Densities and Viscosities of Binary Liquid Mixtures of Trichloroethylene and Tetrachloroethylene with Some Polar and Nonpolar Solvents

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Densities and viscosities of binary liquid mixtures of trichloroethylene and tetrachloroethylene with methanol, ethanol, 1-propanol, 2-propanol, 1-butanol, 2-butanol, acetone, 2-butanone, methyl acetate, ethyl acetate, carbon tetrachloride, benzene, and toluene have been measured at 298.15 K. From the density and viscosity data, the values of viscosity deviations ($\delta\eta$) and excess molar volumes (V^E) have been determined. Furthermore, the viscosities of binary liquid mixtures have been correlated to different viscosity models.

1. Introduction

Nath and Dixit[1] have undertaken studies on the measurement of viscosities of binary liquid mixtures of acetone with tetrachloroethylene (C_2Cl_4), trichloroethylene (C_2HCl_3), methylene chloride (CH_2Cl_2), dichloroethane (CH_2ClCH_2Cl), and cyclohexane (c-C_6H_{12}) at (303.15 ± 0.01) K. On the basis of the values of parameter *d* of Grunberg and Nissan,[2] they have concluded that acetone forms electron donor−acceptor complexes with C_2Cl_4, C_2HCl_3, CH_2Cl_2, and CH_2ClCH_2Cl.

Venkatesulu et al.[3] have reported studies on the measurement of excess volumes and viscosities of binary liquid mixtures of tetrachloroethylene with homologous series of branched alcohols at 303.15 K. The results of the study reveal that observed excess volumes are positive over the whole range of composition for all of the systems. Recently, in another publication Venkatesulu et al.[4] have reported viscosities and densities for binary liquid mixtures of trichloroethylene or tetrachloroethylene with 2-methoxyethanol, 2-ethoxyethanol, and 2-butoxy ethanol at 303.15 K and 313.15 K over the entire composition range.

From the above survey of the literature, it appears that studies relating to the determination of excess thermodynamic properties in binary liquid mixtures of trichloroethylene and tetrachloroethylene with polar and nonpolar solvents are still scarce. The present paper therefore deals with the measurement of the viscosity and density of the following mixtures: trichloroethylene + methanol, + ethanol, + 1-propanol, + 2-propanol, + 1-butanol, + 2-butanol, + acetone, + 2-butanone, + methyl acetate, + ethyl acetate, + carbon-tetrachloride, + benzene, + toluene and tetrachloroethylene + methanol, + ethanol, + 1-propanol, + 2-propanol, + 1-butanol, + 2-butanol, + acetone, + 2-butanone, + methyl acetate, + ethyl acetate, + carbon tetrachloride, + benzene, + toluene.

2. Experimental Section

Materials. All chemicals were of B.D.H. analytical reagent grade. The organic liquids were further purified according to the procedure described in the literature,[5,6] and the purity was better than 99%.

Table 1. Densities (ρ) and Viscosities (η) of Pure Components at 298.15 K

	ρ/g·cm^{-3}		η/mPa·s	
component	exptl	lit	exptl	lit
trichloroethylene	1.4557	1.4514[a]	0.5510	0.5300[a]
tetrachloroethylene	1.6102	1.6064[a]	0.8474	0.7980[a]
methanol	0.7881	0.7867[b]	0.5482	0.5460[b]
ethanol	0.7874	0.7853[c]	1.1120	1.0860[c]
1-propanol	0.8000	0.7995[d]	1.9544	1.9380[d]
2-propanol	0.7843	0.7818[e]	2.0443	2.0498[e]
1-butanol	0.8063	0.8059[b]	2.5343	2.5780[b]
2-butanol	0.8048	0.8024[f]	3.1028	3.0804[f]
acetone	0.7808	0.7843[g]	0.3121	0.2993[h,o]
2-butanone	0.7974	0.7944[i,o]	0.4011	0.3820[i,o]
methyl acetate	0.9239	0.9261[j]	0.3711	0.3650[j]
ethyl acetate	0.8940	0.8941[k]	0.4274	0.4330[k]
carbon tetrachloride	1.5861	1.5852[l]	0.9096	0.9128[l]
benzene	0.8697	0.8727[l]	0.6080	0.6030[m]
toluene	0.8605	0.8621[n]	0.5641	0.5540[n]

[a] Reference 4. [b] Reference 10. [c] Reference 15. [d] Reference 16. [e] Reference 17. [f] Reference 18. [g] Reference 19. [h] Reference 20. [i] Reference 21. [j] Reference 22. [k] Reference 23. [l] Reference 24. [m] Reference 7. [n] Reference 25. [o] At 303.15 K.

Measurements. Mixtures were prepared by mass in a 25-cm^3 flask using a Mettler analytical balance. The corresponding uncertainty in the mole fraction calculation was better than ±0.0001. Density and viscosity measurements were carried out using a thermostatically controlled, well-stirred water bath, where temperature was measured with a thermometer with an uncertainty of ±0.01 K.

Densities of pure liquids and binary liquid mixtures were measured at 298.15 K with an Anton Parr digital vibrating tube densimeter (model 60/602, Anton Parr, Austria). The densimeter was calibrated with degassed water and dehumidified air at atmospheric pressure. More than eight readings were taken for each density measurement. The uncertainty in the density values was better than $\pm 5 \times 10^{-5}$ g cm^{-3}, and the uncertainty in the excess volume values was ±0.007 cm^3 mol^{-1}.

