Densities, Viscosities, Refractive Indexes, and Surface Tensions for Binary Mixtures of 2-Propanol + Benzyl Alcohol, + 2-Phenylethanol and Benzyl Alcohol + 2-Phenylethanol at T = (298.15, 308.15, and 318.15) K

Ching-Ta Yeh and Chein-Hsiun Tu*

Department of Applied Chemistry, Providence University, Shalu 43301, Taiwan

Densities, viscosities, refractive indexes, and surface tensions for three binary systems (2-propanol + benzyl alcohol, 2-propanol + 2-phenylethanol, and benzyl alcohol + 2-phenylethanol) were measured at T = (298.15, 308.15, and 318.15) K over the whole composition range at atmospheric pressure. Densities were determined using a vibrating-tube density meter. Viscosities were measured with an automatic Ubbelholde capillary viscometer. Refractive indexes were measured using a digital Abbe-type refractometer. Surface tensions were determined by the Wilhelmy-plate method. These results are used to calculate excess molar volumes, V_m^E, deviations in the viscosity, $\Delta\eta$, deviations in the refractive index, Δn_D, and the deviations in the surface tension, $\Delta\sigma$, at these three temperatures. The calculated quantities of V_m^E, $\Delta\eta$, Δn_D, and $\Delta\sigma$ were fitted to the Redlich−Kister equation to estimate the binary interaction parameters.

Introduction

The flavor alcohols are vitally interrelated to our daily lives. This paper is concerned with the measurement of the mixing properties for two kinds of flavor alcohols, such as benzyl alcohol or 2-phenylethanol, mixed with 2-propanol. Benzyl alcohol was chosen for the present study because, except for its usage in perfumery, it is widely used in microscopy as the embedding material.[1] Benzyl alcohol is also important as a solvent for gelatin, cellulose acetate, and shellac and in pharmaceutical applications as an antimicrobial agent.[2] 2-Phenylethanol has found usage in artificial essences and as a base solvent for some flavor compounds. On the other hand, 2-propanol is a versatile solvent with protic and self-associated properties, which can be used to study hydrophobic effects.

In this work, we have measured densities, viscosities, refractive indexes, and surface tensions for three binary systems (2-propanol + benzyl alcohol, 2-propanol + 2-phenylethanol, and benzyl alcohol + 2-phenylethanol) at T = (298.15, 308.15, 318.15) K under atmospheric pressure. Several studies for binary mixtures involving either benzyl alcohol or 2-phenylethanol have been conducted recently[3−6] because of their inherent nature of flavoring and forming associations in the form of hydrogen bonds. However, we are not aware of any literature data regarding the properties for the systems proposed in this study.

Experimental Section

Materials. The chemicals used were of analytical grade and were used without further purification. The mass purities and source of the chemicals employed are as follows: 2-propanol (Tedia, > 99.5 %); benzyl alcohol (Merck, > 99.5 %); 2-phenylethanol (Merck, > 99 %). The densities, viscosities, refractive indexes, and surface tensions at T = 298.15 K agreed closely with the accepted literature values (Table 1).

* Corresponding author. E-mail: chtu@pu.edu.tw.

Apparatus and Procedure. Densities were measured with an Anton Paar DMA-5000 vibrating-tube densimeter (Anton-Paar, Graz, Austria) with a stated uncertainty of $\pm\ 5\cdot10^{-6}\ g\cdot cm^{-3}$ in the range (0 to 3) $g\cdot cm^{-3}$. The applied temperature range of this density meter is from (273.15 to 363.15) K with an uncertainty of ± 0.01 K. Calibration was performed periodically under atmospheric pressure, in accordance with specifications, using deionized water and dry air. Precautions were taken to avoid evaporation losses and air dissolved during the experiment. The uncertainty of the density measurements was estimated at $\pm\ 1\cdot10^{-5}\ g\cdot cm^{-3}$. The excess molar volumes were calculated from density data, and the uncertainties were estimated to be within $\pm\ 5\cdot10^{-3}\ cm^3\cdot mol^{-1}$.

The kinematic viscosities were determined with commercial Ubbelohde capillary viscometers (Cannon Instrument Co., State College, PA.) of (0.46, 0.58, and 0.78) mm diameters. The viscometer was kept in a LAUDA D20 KP thermostat controlled to ± 0.01 K with a proportional-integral-differential regulator. A computer-controlled measuring system (LAUDA, Lauda-Königshofen, Germany) with an uncertainty of ± 0.01 s was used for flow-time measurements. The range of the flow time for the liquids investigated is varied from (150 to 950) s. The kinematic viscosities, ν, were determined according to the equation

$$\nu = k(t - \theta) \tag{1}$$

where k is the viscometer constant; t is the flow time; and θ is the Hagenbach correction. The absolute viscosity, η, was then calculated from the density, ρ, by the relation $\eta = \nu\rho$. The k values for several viscometers were provided by the manufacturer and checked with pure water at the working temperatures. The value θ, which is dependent on the flow time and the size of capillary, was taken from the tables supplied by the manufacturer. Triplicate measurements of flow times were reproducible within ± 0.04 %. The uncertainty of the viscosity measurement was estimated to be less than ± 0.4 %.

