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Viscosities and Densities for Binary Mixtures of Anisole with 1-Butanol, 1-Pentanol, 1-Hexanol, 1-Heptanol, and 1-Octanol

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Densities and viscosities were measured for anisole + 1-butanol, + 1-pentanol, + 1-hexanol, + 1-heptanol, and + 1-octanol at 303.15 K, 313.15 K, and 323.15 K. The excess volumes and viscosity deviations from the mole fraction average were calculated and correlated by a Redlich−Kister type equation. While the excess volumes of anisole + 1-butanol are negative, those of the remaining binary mixtures are positive. The viscosity deviations are negative for all systems.

Introduction

Density and viscosity are important properties for thermodynamic model development and engineering applications. In the present study, density and viscosity were measured for the binary mixtures of anisole + 1-butanol, + 1-pentanol, + 1-hexanol, + 1-heptanol, and + 1-octanol at temperatures ranging from 303.15 K to 323.15 K and at atmospheric pressure. The excess volumes (V^{E}) and the viscosity deviations ($\delta\eta$) from the mole fraction average were calculated from the results of measurements. The variations of both excess volume and viscosity deviation with the molecular size of 1-alkanols were investigated. Although the density and viscosity data of the pure components (anisole and 1-alkanols) are available in the literature (Vijayalakshmi and Naidu, 1992; Joshi et al., 1990a,b; Aminabhavi et al., 1990; Singh et al., 1990; TRC, 1994; Hales and Ellender, 1976; Lee et al., 1997; Matsuo and Makita, 1989; Choudary and Kudchadker, 1992; Yu and Tsai, 1994; Sastry and Valand, 1996), no experimental data are to be found for the mixtures at the comparable conditions of this study.

Experimental Section

Anisole, 1-butanol, and 1-pentanol were R.D.H products, 1-hexanol is a Fluka chemical, and 1-heptanol and 1-octanol were supplied from E. Merck and Aldrich Chemical Co., respectively. The purities of these substances are better than 99 mass %. According to gas chromatographic analysis, the impurity is less than 1%. All reagents were used without further purification. The measured densities and viscosities of all the pure components at 303.15 K were compared with the literature values, and the result is presented in Table 1.

Table 1. Experimental Results for Pure Components at 303.15 K

	ρ/g·cm^{-3}		η/mPa·s	
compound	this work	lit.	this work	lit.
anisole	0.9843	0.9846[a]	0.908	0.9315[a] 0.9070[e]
1-butanol	0.8024	0.8022[b] 0.8025[c]	2.261	2.263[b]
1-pentanol	0.8072	0.8079[b] 0.8071[d]	3.056	3.054[b]
1-hexanol	0.8115	0.8127[b] 0.81205[c]	3.861	3.769[b] 3.90[f] 3.84[g] 3.765[h]
1-heptanol	0.8153	0.8148[b] 0.81572[c]	5.035	5.005[b]
1-octanol	0.8181	0.8184[b] 0.82184[c]	6.256	6.01[f] 6.24[g] 6.298[h]

[a] Joshi et al. (1990a). [b] TRC Thermodynamic Tables (1994). [c] Vijayalakshmi and Naidu (1992). [d] Hales and Ellender (1976). [e] Joshi et al. (1990b). [f] Matsuo and Makita (1989). [g] Lee et al. (1997). [h] Singh et al. (1990).

An Anton Paar densimeter (DMA 60/602H) was employed to measure density (ρ). Each sample mixture was prepared by mass with an accuracy of ±0.0001 in mole fraction. The temperature of the measuring cell in the densimeter was controlled to within ±0.03 K by circulation of thermostated water. A precision digital thermometer (model 1560, Hart Scientific) with a thermistor probe was used to read the cell temperature to an accuracy of ±0.015 K. The oscillation period (t) in the vibrating U-tube of the densimeter was converted to density using the following equation

$$\rho = A(\tau^2 - B) \qquad (1)$$

where A and B are apparatus constants determined by using the literature density data of pure water (Harr et al., 1984) and of dry air (Vargaftik, 1975) at temperatures of interest. The uncertainty of the density measurements is estimated to be less than $\pm 1 \times 10^{-4}$ g/cm^3.