The viscosities (η) of pure organic liquids and their binary mixtures were determined with an uncertainty of

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Table 2. Densities, Viscosities, Viscosity Deviations ($\delta\eta$), and Excess Molar Volumes (V^E) of Binary Liquid Mixtures of Trichloroethylene with Polar and Nonpolar Solvents at 298.15 K

x_1	ρ/(g·cm^{-3})	η/(mPa·s)	$\delta\eta$/(mPa·s)	V^E/(cm^3·mol^{-1})	x_1	ρ/(g·cm^{-3})	η/(mPa·s)	$\delta\eta$/(mPa·s)	V^E/(cm^3·mol^{-1})
Trichloroethylene (1) + Methanol (2)									
0.0000	0.7881	0.5482	0.0000	0.0000	0.4033	1.1845	0.6017	0.0524	0.2161
0.0477	0.8537	0.5565	0.0082	0.0611	0.5125	1.2512	0.6021	0.0525	0.2250
0.1014	0.9203	0.5667	0.0182	0.0767	0.6430	1.3184	0.5908	0.0408	0.2061
0.1616	0.9855	0.5738	0.0251	0.1318	0.8021	1.3863	0.5750	0.0246	0.1525
0.2308	1.0521	0.5833	0.0345	0.1445	1.0000	1.4557	0.5510	0.0000	0.0000
0.3105	1.1179	0.5950	0.0459	0.1988					
Trichloroethylene (1) + Ethanol (2)									
0.0000	0.7874	1.1120	0.0000	0.0000	0.4930	1.1824	0.7528	−0.0826	0.3755
0.0673	0.8524	1.0471	−0.0271	0.1379	0.6020	1.2494	0.6984	−0.0759	0.3610
0.1397	0.9182	0.9855	−0.0481	0.2108	0.7215	1.3171	0.6470	−0.0602	0.2996
0.2173	0.9839	0.9272	−0.0629	0.2590	0.8563	1.3856	0.5974	−0.0357	0.1998
0.3018	1.0494	0.8651	−0.0776	0.3475	1.0000	1.4557	0.5510	0.0000	0.0000
0.3932	1.1158	0.8082	−0.0832	0.3618					
Trichloroethylene (1) + 1-Propanol (2)									
0.0000	0.8000	1.9544	0.0000	0.0000	0.5556	1.1883	0.8226	−0.3521	0.3752
0.0848	0.8642	1.7054	−0.1300	0.1310	0.6604	1.2543	0.7262	−0.3014	0.3305
0.1725	0.9286	1.4855	−0.2268	0.2286	0.7691	1.3206	0.6463	−0.2287	0.2634
0.2627	0.9929	1.2807	−0.3050	0.2909	0.8823	1.3875	0.5848	−0.1314	0.1703
0.3567	1.0583	1.0985	−0.3553	0.2942	1.0000	1.4557	0.5510	−0.0000	0.0000
0.4541	1.1224	0.9476	−0.3695	0.3911					
Trichloroethylene (1) + 2-Propanol (2)									
0.0000	0.7843	2.0443	0.0000	0.0000	0.5602	1.1809	0.8218	−0.3860	0.4478
0.08664	0.8504	1.7645	−0.1508	0.1092	0.6650	1.2492	0.7173	−0.3340	0.3685
0.1754	0.9166	1.5144	−0.2680	0.1909	0.7724	1.3168	0.6451	−0.2458	0.3010
0.2667	0.9821	1.3060	−0.3400	0.2910	0.8846	1.3859	0.6004	−0.1229	0.1826
0.3613	1.0476	1.1188	−0.3860	0.4026	1.0000	1.4557	0.5510	0.0000	0.0000
0.4594	1.1139	0.9582	−0.4001	0.4658					
Trichloroethylene (1) + 1-Butanol (2)									
0.0000	0.8063	2.5383	0.0000	0.0000	0.6045	1.1914	0.8696	−0.4674	0.3522
0.1018	0.8700	2.0984	−0.2376	0.1430	0.7042	1.2570	0.7737	−0.3651	0.2976
0.2033	0.9343	1.7335	−0.4008	0.2066	0.8025	1.3219	0.6878	−0.2557	0.2500
0.3038	0.9975	1.4289	−0.5057	0.3284	0.9014	1.3883	0.6227	−0.1242	0.1501
0.4042	1.0619	1.1903	−0.5447	0.3463	1.0000	1.4557	0.5510	−0.0000	0.0000
0.5046	1.1265	1.0079	−0.5276	0.3651					
Trichloroethylene (1) + 2-Butanol (2)									
0.0000	0.8048	3.1028	0.0000	0.0000	0.6051	1.1901	0.9463	−0.6124	0.4141
0.1020	0.8685	2.5025	−0.3400	0.1587	0.7042	1.2557	0.8155	−0.4903	0.3412
0.2035	0.9323	2.0191	−0.5644	0.2798	0.8033	1.3220	0.7014	−0.3515	0.2455
0.3040	0.9963	1.6410	−0.6861	0.3315	0.9014	1.3883	0.6101	−0.1925	0.1332
0.4049	1.0612	1.3439	−0.7257	0.3438	1.0000	1.4557	0.5510	0.0000	0.0000
0.5050	1.1254	1.1281	−0.6860	0.3908					
Trichloroethylene (1) + Acetone (2)									
0.0000	0.7808	0.3121	0.0000	0.0000	0.5528	1.1790	0.4723	0.0281	0.4749
0.0840	0.8459	0.3412	0.0090	0.2219	0.6582	1.2464	0.4906	0.0213	0.4785
0.1712	0.9123	0.3688	0.0158	0.3176	0.7671	1.3156	0.5107	0.0153	0.3307
0.2608	0.9788	0.3958	0.0214	0.3462	0.8815	1.3857	0.5309	0.0082	0.1713
0.3544	1.0450	0.4244	0.0276	0.4303	1.0000	1.4557	0.5510	0.0000	0.0000
0.4519	1.1116	0.4501	0.0300	0.4932					
Trichloroethylene (1) + 2-Butanone (2)									
0.0000	0.7974	0.4011	0.0000	0.0000	0.6007	1.1837	0.5391	0.0480	0.6746
0.1004	0.8612	0.4307	0.0146	0.2289	0.7004	1.2496	0.5455	0.0394	0.6222
0.2005	0.9242	0.4566	0.0254	0.4879	0.8004	1.3155	0.5499	0.0288	0.5905
0.3002	0.9872	0.4835	0.0374	0.6920	0.8998	1.3854	0.5495	0.0135	0.2753
0.4005	1.0525	0.5088	0.0477	0.7080	1.0000	1.4557	0.5510	0.0000	0.0000
0.5005	1.1176	0.5281	0.0520	0.7247					
Trichloroethylene (1) + Methyl Acetate (2)									
0.0000	0.9239	0.3711	0.0000	0.0000	0.5713	1.2309	0.5325	0.0586	0.8441
0.0900	0.9726	0.4128	0.0255	0.3815	0.6748	1.2839	0.5447	0.0522	0.8386
0.1820	1.0228	0.4443	0.0405	0.6106	0.7806	1.3410	0.5550	0.0435	0.5546
0.2755	1.0744	0.4699	0.0492	0.6876	0.8886	1.3979	0.5598	0.0288	0.2875
0.3720	1.1253	0.4925	0.0545	0.8463	1.0000	1.4557	0.5510	0.0000	0.0000
0.4703	1.1775	0.5147	0.0590	0.8818					
Trichloroethylene (1) + Ethyl Acetate (2)									
0.0000	0.8940	0.4274	0.0000	0.0000	0.6215	1.2202	0.5705	0.0663	0.7662
0.1086	0.9442	0.4658	0.0250	0.4324	0.7185	1.2773	0.5681	0.0519	0.6669
0.2151	0.9986	0.5023	0.0483	0.6018	0.8143	1.3356	0.5630	0.0350	0.5147
0.3189	1.0528	0.5302	0.0634	0.7320	0.9080	1.3935	0.5589	0.0193	0.3866
0.4219	1.1086	0.5564	0.0769	0.7594	1.0000	1.4557	0.5510	0.0000	0.0000
0.5226	1.1637	0.5685	0.0765	0.8205					