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Table 1. Comparison of Measured Densities, Viscosities, Refractive Indexes, and Surface Tensions of Pure Components with Literature Values at $T = 298.15$ K

component	ρ/g·cm^{-3}		η/mPa·s		n_D		σ/mN·m^{-1}	
	exptl	lit.	exptl	lit.	exptl	lit.	exptl	lit.
2-propanol	0.78117	0.78126[a]	2.082	2.081[d]	1.37507	1.3752[a]	20.85	20.95[g]
		0.78123[b]		2.079[e]		1.37521[b]		20.93[h]
		0.78112[c]		2.098[f]				20.93[h]
benzyl alcohol	1.04140	1.04127[a]	5.555	5.553[g]	1.53843	1.53837[a]	38.63	38.58[j]
		1.04126[g]		5.737[i]		1.53648[k]		38.54[l]
		1.0414[i,j]						38.9[m]
2-phenylethanol	1.01620		11.405		1.53269		39.43	

[a] Riddick et al., 1986.[7] [b] Bhuiyan et al., 2001.[8] [c] Tamura et al., 1999.[9] [d] Contreras, 2001.[10] [e] Pal and Dass, 2000.[11] [f] Rodriguez et al., 2004.[12] [g] Azizian and Bashavard, 2005.[13] [h] Ouyang et al., 2003.[14] [i] Doz and Solimo, 1995.[15] [j] Azizian et al., 2004.[16] [k] *TRC* Tables, 1996.[17] [l] Dean and Lange, 1985.[18] [m] Glinski et al., 1995.[19]

Table 2. Experimental Densities ρ, Viscosities η, Refractive Indexes n_D, and Surface Tensions σ for x2-Propanol + $(1 - x)$Benzyl Alcohol

x	ρ/g·cm^{-3}	η/mPa·s	n_D	σ/mN·m^{-1}	x	ρ/g·cm^{-3}	η/mPa·s	n_D	σ/mN·m^{-1}
				$T = 298.15$ K					
0.0000	1.04140	5.555	1.53843	38.63	0.5500	0.92421	3.169	1.46310	27.63
0.0500	1.03282	5.299	1.53277	37.50	0.6000	0.91083	3.010	1.45472	26.83
0.1000	1.02374	5.053	1.52684	36.40	0.6500	0.89691	2.858	1.44605	26.05
0.1500	1.01427	4.799	1.52070	35.35	0.7000	0.88244	2.715	1.43707	25.28
0.2000	1.00439	4.559	1.51430	34.30	0.7500	0.86732	2.580	1.42774	24.53
0.2500	0.99422	4.332	1.50772	33.27	0.8000	0.85154	2.460	1.41804	23.78
0.3000	0.98363	4.116	1.50089	32.27	0.8500	0.83511	2.346	1.40795	23.05
0.3500	0.97264	3.911	1.49383	31.27	0.9000	0.81795	2.251	1.39746	22.33
0.4000	0.96120	3.714	1.48652	30.30	0.9500	0.80000	2.148	1.38648	21.61
0.4500	0.94936	3.523	1.47899	29.36	1.0000	0.78117	2.082	1.37507	20.85
0.5000	0.93702	3.335	1.47118	28.45					
				$T = 308.15$ K					
0.0000	1.03360	4.093	1.53421	37.73	0.5500	0.91593	2.370	1.45889	26.93
0.0500	1.02502	3.910	1.52858	36.66	0.6000	0.90249	2.256	1.45050	26.15
0.1000	1.01591	3.730	1.52268	35.63	0.6500	0.88853	2.145	1.44182	25.38
0.1500	1.00640	3.558	1.51654	34.60	0.7000	0.87402	2.042	1.43283	24.61
0.2000	0.99650	3.389	1.51019	33.59	0.7500	0.85891	1.946	1.42350	23.85
0.2500	0.98626	3.230	1.50359	32.58	0.8000	0.84310	1.851	1.41380	23.10
0.3000	0.97559	3.076	1.49674	31.58	0.8500	0.82658	1.761	1.40368	22.35
0.3500	0.96456	2.921	1.48966	30.58	0.9000	0.80939	1.675	1.39319	21.60
0.4000	0.95308	2.772	1.48234	29.60	0.9500	0.79145	1.602	1.38219	20.85
0.4500	0.94119	2.631	1.47480	28.66	1.0000	0.77253	1.550	1.37063	20.05
0.5000	0.92879	2.490	1.46698	27.75					
				$T = 318.15$ K					
0.0000	1.02572	3.120	1.52994	36.75	0.5500	0.90736	1.858	1.45458	26.25
0.0500	1.01709	2.989	1.52435	35.75	0.6000	0.89386	1.769	1.44616	25.48
0.1000	1.00796	2.864	1.51849	34.76	0.6500	0.87984	1.680	1.43746	24.73
0.1500	0.99838	2.745	1.51233	33.77	0.7000	0.86532	1.594	1.42848	23.98
0.2000	0.98843	2.628	1.50598	32.78	0.7500	0.85019	1.511	1.41916	23.23
0.2500	0.97811	2.513	1.49935	31.81	0.8000	0.83429	1.434	1.40943	22.48
0.3000	0.96739	2.400	1.49250	30.83	0.8500	0.81775	1.359	1.39933	21.73
0.3500	0.95629	2.285	1.48542	29.85	0.9000	0.80050	1.295	1.38883	20.96
0.4000	0.94475	2.172	1.47809	28.90	0.9500	0.78246	1.228	1.37780	20.19
0.4500	0.93279	2.059	1.47053	27.95	1.0000	0.76352	1.181	1.36610	19.35
0.5000	0.92032	1.953	1.46269	27.05					

Refractive indexes were measured with a digital Abbe refractometer RX-5000 (ATAGO, Tokyo, Japan), which works at a wavelength of 589 nm corresponding to the D-line of sodium. The temperature was controlled to ± 0.05 K with circulating thermostat water to a jacketed sample vessel. Calibration was performed periodically under atmospheric pressure using double-distilled water. The uncertainty of the refractive index measurement was estimated to be less than ± 0.00002 units.

Surface tensions were measured with an automatic surface tension meter model CBVP-A3 (Kyowa, Japan), which works by the Wilhelmy-plate method. The platinum plate was thoroughly cleaned and flame-dried before each measurement. Calibration was performed periodically under atmospheric pressure, in accordance with specifications, using two 200 mg calibration masses. All liquids were thermostatically controlled to within ± 0.05 K with circulating thermostat water to a jacketed sample vessel. The uncertainty of surface tension measurement was estimated to be within ± 0.3 %.