Viscosities of each sample were measured by using Cannon-Fenske viscometers, size 50 and 75, with flow ranges of 0.8−4 and 1.6−8 cSt, respectively, supplied by Cannon Instrument Co. The viscometer was placed in a

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Table 2. Experimental Density and Viscosity for Anisole (1) + 1-Butanol (2)

x_1	ρ_m/ g·cm^{-3}	V^E/ cm^3·mol^{-1}	η_m/ mPa·s	$\delta\eta$/ mPa·s
		$T = 303.15$ K		
0.0000	0.8024	0.000	2.261	0.000
0.1002	0.8245	−0.094	1.874	−0.252
0.2000	0.8450	−0.103	1.523	−0.467
0.3001	0.8648	−0.109	1.359	−0.496
0.3998	0.8839	−0.123	1.197	−0.523
0.5000	0.9021	−0.099	1.079	−0.506
0.6002	0.9197	−0.078	1.001	−0.448
0.7000	0.9367	−0.065	0.952	−0.362
0.8003	0.9531	−0.039	0.929	−0.249
0.9000	0.9691	−0.038	0.914	−0.129
1.0000	0.9843	0.000	0.908	0.000
		$T = 313.15$ K		
0.0000	0.7947	0.000	1.765	0.000
0.1002	0.8164	−0.073	1.480	−0.187
0.2000	0.8368	−0.093	1.254	−0.315
0.3001	0.8564	−0.097	1.075	−0.396
0.3998	0.8753	−0.108	0.975	−0.398
0.5000	0.8934	−0.092	0.889	−0.387
0.6002	0.9109	−0.079	0.851	−0.327
0.7000	0.9276	−0.049	0.805	−0.275
0.8003	0.9439	−0.029	0.788	−0.194
0.9000	0.9597	−0.022	0.772	−0.112
1.0000	0.9749	0.000	0.786	0.000
		$T = 323.15$ K		
0.0000	0.7852	0.000	1.393	0.000
0.1002	0.8065	−0.054	1.165	−0.158
0.2000	0.8267	−0.076	0.989	−0.264
0.3001	0.8462	−0.094	0.899	−0.283
0.3998	0.8646	−0.070	0.806	−0.306
0.5000	0.8825	−0.053	0.750	−0.292
0.6002	0.8999	−0.049	0.734	−0.238
0.7000	0.9166	−0.040	0.721	−0.181
0.8003	0.9327	−0.015	0.709	−0.122
0.9000	0.9483	−0.004	0.698	−0.063
1.0000	0.9635	0.000	0.691	0.000

Table 3. Experimental Density and Viscosity for Anisole (1) + 1-Pentanol (2)

x_1	ρ_m/ g·cm^{-3}	V^E/ cm^3·mol^{-1}	η_m/ mPa·s	$\delta\eta$/ mPa·s
		$T = 303.15$ K		
0.0000	0.8072	0.000	3.056	0.000
0.1000	0.8246	0.048	2.369	−0.472
0.1998	0.8424	0.053	1.911	−0.715
0.3002	0.8601	0.062	1.658	−0.754
0.4001	0.8777	0.077	1.447	−0.750
0.5000	0.8956	0.051	1.260	−0.722
0.6002	0.9134	0.042	1.109	−0.658
0.6999	0.9312	0.021	1.046	−0.506
0.8001	0.9489	0.019	0.952	−0.386
0.9000	0.9666	0.010	0.914	−0.209
1.0000	0.9843	0.000	0.908	0.000
		$T = 313.15$ K		
0.0000	0.7997	0.000	2.361	0.000
0.1000	0.8170	0.046	1.841	−0.363
0.1998	0.8345	0.050	1.522	−0.524
0.3002	0.8520	0.068	1.326	−0.563
0.4001	0.8694	0.084	1.173	−0.558
0.5000	0.8871	0.069	1.022	−0.552
0.6002	0.9046	0.064	0.929	−0.487
0.6999	0.9222	0.042	0.862	−0.397
0.8001	0.9397	0.041	0.814	−0.287
0.9000	0.9573	0.021	0.791	−0.152
1.0000	0.9749	0.000	0.786	0.000
		$T = 323.15$ K		
0.0000	0.7905	0.000	1.765	0.000
0.1000	0.8073	0.083	1.403	−0.255
0.1998	0.8245	0.113	1.172	−0.378
0.3002	0.8416	0.394	1.062	−0.381
0.4001	0.8589	0.559	0.953	−0.382
0.5000	0.8763	0.635	0.853	−0.375
0.6002	0.8935	0.670	0.792	−0.328
0.6998	0.9110	0.590	0.745	−0.268
0.8001	0.9283	0.480	0.708	−0.178
0.9000	0.9458	0.279	0.696	−0.102
1.0000	0.9635	0.000	0.691	0.000