Table 2 (Continued)

x_1	ρ/(g·cm^{-3})	η/(mPa·s)	$\delta\eta$/(mPa·s)	V^E/(cm^3·mol^{-1})	x_1	ρ/(g·cm^{-3})	η/(mPa·s)	$\delta\eta$/(mPa·s)	V^E/(cm^3·mol^{-1})
Trichloroethylene (1) + Carbon Tetrachloride (2)									
0.0000	1.5861	0.9096	0.0000	0.0000	0.6175	1.4953	0.6511	−0.0371	0.7765
0.1068	1.5681	0.8568	−0.0145	0.3034	0.7152	1.4846	0.6226	−0.0305	0.6317
0.2120	1.5523	0.8098	−0.0238	0.4733	0.8114	1.4750	0.5965	−0.0221	0.4194
0.3150	1.5363	0.7632	−0.0334	0.6618	0.9064	1.4646	0.5727	−0.0119	0.2559
0.4171	1.5208	0.7186	−0.0414	0.8157	1.0000	1.4557	0.5510	0.0000	0.0000
0.5178	1.5067	0.6826	−0.0413	0.8824					
Trichloroethylene (1) + Benzene (2)									
0.0000	0.8697	0.6080	0.0000	0.0000	0.5991	1.2110	0.5573	−0.0166	0.7788
0.0997	0.9238	0.5937	−0.0086	0.4460	0.6991	1.2698	0.5573	−0.0145	0.7227
0.1995	0.9817	0.5840	−0.0126	0.4919	0.7989	1.3303	0.5517	−0.0108	0.5437
0.2988	1.0372	0.5761	−0.0149	0.7116	0.8998	1.3919	0.5499	−0.0068	0.3463
0.3987	1.0946	0.5682	−0.0171	0.7756	1.0000	1.4557	0.5510	0.0000	0.0000
0.4986	1.1523	0.5621	−0.0175	0.8052					
Trichloroethylene (1) + Toluene (2)									
0.0000	0.8605	0.5641	0.0000	0.0000	0.6400	1.2105	0.5445	−0.0112	0.5555
0.1166	0.9175	0.5592	−0.0034	0.2968	0.7348	1.2708	0.5454	−0.0091	0.4814
0.2291	0.9756	0.5535	−0.0076	0.4373	0.8257	1.3315	0.5477	−0.0056	0.3498
0.3367	1.0330	0.5498	−0.0099	0.5752	0.9147	1.3932	0.5495	−0.0026	0.2113
0.4417	1.0909	0.5452	−0.0131	0.7058	1.0000	1.4557	0.5510	0.0000	0.0000
0.5426	1.1490	0.5432	−0.0138	0.7751					

$\pm 3 \times 10^{-3}$ mPa·s using an Ostwald viscometer that was suspended in a thermostat maintained at (298.15 ± 0.01) K. The details of the procedure were reported in an earlier publication.[7]

3. Results and Discussion

The experimental values of densities and viscosities of the pure components have been compared with the literature values and presented in Table 1. It is seen that the experimental values compare fairly well with the literature values.