The densities, viscosities, refractive indexes, and surface tensions for three binary systems (2-propanol + benzyl alcohol, 2-propanol + 2-phenylethanol, and benzyl alcohol + 2-phenylethanol) were measured at $T = (298.15, 308.15, \text{and } 318.15)$ K. The uncertainty in temperature of the measurement was ± 0.01 K. A set with compositions over the whole mole fraction range was prepared by mass in a 50 cm^3 Erlenmeyer flask provided with a ground glass joint stopper, using a Precisa 262SMA balance with an uncertainty of $\pm 3 \cdot 10^{-5}$ g. The uncertainty in the liquid composition of the mixture was estimated at $\pm 1 \cdot 10^{-4}$. All measurements described above were

Table 3. Experimental Densities ρ, Viscosities η, Refractive Indexes n_D, and Surface Tensions σ for x2-Propanol + (1 − x)2-Phenylethanol

x	ρ / $\mathrm{g\cdot cm^{-3}}$	η / mPa·s	n_D	σ / $\mathrm{mN\cdot m^{-1}}$	x	ρ / $\mathrm{g\cdot cm^{-3}}$	η / mPa·s	n_D	σ / $\mathrm{mN\cdot m^{-1}}$
				T = 298.15 K					
0.0000	1.01620	11.405	1.53269	39.43	0.5500	0.91804	4.978	1.46611	27.65
0.0500	1.00941	10.665	1.52795	38.10	0.6000	0.90621	4.571	1.45816	26.70
0.1000	1.00207	9.933	1.52300	36.90	0.6500	0.89362	4.173	1.44975	25.80
0.1500	0.99441	9.256	1.51780	35.80	0.7000	0.88035	3.793	1.44087	24.98
0.2000	0.98636	8.618	1.51235	34.70	0.7500	0.86625	3.438	1.43149	24.20
0.2500	0.97795	8.000	1.50661	33.63	0.8000	0.85134	3.101	1.42156	23.45
0.3000	0.96914	7.407	1.50063	32.61	0.8500	0.83547	2.808	1.41100	22.75
0.3500	0.95991	6.858	1.49437	31.60	0.9000	0.81857	2.541	1.39973	22.10
0.4000	0.95021	6.350	1.48780	30.60	0.9500	0.80054	2.281	1.38776	21.50
0.4500	0.94002	5.862	1.48091	29.60	1.0000	0.78117	2.082	1.37507	20.85
0.5000	0.92931	5.412	1.47367	28.62					
				T = 308.15 K					
0.0000	1.00863	7.518	1.52852	38.93	0.5500	0.90998	3.389	1.46193	27.17
0.0500	1.00231	7.050	1.52391	37.70	0.6000	0.89808	3.124	1.45395	26.20
0.1000	0.99492	6.594	1.51896	36.58	0.6500	0.88547	2.876	1.44553	25.30
0.1500	0.98676	6.148	1.51375	35.47	0.7000	0.87212	2.634	1.43664	24.48
0.2000	0.97865	5.726	1.50826	34.38	0.7500	0.85798	2.407	1.42725	23.68
0.2500	0.97019	5.341	1.50253	33.28	0.8000	0.84299	2.201	1.41733	22.90
0.3000	0.96131	4.969	1.49652	32.23	0.8500	0.82704	2.009	1.40678	22.20
0.3500	0.95204	4.621	1.49025	31.19	0.9000	0.81009	1.859	1.39547	21.50
0.4000	0.94230	4.286	1.48365	30.17	0.9500	0.79200	1.693	1.38342	20.80
0.4500	0.93205	3.964	1.47673	29.16	1.0000	0.77253	1.550	1.37063	20.05
0.5000	0.92129	3.670	1.46950	28.16					
				T = 318.15 K					
0.0000	1.00098	5.232	1.52427	38.35	0.5500	0.90170	2.524	1.45763	26.68
0.0500	0.99422	4.953	1.51972	37.20	0.6000	0.88970	2.342	1.44964	25.70
0.1000	0.98678	4.645	1.51478	36.13	0.6500	0.87703	2.162	1.44120	24.83
0.1500	0.97899	4.366	1.50956	35.05	0.7000	0.86360	1.989	1.43230	24.00
0.2000	0.97082	4.103	1.50405	33.97	0.7500	0.84939	1.823	1.42290	23.20
0.2500	0.96228	3.850	1.49832	32.88	0.8000	0.83430	1.665	1.41297	22.45
0.3000	0.95336	3.600	1.49228	31.80	0.8500	0.81829	1.526	1.40239	21.70
0.3500	0.94399	3.362	1.48598	30.75	0.9000	0.80128	1.415	1.39112	20.97
0.4000	0.93420	3.132	1.47938	29.70	0.9500	0.78308	1.298	1.37903	20.18
0.4500	0.92392	2.912	1.47245	28.68	1.0000	0.76352	1.181	1.36610	19.35
0.5000	0.91306	2.713	1.46522	27.68					

Table 4. Experimental Densities ρ, Viscosities η, Refractive Indexes n_D, and Surface Tensions σ for xBenzyl Alcohol + (1 − x)2-Phenylethanol