thermostated water bath (TV-4000, TAMSON) with temperature regulated within ±0.01 K. An electronic stop watch was used to measure flow times. Triplicate or more measurements of flow times were reproducible within 0.2% or less. The kinematic viscosities, ν, in cSt were obtained from the relation

$$\nu = kt \tag{2}$$

where k/cSt.s^{-1} is the capillary constant of viscometer and t/s is the flow time. The viscometer was calibrated with double-distilled water at all working temperatures, and the averages of 10 calculated k values was used in the calculations, which did not differ by more than ±0.001. The estimated deviation in viscosity was within ±1.0%, and the values of absolute viscosities, η, in cP were calculated by using the relation $\eta = \rho\nu$.

Results and Discussion

The densities and viscosities of the pure components are reported in Table 1. The results are in good agreement with the literature values. The experimental density, viscosity, excess volume, and the viscosity deviation from the mole fraction average for the binary systems of anisole + 1-butanol, + 1-pentanol, + 1-hexanol, + 1-heptanol, and + 1-octanol are given in Tables 2−6, respectively. The tabulated excess volume and viscosity deviation were calculated respectively by

$$V^E = V_m - (x_1V_1 + x_2V_2) \tag{3}$$

$$\delta\eta = \eta_m - (x_1\eta_1 + x_2\eta_2) \tag{4}$$

where x_i, V_i, and η_i are the mole fraction, molar volume, and viscosity of the pure component i, respectively. The subscript m represents mixture properties. The composition dependence of either V^E or $\delta\eta$ isotherm was represented by a Redlich−Kister type equation (Redlich and Kister, 1984)

$$Y = x_1x_2\sum_{i=0}^{p} a_i\,(x_1 - x_2)^i \tag{5}$$

where Y refers to V^E/cm^3·mol^{-1} or $\delta\eta$/mPa·s and x_1 and x_2 are the mole fractions of anisole and 1-alkanol, respectively. The variables a_i are the equation coefficients, which were obtained by fitting the equation to the experimental results with a least-squares regression method. The correlated results are given in Tables 7 and 8, in which the tabulated standard deviation (σ) was defined as

$$\sigma = \left[\frac{\sum(Y_{exp} - Y_{cal})^2}{n - p}\right]^{1/2} \tag{6}$$

where n is the number of data points and p is the number of coefficients. The subscript of cal denotes the correlated value.

The variation of the excess volumes and the viscosity deviations varying with the mole fraction of anisole for the investigated binary mixtures at 313.15 K are presented in