The viscosity deviation ($\delta\eta$) of a given binary liquid mixtures was evaluated from the observed viscosity of a mixture and that of its pure components using the following equation:[8]

$$\delta\eta = \eta - (x_1\eta_1 + x_2\eta_2) \tag{1}$$

where η is the viscosity of the binary liquid mixtures, η_1 and η_2 are the viscosities of pure components 1 and 2, respectively, and x_1 and x_2 are the mole fractions of components 1 and 2, respectively.

The excess molar volume (V^E) of the binary liquid mixtures was evaluated from the molar volume of the mixtures (V) and that of the pure components (V_1 and V_2) using the following equation:[9]

$$V^E = V - (x_1V_1 + x_2V_2) \tag{2}$$

The molar volume V of the binary liquid mixture was calculated from the measured density (ρ) of mixtures using the following equation:[10]

$$V = \frac{(x_1M_1 + x_2M_2)}{\rho} \tag{3}$$

where x_1 and x_2 are the mole fractions of components 1 and 2 of the binary liquid mixtures, respectively, V_1 is M_1/ρ_1 and V_2 is M_2/ρ_2, ρ_1 and ρ_2 are the densities of components 1 and 2 of binary liquid mixtures, respectively.

The first component of the binary liquid mixtures under discussion is trichloroethylene or tetrachloroethylene.

Trichloroethylene, having a dipole moment of $\mu = 0.8$ D, is a slightly polar liquid, and tetrachloroethylene, having a dipole moment of $\mu = 0.0$ D, is a nonpolar liquid. On account of the presence of chlorine atoms and a π-electron system, these liquids can act as both σ- and π-type electron acceptors toward benzene and toluene and a π-type electron donor toward other liquids that have been considered to be the second component in these binary mixtures. The second component of the mixtures is either a polar solvent or a nonpolar solvent. The polar solvents include aliphatic alcohols (both with straight and branched carbon chain lengths), ketones, and esters, and the nonpolar solvents include carbon tetrachloride, benzene, and toluene. The values of the density (ρ), viscosity (η), viscosity deviations ($\delta\eta$), and excess molar volume (V^E) at a constant temperature 298.15 K and as a function of the composition of the binary mixtures have been presented in Tables 2 and 3. The results of the study are discussed below.

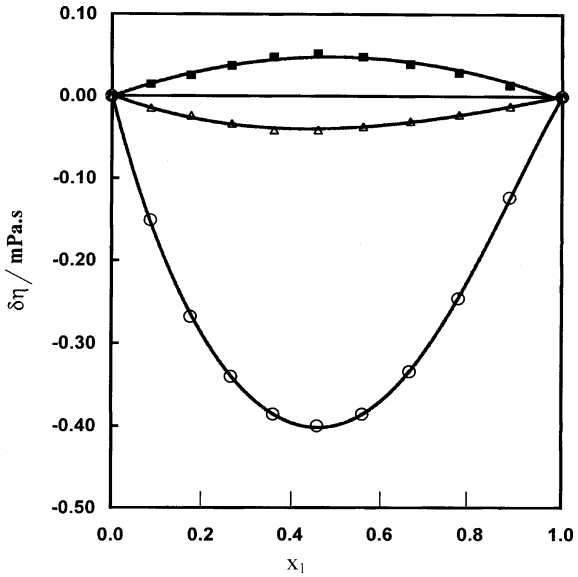

Figure 1. Variation of viscosity deviations ($\delta\eta$) at 298.15 K: ○, trichloroethylene (1) + 2-propanol (2); ■, trichloroethylene (1) + 2-butanone (2); and △, trichloroethylene (1) + carbon tetrachloride (2).

Viscosity Deviations (δη). It is seen from Tables 2 and 3 that the values of $\delta\eta$ are negative over the entire range of composition for the binary mixtures of trichloroethylene and tetrachloroethylene with all of the aliphatic alcohols (except methanol) and with the nonpolar solvents, viz., carbon tetrachloride, benzene, and toluene. However, the

Table 3. Densities, Viscosities, Viscosity Deviations ($\Delta\eta$), and Excess Molar Volumes (V^E) of Binary Liquid Mixtures of Tetrachloroethylene with Polar and Nonpolar Solvents at 298.15 K