x	ρ / $\mathrm{g\cdot cm^{-3}}$	η / mPa·s	n_D	σ / $\mathrm{mN\cdot m^{-1}}$	x	ρ / $\mathrm{g\cdot cm^{-3}}$	η / mPa·s	n_D	σ / $\mathrm{mN\cdot m^{-1}}$
				T = 298.15 K					
0.0000	1.01620	11.405	1.53269	39.43	0.5500	1.03633	7.913	1.53689	
0.0500	1.01811	11.068	1.53322		0.6000	1.03732	7.628	1.53712	38.60
0.1000	1.02014	10.734	1.53367	39.20	0.6500	1.03801	7.351	1.53733	
0.1500	1.02233	10.406	1.53410		0.7000	1.03862	7.081	1.53752	38.60
0.2000	1.02445	10.082	1.53454	39.00	0.7500	1.03906	6.813	1.53772	
0.2500	1.02656	9.759	1.53495		0.8000	1.03943	6.554	1.53789	38.60
0.3000	1.02852	9.440	1.53532	38.83	0.8500	1.03972	6.296	1.53804	
0.3500	1.03034	9.125	1.53568		0.9000	1.04000	6.036	1.53819	38.60
0.4000	1.03211	8.816	1.53601	38.70	0.9500	1.04059	5.787	1.53833	
0.4500	1.03380	8.506	1.53633		1.0000	1.04140	5.555	1.53843	38.63
0.5000	1.03525	8.203	1.53663	38.60					
				T = 308.15 K					
0.0000	1.00863	7.518	1.52852	38.93	0.5500	1.02916	5.467	1.53281	
0.0500	1.01083	7.322	1.52911		0.6000	1.03012	5.302	1.53304	37.90
0.1000	1.01311	7.132	1.52961	38.70	0.6500	1.03089	5.140	1.53325	
0.1500	1.01532	6.940	1.53006		0.7000	1.03156	4.979	1.53344	37.85
0.2000	1.01742	6.752	1.53050	38.48	0.7500	1.03190	4.821	1.53362	
0.2500	1.01952	6.564	1.53089		0.8000	1.03223	4.666	1.53377	37.80
0.3000	1.02144	6.372	1.53125	38.28	0.8500	1.03244	4.519	1.53391	
0.3500	1.02325	6.186	1.53159		0.9000	1.03265	4.374	1.53403	37.76
0.4000	1.02495	5.999	1.53193	38.10	0.9500	1.03306	4.232	1.53414	
0.4500	1.02661	5.815	1.53225		1.0000	1.03360	4.093	1.53421	37.73
0.5000	1.02806	5.636	1.53255	37.95					
				T = 318.15 K					
0.0000	1.00098	5.232	1.52427	38.35	0.5500	1.02187	3.997	1.52864	
0.0500	1.00342	5.116	1.52495		0.6000	1.02284	3.897	1.52888	37.12
0.1000	1.00598	5.000	1.52549	38.11	0.6500	1.02363	3.797	1.52910	
0.1500	1.00823	4.883	1.52594		0.7000	1.02426	3.697	1.52929	37.02
0.2000	1.01036	4.770	1.52636	37.86	0.7500	1.02463	3.599	1.52947	
0.2500	1.01241	4.655	1.52674		0.8000	1.02486	3.500	1.52961	36.92
0.3000	1.01425	4.542	1.52710	37.63	0.8500	1.02499	3.402	1.52973	
0.3500	1.01599	4.430	1.52745		0.9000	1.02518	3.306	1.52984	36.84
0.4000	1.01765	4.320	1.52777	37.41	0.9500	1.02543	3.213	1.52993	
0.4500	1.01928	4.210	1.52809		1.0000	1.02572	3.120	1.52994	36.75
0.5000	1.02074	4.101	1.52839	37.21					

Table 5. Excess Molar Volumes V_m^E, Viscosity Deviations $\Delta\eta$, Refractive Index Deviations Δn_D, and Surface Tension Deviations $\Delta\sigma$ for x2-Propanol + (1 − x)Benzyl Alcohol

x	V_m^E / $cm^3 \cdot mol^{-1}$	$\Delta\eta$ / mPa·s	Δn_D	$\Delta\sigma$ / $mN \cdot m^{-1}$	x	V_m^E / $cm^3 \cdot mol^{-1}$	$\Delta\eta$ / mPa·s	Δn_D	$\Delta\sigma$ / $mN \cdot m^{-1}$
				T = 298.15 K					
0.0500	−0.118	−0.082	0.00047	−0.24	0.5500	−0.624	−0.476	0.00230	−1.22
0.1000	−0.211	−0.154	0.00084	−0.45	0.6000	−0.617	−0.461	0.00228	−1.13
0.1500	−0.291	−0.235	0.00116	−0.61	0.6500	−0.598	−0.440	0.00222	−1.02
0.2000	−0.359	−0.301	0.00140	−0.77	0.7000	−0.569	−0.409	0.00213	−0.90
0.2500	−0.426	−0.355	0.00164	−0.92	0.7500	−0.521	−0.370	0.00198	−0.76
0.3000	−0.482	−0.397	0.00183	−1.03	0.8000	−0.456	−0.317	0.00175	−0.63
0.3500	−0.529	−0.428	0.00199	−1.14	0.8500	−0.376	−0.257	0.00146	−0.47
0.4000	−0.565	−0.452	0.00210	−1.22	0.9000	−0.277	−0.178	0.00109	−0.30
0.4500	−0.596	−0.469	0.00221	−1.27	0.9500	−0.154	−0.108	0.00058	−0.13
0.5000	−0.614	−0.484	0.00227	−1.29					
				T = 308.15 K					
0.0500	−0.126	−0.056	0.00053	−0.19	0.5500	−0.650	−0.324	0.00257	−1.08
0.1000	−0.224	−0.109	0.00095	−0.33	0.6000	−0.642	−0.311	0.00254	−0.97
0.1500	−0.308	−0.154	0.00130	−0.48	0.6500	−0.623	−0.295	0.00249	−0.86
0.2000	−0.381	−0.195	0.00162	−0.60	0.7000	−0.593	−0.271	0.00239	−0.74
0.2500	−0.448	−0.227	0.00187	−0.73	0.7500	−0.548	−0.240	0.00223	−0.62
0.3000	−0.503	−0.254	0.00206	−0.85	0.8000	−0.481	−0.207	0.00201	−0.49
0.3500	−0.553	−0.282	0.00222	−0.96	0.8500	−0.393	−0.170	0.00167	−0.35
0.4000	−0.592	−0.304	0.00234	−1.06	0.9000	−0.290	−0.129	0.00129	−0.22
0.4500	−0.624	−0.318	0.00246	−1.11	0.9500	−0.166	−0.075	0.00075	−0.08
0.5000	−0.641	−0.332	0.00253	−1.14					
				T = 318.15 K					
0.0500	−0.131	−0.034	0.00060	−0.13	0.5500	−0.674	−0.196	0.00281	−0.93
0.1000	−0.237	−0.062	0.00110	−0.25	0.6000	−0.666	−0.188	0.00277	−0.83
0.1500	−0.324	−0.084	0.00146	−0.37	0.6500	−0.646	−0.180	0.00271	−0.71
0.2000	−0.400	−0.104	0.00181	−0.49	0.7000	−0.619	−0.169	0.00263	−0.59
0.2500	−0.469	−0.122	0.00206	−0.59	0.7500	−0.577	−0.155	0.00249	−0.47
0.3000	−0.527	−0.138	0.00228	−0.70	0.8000	−0.503	−0.134	0.00223	−0.35
0.3500	−0.578	−0.156	0.00246	−0.81	0.8500	−0.415	−0.113	0.00191	−0.23
0.4000	−0.618	−0.172	0.00260	−0.89	0.9000	−0.306	−0.080	0.00151	−0.13
0.4500	−0.651	−0.188	0.00272	−0.97	0.9500	−0.171	−0.050	0.00091	−0.03
0.5000	−0.668	−0.198	0.00279	−1.00					