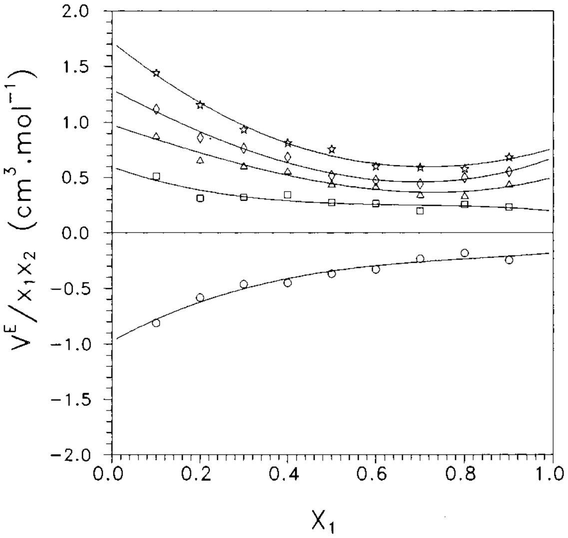

Figure 1. Excess volumes (V^E) of anisole (1) + 1-alkanol (2) at 313.15 K: (○) anisole + 1-butanol; (□) anisole + 1-pentanol; (△) anisole + 1-hexanol; (◇) anisole + 1-heptanol; (☆) anisole + 1-octanol; (—) calculated from eq 5.

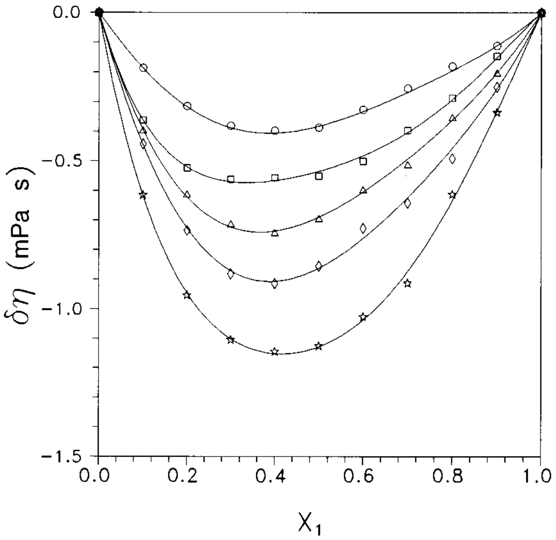

Figure 2. Viscosity deviations ($\delta\eta$) of anisole (1) + 1-alkanol (2) at 313.15 K: (○) anisole + 1-butanol; (□) anisole + 1-pentanol; (△) anisole + 1-hexanol; (◇) anisole + 1-heptanol; (☆) anisole + 1-octanol; (—) calculated from eq 5.

Table 4. Experimental Density and Viscosity for Anisole (1) + 1-Hexanol (2)

x_1	ρ_m/ g·cm^{-3}	V^E/ cm^3·mol^{-1}	η_m/ mPa·s	$\delta\eta$/ mPa·s
		T = 303.15 K		
0.0000	0.8115	0.000	3.861	0.000
0.0998	0.8264	0.051	3.055	−0.511
0.2000	0.8419	0.079	2.413	−0.857
0.3002	0.8579	0.094	1.969	−1.006
0.4000	0.8743	0.102	1.661	−1.019
0.5000	0.8914	0.082	1.423	−0.962
0.6002	0.9089	0.076	1.270	−0.819
0.6997	0.9270	0.041	1.097	−0.698
0.8001	0.9455	0.040	1.009	−0.490
0.9000	0.9646	0.021	0.927	−0.276
1.0000	0.9843	0.000	0.908	0.000
		T = 313.15 K		
0.0000	0.8043	0.000	2.936	0.000
0.0998	0.8188	0.079	2.325	−0.396
0.2000	0.8342	0.106	1.886	−0.620
0.3002	0.8499	0.128	1.569	−0.722
0.4000	0.8661	0.138	1.334	−0.742
0.5000	0.8830	0.111	1.166	−0.695
0.6002	0.9003	0.101	1.049	−0.597
0.6997	0.9181	0.073	0.932	−0.499
0.8001	0.9365	0.054	0.858	−0.358
0.9000	0.9553	0.040	0.798	−0.203
1.0000	0.9749	0.000	0.786	0.000
		T = 323.15 K		
0.0000	0.7953	0.000	2.248	0.000
0.0998	0.8094	0.118	1.798	−0.294
0.2000	0.8245	0.144	1.481	−0.456
0.3002	0.8399	0.184	1.248	−0.533
0.4000	0.8556	0.229	1.107	−0.518
0.5000	0.8723	0.196	0.966	−0.504
0.6002	0.8895	0.164	0.878	−0.436
0.6997	0.9071	0.128	0.786	−0.373
0.8001	0.9252	0.111	0.744	−0.258
0.9000	0.9439	0.074	0.699	−0.148
1.0000	0.9635	0.000	0.691	0.000