x_1	ρ/(g·cm^{-3})	η/(mPa·s)	$\delta\eta$/(mPa·s)	V^E/(cm^3·mol^{-1})	x_1	ρ/(g·cm^{-3})	η/(mPa·s)	$\delta\eta$/(mPa·s)	V^E/(cm^3·mol^{-1})
Tetrachloroethylene (1) + Methanol (2)									
0.0000	0.7881	0.5482	0.0000	0.0000	0.3720	1.2744	0.6751	0.0156	0.3524
0.0420	0.8687	0.5644	0.0036	0.0785	0.4795	1.3559	0.7069	0.0152	0.4004
0.0897	0.9501	0.5806	0.0056	0.1081	0.6123	1.4397	0.7412	0.0098	0.3342
0.1446	1.0301	0.5981	0.0066	0.2165	0.7804	1.5243	0.7875	0.0058	0.2173
0.2082	1.1120	0.6209	0.0104	0.2302	1.0000	1.6102	0.8474	0.0000	0.0000
0.2828	1.1926	0.6449	0.0121	0.3089					
Tetrachloroethylene (1) + Ethanol (2)									
0.0000	0.7874	1.1120	0.0000	0.0000	0.4601	1.2737	0.9189	−0.0714	0.4578
0.0593	0.8681	1.0726	0.0237	0.1041	0.5700	1.3560	0.8939	−0.0673	0.4549
0.1243	0.9496	1.0404	−0.0387	0.1538	0.6944	1.4400	0.8729	−0.0554	0.3493
0.1957	1.0294	1.0075	−0.0527	0.3085	0.8364	1.5249	0.8551	−0.0356	0.1890
0.2746	1.1113	0.9767	−0.0626	0.3257	1.0000	1.6102	0.8474	0.0000	0.0000
0.3619	1.1918	0.9475	−0.0687	0.4162					
Tetrachloroethylene (1) + 1-Propanol (2)									
0.0000	0.8000	1.9544	0.0000	0.0000	0.5229	1.2789	1.1103	−0.2652	0.5289
0.0749	0.8790	1.7901	−0.0814	0.1706	0.6302	1.3609	1.0114	−0.2454	0.4392
0.1541	0.9584	1.6319	−0.1519	0.2903	0.7450	1.4428	0.9253	−0.2044	0.3672
0.2379	1.0385	1.4878	−0.2032	0.3392	0.8679	1.5257	0.8657	−0.1279	0.2301
0.3269	1.1174	1.3500	−0.2425	0.4841	1.0000	1.6102	0.8474	0.0000	0.0000
0.4214	1.1975	1.2178	−0.2701	0.5282					
Tetrachloroethylene (1) + 2-Propanol (2)									
0.0000	0.7843	2.0443	0.0000	0.0000	0.5276	1.2716	1.1232	−0.2896	0.5963
0.0763	0.8649	1.8547	−0.0983	0.1752	0.6349	1.3554	1.0249	−0.2595	0.5038
0.1567	0.9464	1.6762	−0.1805	0.2508	0.7486	1.4376	0.9401	−0.2082	0.5018
0.2417	1.0267	1.5104	−0.2446	0.4278	0.8705	1.5236	0.8824	−0.1200	0.2805
0.3313	1.1075	1.3636	−0.2812	0.5334	1.0000	1.6102	0.8474	0.0000	0.0000
0.4266	1.1893	1.2364	−0.2973	0.5858					
Tetrachloroethylene (1) + 1-Butanol (2)									
0.0000	0.8063	2.5383	0.0000	0.0000	0.5727	1.2830	1.1579	−0.4120	0.4472
0.0901	0.8852	2.2550	−0.1309	0.1445	0.6759	1.3642	1.0454	−0.3500	0.3681
0.1823	0.9643	1.9862	−0.2438	0.2592	0.7809	1.4446	0.9519	−0.2660	0.3198
0.2766	1.0435	1.7174	−0.3532	0.3541	0.8891	1.5260	0.8894	−0.1455	0.2443
0.3727	1.1225	1.4955	−0.4126	0.4328	1.0000	1.6102	0.8474	0.0000	0.0000
0.4713	1.2017	1.3136	−0.4278	0.5082					
Tetrachloroethylene (1) + 2-Butanol (2)									
0.0000	0.8048	3.1028	0.0000	0.0000	0.5733	1.2819	1.2616	−0.5482	0.4951
0.0903	0.8836	2.6601	−0.2393	0.1758	0.6759	1.3626	1.1187	−0.4597	0.4298
0.1825	0.9626	2.2804	−0.4108	0.3024	0.7817	1.4443	1.0048	−0.3350	0.3453
0.2769	1.0425	1.9441	−0.5342	0.3448	0.8891	1.5258	0.9029	−0.1946	0.2387
0.3734	1.1211	1.6666	−0.5940	0.4954	1.0000	1.6102	0.8474	0.0000	0.0000
0.4718	1.2012	1.4533	−0.5854	0.4911					
Tetrachloroethylene (1) + Acetone (2)									
0.0000	0.7808	0.3121	0.0000	0.0000	0.5201	1.2723	0.6021	0.0116	0.4353
0.0742	0.8622	0.3537	0.0019	0.1279	0.6279	1.3562	0.6581	0.0099	0.3678
0.1529	0.9438	0.3980	0.0041	0.2361	0.7428	1.4403	0.7167	0.0070	0.2636
0.2362	1.0255	0.4442	0.0057	0.3125	0.8671	1.5246	0.7802	0.0039	0.1909
0.3247	1.1077	0.4942	0.0083	0.3454	1.0000	1.6102	0.8474	0.0000	0.0000
0.4192	1.1896	0.5459	0.0094	0.4177					
Tetrachloroethylene (1) + 2-Butanone (2)									
0.0000	0.7974	0.4011	0.0000	0.0000	0.5688	1.2755	0.7069	0.0519	0.7553
0.0888	0.8756	0.4563	0.0156	0.3133	0.6719	1.3565	0.7447	0.0437	0.7125
0.1798	0.9551	0.5095	0.0282	0.4541	0.7786	1.4417	0.7802	0.0316	0.4242
0.2732	1.0344	0.5626	0.0396	0.6031	0.8873	1.5242	0.8161	0.0190	0.2962
0.3692	1.1141	0.6147	0.0488	0.7156	1.0000	1.6102	0.8474	0.0000	0.0000
0.4672	1.1939	0.6642	0.0546	0.7759					
Tetrachloroethylene (1) + Methyl Acetate (2)									
0.0000	0.9239	0.3711	0.0000	0.0000	0.5388	1.3227	0.6708	0.0431	0.9116
0.0796	0.9892	0.4237	0.0147	0.2747	0.6452	1.3931	0.7166	0.0382	0.7736
0.1628	1.0547	0.4749	0.0263	0.5057	0.7573	1.4642	0.7614	0.0296	0.5960
0.2500	1.1207	0.5226	0.0324	0.6856	0.8749	1.5354	0.8038	0.0160	0.3947
0.3415	1.1886	0.5729	0.0391	0.7166	1.0000	1.6102	0.8474	0.0000	0.0000
0.4373	1.2553	0.6243	0.0449	0.8215					
Tetrachloroethylene (1) + Ethyl Acetate (2)									
0.0000	0.8940	0.4274	0.0000	0.0000	0.5901	1.3136	0.7481	0.0729	0.7225
0.0962	0.9612	0.4946	0.0268	0.2521	0.6911	1.3857	0.7788	0.0611	0.6566
0.1932	1.0308	0.5525	0.0440	0.4439	0.7937	1.4600	0.8078	0.0470	0.4791
0.2910	1.1006	0.6095	0.0599	0.5949	0.8964	1.5345	0.8295	0.0256	0.2683
0.3899	1.1710	0.6633	0.0721	0.6954	1.0000	1.6102	0.8474	0.0000	0.0000
0.4894	1.2418	0.7110	0.0781	0.7396					