Table 6. Excess Molar Volumes V_m^E, Viscosity Deviations $\Delta\eta$, Refractive Index Deviations Δn_D, and Surface Tension Deviations $\Delta\sigma$ for x2-Propanol + (1 − x)2-Phenylethanol

x	V_m^E / $cm^3 \cdot mol^{-1}$	$\Delta\eta$ / mPa·s	Δn_D	$\Delta\sigma$ / $mN \cdot m^{-1}$	x	V_m^E / $cm^3 \cdot mol^{-1}$	$\Delta\eta$ / mPa·s	Δn_D	$\Delta\sigma$ / $mN \cdot m^{-1}$
				T = 298.15 K					
0.0500	−0.102	−0.274	0.00040	−0.40	0.5500	−0.524	−1.299	0.00260	−1.56
0.1000	−0.170	−0.540	0.00077	−0.67	0.6000	−0.533	−1.240	0.00267	−1.58
0.1500	−0.235	−0.751	0.00110	−0.84	0.6500	−0.521	−1.172	0.00266	−1.55
0.2000	−0.291	−0.922	0.00140	−1.01	0.7000	−0.502	−1.086	0.00258	−1.44
0.2500	−0.344	−1.074	0.00163	−1.15	0.7500	−0.465	−0.975	0.00244	−1.29
0.3000	−0.390	−1.201	0.00186	−1.25	0.8000	−0.417	−0.846	0.00221	−1.12
0.3500	−0.432	−1.284	0.00207	−1.33	0.8500	−0.349	−0.672	0.00186	−0.89
0.4000	−0.465	−1.326	0.00225	−1.40	0.9000	−0.261	−0.473	0.00134	−0.61
0.4500	−0.492	−1.348	0.00239	−1.47	0.9500	−0.149	−0.267	0.00071	−0.28
0.5000	−0.512	−1.332	0.00249	−1.52					
				T = 308.15 K					
0.0500	−0.113	−0.170	0.00051	−0.29	0.5500	−0.554	−0.847	0.00285	−1.38
0.1000	−0.186	−0.327	0.00096	−0.46	0.6000	−0.561	−0.813	0.00290	−1.40
0.1500	−0.252	−0.475	0.00130	−0.63	0.6500	−0.553	−0.763	0.00289	−1.36
0.2000	−0.309	−0.598	0.00158	−0.77	0.7000	−0.531	−0.706	0.00282	−1.23
0.2500	−0.363	−0.685	0.00185	−0.93	0.7500	−0.494	−0.635	0.00267	−1.09
0.3000	−0.410	−0.759	0.00208	−1.04	0.8000	−0.442	−0.543	0.00246	−0.93
0.3500	−0.454	−0.808	0.00230	−1.13	0.8500	−0.369	−0.436	0.00212	−0.68
0.4000	−0.491	−0.845	0.00247	−1.21	0.9000	−0.278	−0.288	0.00155	−0.44
0.4500	−0.518	−0.868	0.00260	−1.27	0.9500	−0.160	−0.155	0.00083	−0.19
0.5000	−0.539	−0.864	0.00273	−1.33					
				T = 318.15 K					
0.0500	−0.125	−0.076	0.00064	−0.20	0.5500	−0.587	−0.480	0.00308	−1.22
0.1000	−0.200	−0.182	0.00109	−0.32	0.6000	−0.592	−0.459	0.00314	−1.25
0.1500	−0.268	−0.258	0.00145	−0.45	0.6500	−0.585	−0.437	0.00313	−1.17
0.2000	−0.328	−0.319	0.00174	−0.58	0.7000	−0.561	−0.407	0.00305	−1.05
0.2500	−0.383	−0.369	0.00204	−0.72	0.7500	−0.523	−0.371	0.00291	−0.90
0.3000	−0.435	−0.417	0.00226	−0.85	0.8000	−0.466	−0.326	0.00269	−0.70
0.3500	−0.478	−0.452	0.00248	−0.95	0.8500	−0.391	−0.263	0.00231	−0.50
0.4000	−0.518	−0.480	0.00267	−1.05	0.9000	−0.297	−0.171	0.00177	−0.28
0.4500	−0.551	−0.497	0.00281	−1.12	0.9500	−0.170	−0.086	0.00100	−0.12
0.5000	−0.570	−0.494	0.00296	−1.17					