Table 5. Experimental Density and Viscosity for Anisole (1) + 1-Heptanol (2)

x_1	ρ_m/ g·cm^{-3}	V^E/ cm^3·mol^{-1}	η_m/ mPa·s	$\delta\eta$/ mPa·s
		T = 303.15 K		
0.0000	0.8153	0.000	5.035	0.000
0.1002	0.8282	0.077	3.922	−0.700
0.1999	0.8420	0.096	3.023	−1.187
0.3000	0.8565	0.119	2.457	−1.340
0.4003	0.8717	0.151	1.996	−1.387
0.5000	0.8881	0.109	1.701	−1.231
0.6000	0.9052	0.098	1.448	−1.111
0.7002	0.9233	0.084	1.213	−0.933
0.8002	0.9424	0.068	1.072	−0.661
0.9001	0.9627	0.039	0.969	−0.352
1.0000	0.9843	0.000	0.908	0.000
		T = 313.15 K		
0.0000	0.8082	0.000	3.671	0.000
0.1002	0.8208	0.101	2.940	−0.443
0.1999	0.8343	0.138	2.359	−0.735
0.3000	0.8486	0.161	1.932	−0.874
0.4003	0.8637	0.165	1.611	−0.905
0.5000	0.8799	0.130	1.373	−0.855
0.6000	0.8968	0.114	1.212	−0.728
0.7002	0.9147	0.093	1.010	−0.642
0.8002	0.9335	0.080	0.892	−0.470
0.9001	0.9535	0.051	0.824	−0.251
1.0000	0.9749	0.000	0.786	0.000
		T = 323.15 K		
0.0000	0.7994	0.000	2.741	0.000
0.1002	0.8115	0.156	2.245	−0.291
0.1999	0.8249	0.174	1.812	−0.519
0.3000	0.8389	0.210	1.554	−0.572
0.4003	0.8532	0.311	1.292	−0.629
0.5000	0.8694	0.222	1.161	−0.555
0.6000	0.8862	0.179	0.998	−0.513
0.7002	0.9038	0.157	0.864	−0.442
0.8002	0.9223	0.142	0.768	−0.332
0.9001	0.9421	0.095	0.714	−0.182
1.0000	0.9635	0.000	0.691	0.000

Figures 1 and 2, respectively. Figure 1 shows that the excess volumes of anisole + 1-butanol are negative. However, those of the other mixtures are positive, and their excess volumes increase with the increase of chain length of 1-alkanols. It means that volume contraction occurs by adding anisole into 1-butanol and volume expansion by blending anisole with a heavier 1-alkanol. The expansion effects are intensified with the molecular size of the 1-alkanol components. Figure 2 illustrates that the viscosity deviations are negative for all investigated systems. The absolute value of the deviations increase with increasing chain length of 1-alkanols.

Table 6. Experimental Density and Viscosity for Anisole (1) + 1-Octanol (2)

x_1	ρ_m/ g·cm^{-3}	V^E/ cm^3·mol^{-1}	η_m/ mPa·s	$\delta\eta$/ mPa·s
		T = 303.15 K		
0.0000	0.8181	0.000	6.256	0.000
0.1001	0.8294	0.102	4.860	−0.861
0.2000	0.8419	0.116	3.795	−1.389
0.3002	0.8551	0.163	3.074	−1.578
0.3998	0.8692	0.199	2.432	−1.685
0.5000	0.8849	0.162	1.966	−1.616
0.6002	0.9017	0.140	1.576	−1.471
0.7001	0.9199	0.102	1.217	−1.335
0.8002	0.9395	0.082	1.108	−0.864
0.9000	0.9608	0.054	0.968	−0.475
1.0000	0.9843	0.000	0.908	0.000
		T = 313.15 K		
0.0000	0.8111	0.000	4.584	0.000
0.1001	0.8221	0.130	3.589	−0.615
0.2000	0.8342	0.185	2.872	−0.952
0.3002	0.8474	0.197	2.342	−1.103
0.3998	0.8615	0.196	1.922	−1.143
0.5000	0.8768	0.190	0.561	−1.125
0.6002	0.8935	0.145	1.280	−1.025
0.7001	0.9113	0.125	1.014	−0.911
0.8002	0.9307	0.093	0.934	−0.612
0.9000	0.9517	0.062	0.831	−0.335
1.0000	0.9749	0.000	0.786	0.000
		T = 323.15 K		
0.0000	0.8023	0.000	3.361	0.000
0.1001	0.8130	0.157	2.702	−0.392
0.2000	0.8250	0.195	2.163	−0.664
0.3002	0.8378	0.242	1.863	−0.697
0.3998	0.8514	0.290	1.547	−0.746
0.5000	0.8667	0.237	1.288	−0.738
0.6002	0.8830	0.210	1.054	−0.705
0.7001	0.9006	0.175	0.843	−0.649
0.8002	0.9196	0.151	0.789	−0.436
0.9000	0.9403	0.110	0.725	−0.233
1.0000	0.9635	0.000	0.691	0.000