Table 3 (Continued)

x_1	ρ/(g·cm^{-3})	η/(mPa·s)	$\delta\eta$/(mPa·s)	V^E/(cm^3·mol^{-1})	x_1	ρ/(g·cm^{-3})	η/(mPa·s)	$\delta\eta$/(mPa·s)	V^E/(cm^3·mol^{-1})
Tetrachloroethylene (1) + Carbon Tetrachloride (2)									
0.0000	1.5861	0.9096	0.0000	0.0000	0.5859	1.5872	0.8452	−0.0280	0.8466
0.0946	1.5835	0.8943	−0.0094	0.3084	0.6876	1.5901	0.8407	−0.0261	0.8189
0.1904	1.5824	0.8803	−0.0175	0.5281	0.7904	1.5968	0.8422	−0.0182	0.5469
0.2873	1.5820	0.8675	−0.0242	0.7065	0.8946	1.6032	0.8445	−0.0095	0.2933
0.3853	1.5825	0.8569	−0.0287	0.8302	1.0000	1.6102	0.8474	0.0000	0.0000
0.4845	1.5838	0.8504	−0.0291	0.9043					
Tetrachloroethylene (1) + Benzene (2)									
0.0000	0.8697	0.6080	0.0000	0.0000	0.5671	1.3023	0.7088	−0.0350	0.8932
0.0883	0.9398	0.6141	−0.0150	0.3794	0.6706	1.3774	0.7367	−0.0318	0.7681
0.01788	1.0115	0.6279	−0.0229	0.5598	0.7770	1.4532	0.7693	−0.0247	0.6034
0.2720	1.0846	0.6438	−0.0293	0.6200	0.8873	1.5317	0.8051	−0.0153	0.3086
0.3674	1.1567	0.6618	−0.0342	0.7377	1.0000	1.6102	0.8474	0.0000	0.0000
0.4655	1.2288	0.6834	−0.0360	0.8512					
Tetrachloroethylene (1) + Toluene (2)									
0.0000	0.8605	0.5641	0.0000	0.0000	0.6092	1.3001	0.7053	−0.0314	0.8155
0.1034	0.9320	0.5799	−0.0135	0.3837	0.7083	1.3768	0.7377	−0.0271	0.6531
0.2062	1.0047	0.6014	−0.0211	0.5989	0.8060	1.4517	0.7701	−0.0223	0.6032
0.3079	1.0784	0.6234	−0.0279	0.6630	0.9038	1.5301	0.8084	−0.0117	0.3648
0.4093	1.1513	0.6477	−0.0324	0.8257	1.0000	1.6102	0.8474	0.0000	0.0000
0.5095	1.2253	0.6743	−0.0341	0.8460					

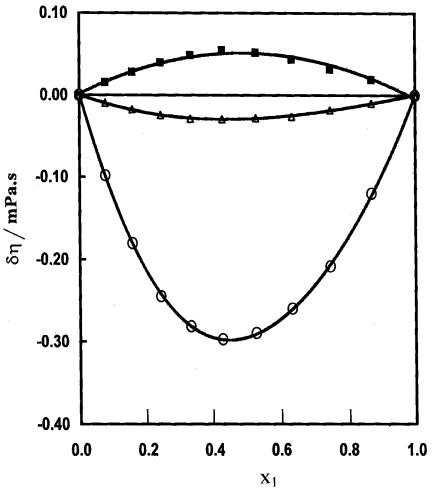

Figure 2. Variation of viscosity deviations ($\delta\eta$) at 298.15 K: ○, tetrachloroethylene (1) + 2-propanol (2); ■, tetrachloroethylene (1) + methyl ethyl ketone (2); and △, tetrachloroethylene (1) + carbon tetrachloride (2).

values of $\delta\eta$ are positive over the entire range of composition for the mixtures involving methanol, aliphatic ketones, (acetone, 2-butanone) and aliphatic esters (methyl acetate, ethyl acetate) as the second component.

Plots of $\delta\eta$ versus x_1 (the mole fraction of trichloroethylene/ tetrachloroethylene) have been presented in the representative Figures 1 and 2. It is seen that the plots are of parabolic shape and are characterized by the presence of well-defined minima/maxima occurring at the composition $x_1 \approx 0.5$.