Table 7. Excess Molar Volumes V_m^E, Viscosity Deviations $\Delta\eta$, Refractive Index Deviations Δn_D, and Surface Tension Deviations $\Delta\sigma$ for xBenzyl Alcohol + (1 − x)2-Phenylethanol

x	V_m^E / $cm^3 \cdot mol^{-1}$	$\Delta\eta$ / mPa·s	Δn_D	$\Delta\sigma$ / $mN \cdot m^{-1}$	x	V_m^E / $cm^3 \cdot mol^{-1}$	$\Delta\eta$ / mPa·s	Δn_D	$\Delta\sigma$ / $mN \cdot m^{-1}$
				$T = 298.15$ K					
0.0500	−0.095	−0.045	0.00028		0.5500	−0.771	−0.275	0.00125	
0.1000	−0.201	−0.086	0.00048	−0.15	0.6000	−0.734	−0.267	0.00119	−0.35
0.1500	−0.322	−0.121	0.00065		0.6500	−0.664	−0.251	0.00110	
0.2000	−0.431	−0.153	0.00083	−0.27	0.7000	−0.584	−0.229	0.00099	−0.27
0.2500	−0.535	−0.183	0.00098		0.7500	−0.486	−0.205	0.00089	
0.3000	−0.618	−0.210	0.00108	−0.36	0.8000	−0.380	−0.171	0.00075	−0.19
0.3500	−0.682	−0.233	0.00117		0.8500	−0.265	−0.136	0.00058	
0.4000	−0.738	−0.249	0.00122	−0.41	0.9000	−0.149	−0.104	0.00041	−0.11
0.4500	−0.782	−0.267	0.00126		0.9500	−0.064	−0.061	0.00023	
0.5000	−0.798	−0.277	0.00128	−0.43					
				$T = 308.15$ K					
0.0500	−0.133	−0.025	0.00034		0.5500	−0.839	−0.167	0.00134	
0.1000	−0.270	−0.043	0.00059	−0.11	0.6000	−0.799	−0.161	0.00128	−0.31
0.1500	−0.396	−0.064	0.00079		0.6500	−0.737	−0.152	0.00120	
0.2000	−0.504	−0.081	0.00097	−0.21	0.7000	−0.663	−0.142	0.00111	−0.24
0.2500	−0.609	−0.098	0.00108		0.7500	−0.554	−0.128	0.00098	
0.3000	−0.690	−0.118	0.00116	−0.29	0.8000	−0.443	−0.112	0.00083	−0.17
0.3500	−0.755	−0.133	0.00124		0.8500	−0.319	−0.088	0.00066	
0.4000	−0.804	−0.149	0.00129	−0.35	0.9000	−0.195	−0.061	0.00046	−0.09
0.4500	−0.846	−0.162	0.00132		0.9500	−0.091	−0.033	0.00024	
0.5000	−0.863	−0.170	0.00135	−0.38					
				$T = 318.15$ K					
0.0500	−0.165	−0.010	0.00043		0.5500	−0.904	−0.073	0.00146	
0.1000	−0.339	−0.021	0.00072	−0.08	0.6000	−0.865	−0.068	0.00141	−0.27
0.1500	−0.472	−0.032	0.00092		0.6500	−0.805	−0.062	0.00134	
0.2000	−0.586	−0.040	0.00108	−0.17	0.7000	−0.727	−0.057	0.00123	−0.21
0.2500	−0.687	−0.049	0.00120		0.7500	−0.620	−0.049	0.00111	
0.3000	−0.760	−0.056	0.00130	−0.24	0.8000	−0.498	−0.042	0.00094	−0.15
0.3500	−0.819	−0.063	0.00138		0.8500	−0.365	−0.035	0.00075	
0.4000	−0.865	−0.067	0.00143	−0.30	0.9000	−0.238	−0.025	0.00055	−0.07
0.4500	−0.905	−0.072	0.00147		0.9500	−0.117	−0.013	0.00032	
0.5000	−0.924	−0.075	0.00149	−0.34					

performed at atmospheric pressure (100.8 ± 0.4) kPa, and an average of at least three measurements was calculated for each composition.

Results and Discussion

The experimental data of densities ρ, viscosities η, refractive indexes n_D, and surface tensions σ for the three binary systems are listed in Tables 2 to 4. Excess molar volumes, V_m^E, were calculated from density data according to the following equation

$$V_m^E = \sum_{i=1}^{2} x_i M_i \left(\frac{1}{\rho} - \frac{1}{\rho_i}\right) \tag{2}$$

where x_i, M_i, and ρ_i are the mole fraction, molar mass, and density of pure component i, respectively. ρ is the density of

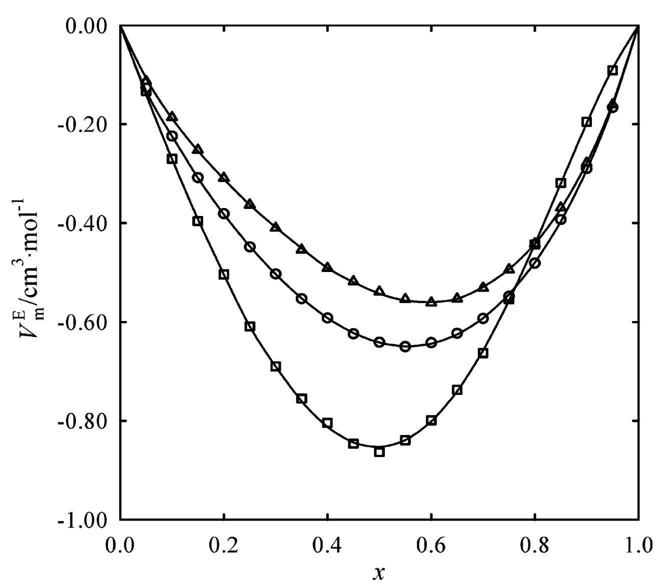

Figure 1. Variation of excess molar volume V_m^E with mole fraction x at T = 308.15 K: ○, x2-propanol + (1 − x)benzyl alcohol; Δ, x2-propanol + (1 − x)2-phenylethanol; □, $x$benzyl alcohol + (1 − x)2-phenylethanol. Solid lines were calculated from the Redlich−Kister equation.