Table 7. Correlated Results for Excess Volumes (V^E)

mixture (1) + (2)	T/K	a_0	a_1	a_2	a_3	$\sigma \times 10^3$ cm^3·mol^{-1}
anisole + 1-butanol	303.15	−0.3544	1.2309	0.5416	−1.2563	0.269
	313.15	−0.3479	0.2033	−0.2255	0.2786	0.183
	323.15	−0.2211	0.2627	−0.3282	0.1461	0.245
anisole + 1-pentanol	303.15	0.1748	−0.1259	0.1561	−0.1398	0.164
	313.15	0.2978	−1.7547	0.1662	−0.0351	0.166
	323.15	0.5221	−0.0844	0.3161	−0.2061	0.180
anisole + 1-hexanol	303.15	0.3098	−0.2236	0.2065	0.0042	0.144
	313.15	0.4221	−0.2199	0.3218	−0.0586	0.180
	323.15	0.7198	−0.2929	0.4836	−0.1003	0.401
anisole + 1-heptanol	303.15	0.4430	−0.2946	0.2511	0.1266	0.211
	313.15	0.5543	−0.4593	0.4058	0.2063	0.116
	323.15	0.8331	−0.4581	0.6480	0.1754	0.519
anisole + 1-octanol	303.15	0.6121	−0.3425	0.2309	0.1091	0.303
	313.15	0.6822	−0.4792	0.6668	0.0857	0.182
	323.15	0.9195	−0.4676	0.7414	0.1869	0.354

Table 8. Correlated Results for Viscosity Deviations ($\delta\eta$)

mixture (1) + (2)	T/K	a_0	a_1	a_2	a_3	$\sigma \times 10^2$ mPa·s
anisole + 1-butanol	303.15	−2.0383	1.0050	−0.2169	−0.1684	0.238
	313.15	−1.5311	0.7799	−0.2019	−0.4031	0.022
	323.15	−1.1242	0.6959	−0.1644	−0.0439	0.047
anisole + 1-pentanol	303.15	−2.8512	1.3312	−1.4757	0.8214	0.193
	313.15	−2.1409	0.8387	−1.1157	0.9778	0.051
	323.15	−1.4549	0.6162	−0.8436	0.7149	0.057
anisole + 1-hexanol	303.15	−3.8569	2.0683	−0.8595	−0.6591	0.124
	313.15	−2.7613	1.3854	0.8707	−0.0718	0.016
	323.15	−1.9955	0.9513	−0.7158	0.1205	0.044
anisole + 1-heptanol	303.15	−5.1960	2.7463	−1.1606	−0.4562	0.398
	313.15	−3.4481	1.5223	−0.7008	−0.3178	0.185
	323.15	−2.3395	1.0155	−0.5549	−0.3766	0.261
anisole + 1-octanol	303.15	−6.5420	1.9586	−1.4147	1.2414	0.620
	313.15	−4.5120	1.1447	−1.1842	1.3111	0.227
	323.15	−3.0348	0.4884	−0.7974	1.0784	0.545

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