Nagata.[12]

Table 5 lists the results of fitting the solubility curves by the Wilson equation and Table 6 those by the UNIQUAC equation.

Better approximation was obtained with the UNIQUAC equation (root-mean-square deviations do not exceed 1.8 K) in comparison with the Wilson equation.

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