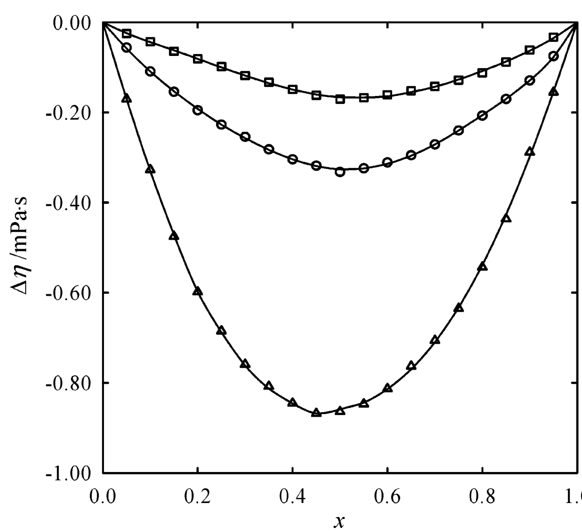

Figure 2. Variation of viscosity deviation $\Delta\eta$ with mole fraction x at T = 308.15 K: ○, x2-propanol + (1 − x)benzyl alcohol; Δ, x2-propanol + (1 − x)2-phenylethanol; □, $x$benzyl alcohol + (1 − x)2-phenylethanol. Solid lines were calculated from the Redlich−Kister equation.

Table 8. Coefficients of the Redlich−Kister Equation and Standard Deviations for V_m^E, Δη, Δn_D, and Δσ of Binary Mixtures from T = 298.15 K to T = 318.15 K

Y	T/K	a_0	a_1	a_2	a_3	a_4	$\delta\cdot 10^{-3}$
				x2-Propanol + (1 − x)Benzyl Alcohol			
V_m^E/cm³·mol⁻¹	298.15	−2.461	−0.538	−0.128	0.124	−0.409	1.6
	308.15	−2.567	−0.547	−0.186	0.115	−0.451	2.2
	318.15	−2.668	−0.551	−0.319	0.075	−0.354	2.9
Δη/mPa·s	298.15	−1.914	−0.040	−0.012	−0.203		4.2
	308.15	−1.303	−0.060	0.398	−0.097	−0.660	3.0
	318.15	−0.772	−0.182	0.303	0.049	−0.563	2.5
Δn_D	298.15	0.00895	0.00185	0.00165	−0.00064		0.029
	308.15	0.00987	0.00193	0.00315			0.026
	318.15	0.01098	0.00175	0.00203	0.00179	0.00492	0.031
Δσ/mN·m⁻¹	298.15	−5.041	0.699	2.831	0.438	−2.215	14.4
	308.15	−4.432	0.601	4.206	0.283	−3.260	1.7
	318.15	−3.840	0.592	4.916	0.431	−3.440	1.9
				x2-Propanol + (1 − x)2-Phenylethanol			
V_m^E/cm³·mol⁻¹	298.15	−2.058	−0.679	−0.289	0.095	−0.417	2.5
	308.15	−2.170	−0.768	−0.266	0.224	−0.627	3.1
	318.15	−2.299	−0.798	−0.256	0.233	−0.765	3.1
Δη/mPa·s	298.15	−5.335	0.799	−0.633	−0.778	0.265	7.8
	308.15	−3.438	0.336	−0.516	−0.175	0.676	5.1
	318.15	−1.954	0.099	−0.255	−0.224	0.407	7.6
Δn_D	298.15	0.00989	0.00456	0.00298	−0.00140		0.029
	308.15	0.01083	0.00457	0.00409	−0.00050		0.039
	318.15	0.01165	0.00489	0.00477	−0.00010	0.00146	0.024
Δσ/mN·m⁻¹	298.15	−6.123	−1.855	−1.807	3.672	0.659	13.4
	308.15	−5.380	−1.894	−0.514	3.285	1.594	18.5
	318.15	−4.789	−1.877	1.805	3.414	0.541	16.0
				xBenzyl Alcohol + (1 − x)2-Phenylethanol			
V_m^E/cm³·mol⁻¹	298.15	−3.151	0.134	1.784	0.364		5.1
	308.15	−3.413	0.090	1.268	0.643		4.8
	318.15	−3.656	0.064	0.752	0.983		6.9
Δη/mPa·s	298.15	−1.099	−0.123	0.431	0.022	−0.548	2.4
	308.15	−0.664	−0.154	0.323	0.034	−0.333	2.2
	318.15	−0.292	0.005	0.159	−0.046	−0.160	1.1
Δn_D	298.15	0.00482	−0.00060	−0.00081	0.00052		0.027
	308.15	0.00531	−0.00013	−0.00023	−0.00113		0.029
	318.15	0.00567	−0.00004	0.00141	−0.00190		0.026
Δσ/mN·m⁻¹	298.15	−1.664	0.627	1.211	−0.559	−1.414	8.0
	308.15	−1.460	0.371	1.344	−0.396	−1.330	9.2
	318.15	−1.281	0.243	1.327	−0.315	−1.092	12.2

the mixture. The deviations in the viscosity Δη were calculated from the following relation

$$\Delta\eta = \eta - \sum_{i=1}^{2} x_i \eta_i \qquad (3)$$

where η is the absolute viscosity of the mixture and η_i is the absolute viscosity of pure component i. The deviation in the refractive index, Δn_D, as stated by Fialkov,[20] is

$$\Delta n_D = n_D - \sum_{i=1}^{2} \phi_i n_{Di} \qquad (4)$$

ϕ_i is the volume fraction of the ith component and is defined by

$$\phi_i = \frac{x_i V_i}{\sum_{i=1}^{2} x_i V_i} \qquad (5)$$

where V_i is the molar volume of pure component i. The deviations in the surface tension Δσ were calculated from the following equation

$$\Delta\sigma = \sigma - \sum_{i=1}^{2} x_i \sigma_i \qquad (6)$$

where σ is the surface tension of the mixture and σ_i is the surface tension of pure component i. The results of V_m^E, Δη, Δn_D, and Δσ are presented in Tables 5 to 7.

The values of V_m^E, Δη, Δn_D, and Δσ for each mixture were fitted to the Redlich−Kister equation[21]

$$Y = x(1-x)\sum_{k=0}^{m} a_k (2x-1)^k \qquad (7)$$

where Y refers to V_m^E/cm³·mol⁻¹, Δη/mPa·s, Δn_D, or Δσ/mN·m⁻¹ and x is the mole fraction. The values of coefficients, a_k, were determined by a nonlinear regression analysis based on the least-squares method. The binary parameters a_k along with the standard deviations δ of these fits are summarized in Table 8. The expression used to calculate δ was

$$\delta(Y) = \left[\sum_{i=1}^{n} \frac{(Y_i - Y_i(\text{calcd}))^2}{n-p}\right]^{1/2} \qquad (8)$$

where n is the number of experimental data and p is the number of parameters.