A comparison of values of $\delta\eta$ at mid composition ($x_1 \approx 0.5$) shows that the values of $\delta\eta$ are arranged in the following order with respect to the binary mixtures involving polar solvents (as the second component).

Aliphatic Alcohols: $\delta\eta$(methanol) > $\delta\eta$(ethanol) > $\delta\eta$(1-propanol) > $\delta\eta$(2-propanol) > $\delta\eta$(1-butanol) > $\delta\eta$(2-butanol).

Aliphatic Ketones: $\delta\eta$(2-butanone) > $\delta\eta$(acetone).

Aliphatic Esters: $\boldsymbol{\delta\eta}$(ethyl acetate) > $\boldsymbol{\delta\eta}$(methyl acetate).

From the above order of the values of $\delta\eta$, we infer that for aliphatic alcohols the strength of interaction decreases with the carbon chain length in the molecule. In the case of aliphatic ketones and esters that involve a ketone group

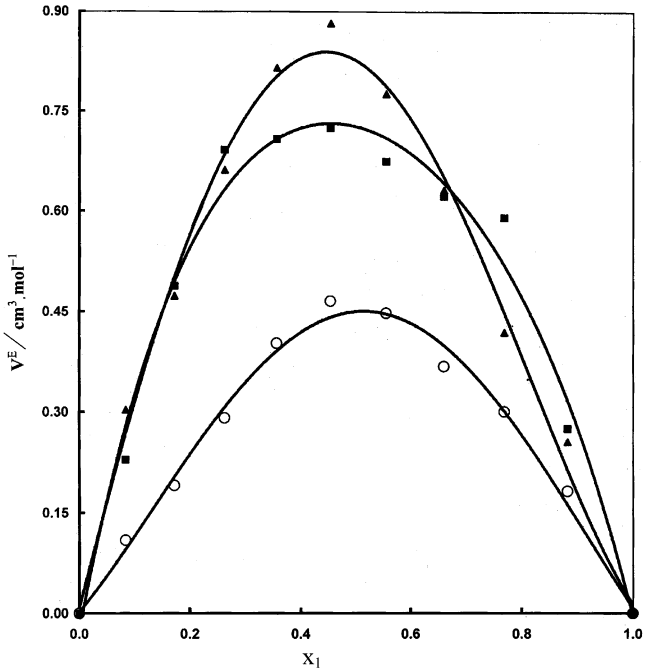

Figure 3. Variation of the excess molar volume (V^E) at 298.15 K: ○, trichloroethylene (1) + 2-propanol (2); ■, trichloroethylene (1) + 2-butanone (2); and ▲, trichloroethylene (1) + carbon tetrachloride (2).

with a higher value of the dipole moment (2.3 D), the strength of interaction increases with the size of the molecules.

Excess Molar Volume (V^E). The values of V^E (Tables 2 and 3) are positive over the entire range of composition for all of the binary mixtures. The plots of V^E versus x_1 are of parabolic shape (representative Figures 3 and 4) with well-defined maxima occurring at $x_1 \approx 0.5$.

Viscosity Models and Interaction Parameters. The viscosities of the binary mixtures under discussion have been correlated to the following viscosity models.

Grunberg and Nissan[2] suggested the following logarithmic relation between the viscosity of the binary liquid mixture and pure components:

$$\ln \eta = x_1 \ln \eta_1 + x_2 \ln \eta_2 + x_1 x_2 d_{12} \qquad (4)$$

where d_{12} is a constant.

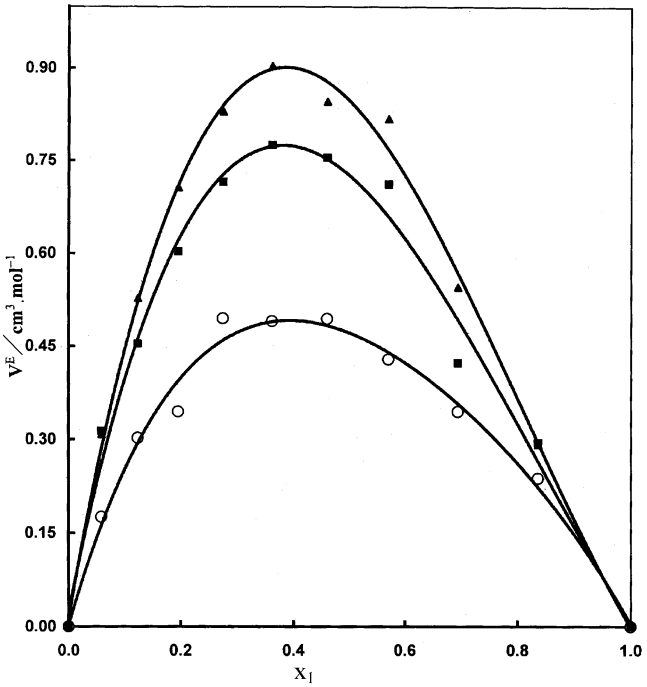

Figure 4. Variation of excess molar volume (V^E) at 298.15 K: ○, tetrachloroethylene (1) + 2-propanol (2); ■, tetrachloroethylene (1) +2-butanone (2); ▲, tetrachloroethylene (1) + carbon tetrachloride (2).