As illustrated in Figure 1, the values of excess molar volume for the three binary systems at T = 308.15 K are negative over the entire mole fraction range. The excess molar volume $V_m^E(x = 0.5)$ increases in the sequence as: benzyl alcohol + 2-phenylethanol < 2-propanol + benzyl alcohol < 2-propanol + 2-phenylethanol < 0. The values of $V_m^E(x = 0.5)$ vary from −0.863 cm³·mol⁻¹ to −0.539 cm³·mol⁻¹. The V_m^E results at

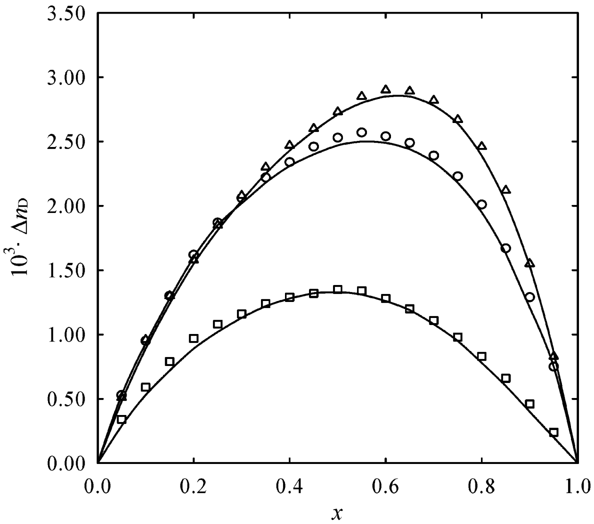

Figure 3. Variation of refractive index deviation Δn_D with mole fraction x at $T = 308.15$ K: ○, x2-propanol + $(1 - x)$benzyl alcohol; Δ, x2-propanol + $(1 - x)$2-phenylethanol; □, $x$benzyl alcohol + $(1 - x)$2-phenylethanol. Solid lines were calculated from the Redlich−Kister equation.

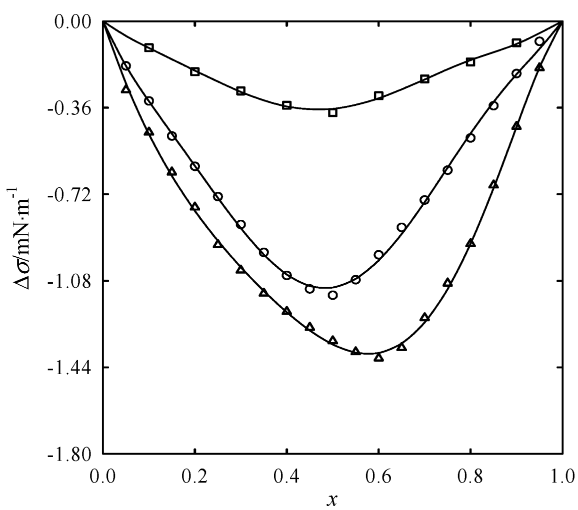

Figure 4. Variation of surface tension deviation $\Delta\sigma$ with mole fraction x at $T = 308.15$ K: ○, x2-propanol + $(1 - x)$benzyl alcohol; Δ, x2-propanol + $(1 - x)$2-phenylethanol (3); □, $x$benzyl alcohol + $(1 - x)$2-phenylethanol. Solid lines were calculated from the Redlich−Kister equation.

other temperatures follow the same trends. Increasing the temperature from $T = 298.15$ K to $T = 318.15$ K decreases the values of V_m^E for all these binary systems.

The $\Delta\eta$ values are also graphically represented as a function of mole fraction for the three binary systems at $T = 308.15$ K in Figure 2. It is observed that the $\Delta\eta$ values are negative over the entire mole fraction range for all these binary mixtures. The viscosity deviation $\Delta\eta(x = 0.5)$ shows the order as: 2-propanol + 2-phenylethanol < 2-propanol + benzyl alcohol < benzyl alcohol + 2-phenylethanol < 0. The values of $\Delta\eta(x = 0.5)$ vary from −0.864 mPa·s to −0.170 mPa·s. The $\Delta\eta$ results at other temperatures follow the same trends. The $\Delta\eta$ values increase from $T = 298.15$ K to $T = 318.15$ K for all these binary systems.

The deviation in the refractive index, Δn_D, was calculated on a volume fraction basis in which case it has simple theoretical significance as reflecting changes in free volume.[22] As illustrated in Figure 3, the Δn_D values at $T = 308.15$ K are positive for the three binary systems over the whole composition range. The refractive index deviation $\Delta n_D(x = 0.5)$ shows the order as: 0 < benzyl alcohol + 2-phenylethanol < 2-propanol + benzyl alcohol < 2-propanol + 2-phenylethanol. The values of $\Delta n_D(x = 0.5)$ vary from 0.00135 to 0.00273. The Δn_D results at other temperatures follow the same trends. The Δn_D values increase from $T = 298.15$ K to $T = 318.15$ K for all these binary systems.

From the curves of $\Delta\sigma$ vs x at $T = 308.15$ K illustrated in Figure 4, the $\Delta\sigma$ values are negative for the three binary systems over the whole concentration range. The surface tension deviation $\Delta\sigma(x = 0.5)$ increases in the sequence as: 2-propanol + 2-phenylethanol < 2-propanol + benzyl alcohol < benzyl alcohol + 2-phenylethanol < 0. The values of $\Delta\sigma(x = 0.5)$ vary from −1.33 mN·m^{-1} to −0.38 mN·m^{-1}. The $\Delta\sigma$ results at other temperatures follow the same trends. Increasing the temperature from $T = 298.15$ K to $T = 318.15$ K decreases the values of $\Delta\sigma$ for all these binary systems.

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