Tamura and Kurata[11] developed the following equation for the viscosity of binary liquid mixtures:

$$\eta = x_1\phi_1\eta_1 + x_2\phi_2\eta_2 + 2(x_1x_2\phi_1\phi_2)^{0.5}\, T_{12} \qquad (5)$$

where T_{12} is an interaction parameter and ϕ_1 and ϕ_2 are the volume fractions.

Hind et al.[12] suggested the following equation for the viscosity of binary liquid mixtures:

$$\eta = x_1^2\eta_1 + x_2^2\eta_2 + 2x_1x_2H_{12} \qquad (6)$$

where H_{12} is the Hind interaction parameter and is attributed to unlike pair interactions.

McAllister's[13] two-parameter equation based on Eyring's theory of absolute reaction rates takes into account interactions of both like and unlike molecules by a 2D three-body model. The equation is

$$\ln \eta = x_1^3 \ln \eta_1 + 3x_1^2x_2 \ln Z_{12} + 3x_1 x_2^2 \ln Z_{21} + x_2^3 \ln \eta_2 + \ln\left(x_1 + x_2\frac{M_2}{M_1}\right) + 3x_1^2x_2 \ln\left[\frac{\left(\frac{2 + M_2}{M_1}\right)}{3}\right] + 3x_1x_2^2 \ln\left[\left(\frac{1 + 2\frac{M_2}{M_1}}{3}\right)\right] + x_2^2 \ln\left(\frac{M_2}{M_1}\right) \qquad (7)$$

where M_1 and M_2 are the molecular weights of components 1 and 2, respectively, and Z_{12} and Z_{21} are the McAllister interaction parameters.

Heric and Brewer[14] proposed the following equation for the kinematic viscosity λ (η/ρ) of the binary liquid mixtures:

$$\lambda = x_1\lambda_1 + x_2\lambda_2 + x_1x_2[a + b(x_1 - x_2) + c(x_1 - x_2)^2] \qquad (8)$$

Table 4. Values of McAllister Parameters (Z_{12} and Z_{21}) and Brewer Parameters (a, b, c) at 298.15 K

system	Z_{12}	Z_{21}	$a \times 10^2$ (cm^2·s^{-1})	$b \times 10^2$ (cm^2·s^{-1})	$c \times 10^2$ (cm^2·s^{-1})
trichloroethylene+					
methanol	0.5884	0.2679	−0.2084	0.1891	−0.2479
ethanol	0.6648	0.3090	−0.0535	0.5496	−0.2937
1-propanol	0.6286	0.4070	−2.5592	1.1104	−0.3528
2-propanol	0.6542	0.4044	−2.8153	1.2978	−0.4600
1-butanol	0.7831	0.4421	−3.4388	1.6554	−0.2858
2-butanol	0.7769	0.5214	−4.4277	2.2597	−0.8434
acetone	0.5031	0.1611	0.0528	−0.0301	−0.0306
2-butanone	0.5662	0.1790	0.1226	−0.0175	−0.0715
methyl acetate	0.5706	0.1871	0.1792	−0.0468	−0.0909
ethyl acetate	0.59	0.20	0.2473	−0.0833	−0.0802
carbon tetrachloride	0.6276	0.2511	−0.0775	0.0032	0.0254
benzene	0.5534	0.1915	−0.2046	0.0598	−0.0249
toluene	0.5435	0.1833	−0.1323	0.0221	−0.0233
tetrachloroethylene+					
methanol	0.6887	0.3417	−0.3549	0.2888	−0.3177
ethanol	0.8582	0.3704	−1.0768	0.6749	−0.4920
1-propanol	0.8720	0.4964	−2.3400	1.0813	−0.6276
2-propanol	0.9166	0.4926	−2.5743	1.3386	−0.7242
1-butanol	0.9264	0.5771	−3.2257	1.2970	−0.2320
2-butanol	1.0140	0.6201	−4.2100	2.1338	−0.8787
acetone	0.6945	0.2092	0.0274	0.0005	−0.0192
2-butanone	0.7677	0.2381	0.1616	−0.0515	−0.0308
methyl acetate	0.7367	0.2331	0.1558	−0.0552	0.0136
ethyl acetate	0.80	0.25	0.2726	−0.0766	−0.0130
carbon tetrachloride	0.8315	0.2837	−0.0567	0.0013	0.0097
benzene	0.7422	0.2219	−0.2433	0.0960	−0.0549
toluene	0.7271	0.2111	−0.1560	0.0504	−0.0138

where λ_1 and λ_2 are the kinematic viscosities of components 1 and 2, respectively, and a, b, and c are the Heric and Brewer interaction parameters.

The values of various interaction parameters, viz., d_{12}, T_{12}, H_{12}, Z_{12}, Z_{21}, a, b, and c, have been obtained from eqs 7−11, respectively, as a function of the composition of the binary mixtures. It is seen that the values of d_{12} are negative for all of the binary mixtures of trichloroethylene and tetrachloroethylene with all the aliphatic alcohols except methyl alcohol. The values are also negative in the case of binary mixtures with nonpolar solvents. However, the values of d_{12} are positive for all of the binary mixtures involving aliphatic ketones and esters.

It is seen that the values of T_{12} and H_{12} are positive for all of the binary mixtures of trichloroethylene and tetrachloroethylene with polar and nonpolar solvents.

The values of Z_{12}, Z_{21}, a, b, and c are listed in Table 4. It is seen that the values of Z_{12} and Z_{21} are positive for all of the binary mixtures of trichloroethylene and tetrachloroethylene with polar and nonpolar solvents. However, the values of constants a, b, and c do not show any regularity with regard to the magnitude and sign.

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