Acoustical and Excess Properties of {Chlorobenzene + 1-Hexanol, or 1-Heptanol, or 1-Octanol, or 1-Nonanol, or 1-Decanol} at (298.15, 303.15, 308.15, and 313.15) K

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Isentropic compressibility k_s, excess isentropic compressibility k_s^E, excess molar volume V^E, viscosity deviations $\Delta\eta$, and speed of sound deviations u^D for {chlorobenzene + 1-hexanol or 1-heptanol, or 1-octanol, or 1-nonanol, or 1-decanol} binary mixtures at temperatures ranging from (298.15 to 313.15) K and at atmospheric pressure were derived from experimental viscosity η, density ρ, and speed of sound u data. The calculated excess and deviation functions were further fitted to the polynomial relation to estimate the coefficients and standard errors. While the experimental viscosity data was compared with the predicted values obtained from empirical expressions, the speeds of sound data was analyzed in term of Schaaffs' collision factor theory and Jacobson's intermolecular free length theory of solutions. The effects of *n*-alkan-1-ol chain length as well as the temperature on the excess molar volume were studied.

Introduction

The knowledge of transport and thermodynamic properties of binary liquid mixtures containing halogenated hydrocarbons are very important due to their practical applications in various fields including detergents, rubber, plastics, and aerosol propellants. Chlorobenzene is one of the halobenzenes that is used as a degreaser in the metal industry and a thinning, dissolving, and starting point for preparation of various derivatives. It is also used together with 1-alkanols as mixed solvents in the production of emulsifiers, absorbents, and surfactants. A perusal of the literature on physical properties of halobenzene with 1-alkanols revealed that the databases are limited,[1−7] so it seems to be very useful in this area of research to carry out systematic investigations involving the physical properties for the binary mixtures containing chlorobenzene + 1-alkanols. In this study, we measured densities, viscosities, and speed of sound for {chlorobenzene (1) + 1-alkanol (2)} binary mixtures at temperatures ranging from (298.15 to 313.15) K and atmospheric pressure. The corresponding derived magnitudes of excess molar volume V^E, excess isentropic compressibility k_s^E, viscosity deviations $\Delta\eta$, and speed of sound deviations u^D were calculated. The excess functions were fitted to the Redlich and Kister type polynomial equation[8] to derive the binary coefficients and estimate the standard deviations between experimental and calculated data. The viscosity data were correlated with single-parameter equation of Grunberg and Nissan,[9] McAllister's three- and four-body models,[10] and the Heric and Brewer equation.[11] The speeds of sound in the binary mixtures were predicted using Schaaffs' collision factor theory (CFT)[12] and Jacobson's intermolecular free length theory (FLT)[13] and compared with the experimental values.

Experimental Section

Chemicals. Chlorobenzene was an Aldrich product. 1-Hexanol, 1-heptanol, 1-octanol, and 1-decanol were purchased from the Fluka Chemical Co. The purities of these substances range from 0.990 to 0.997 on a mass fraction according to gas chromatographic Varian GC (star 3400 cx) analysis using a FID (flame ionization detector), (WCOT fused silica 10 m long, 0.53 mm. diameter) CP-Sil 5 (Catalog No. 7645) and (WCOT fused silica 50 m long, 0.32 mm. diameter) CP-Wax 52 (Catalog No.7753), and Chrompack capillary columns for chlorobenzene and 1-alkanol, respectively. All reagents were used without further purification. The purity of these solvents was ascertained by comparing the measured densities, viscosities, and speed of sound of the pure components at (298.15 and 303.15) K with the available literature[1,8,14−20] shown in Table 1. The reported experimental values conform closely to their corresponding literature values, with an average absolute value of deviation of 3.2×10^{-3} kg·m^{-3}, 2.8×10^{-3} mPa·s, and 0.25 m·s^{-1} for density, dynamic viscosity, and speed of sound, respectively.

Measurements. All samples were stored in dark bottles over freshly activated molecular sieve (Union Carbide type 4A 1/16 in., pellets) to minimize adsorption of moisture. As soon as the bottles were opened, the water contents of chemicals were checked by a Mettler Toledo DL39-KF coulometer, and the moistures were in the range of (13×10^{-4} to 22×10^{-4}) mg·g^{-1}. Each sample mixture was prepared, on mass basis, by mixing the calculated volumes of liquid components in specially designed glass stopper bottles. An electronic balance model (Mettler AT460) with a precision of $\pm 10^{-7}$ kg was used for the mass measurement. The uncertainty in the mole fraction composition was estimated to be $\pm 0.6 \times 10^{-4}$ units.

A set of three compositions was prepared for each system, and the density ρ and speed of sound u were measured on the same day at temperatures of interest using a precision digital Anton Paar densimeter/speed of sound (model DMA 5000). The instrument is made up of two oscillating U-tubes, one designed for measuring density based on the relation between oscillation period and density and the second one equipped with a Piezo transmitter for measuring the speed of sound from the time the sound impulse takes to travel the set distance at constant sample

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Table 1. Experimental Results for Pure Component at (298.15 and 303.15) K

$T = 298.15$ K						$T = 303.15$ K					
ρ/kg·m^{-3}		η/mPa·s		n_D		u/m·s^{-1}		k_s/TPa^{-1}		α/kK^{-1}	
this work	lit.	this work	lit.	this work	lit.	this work	lit.	this work	lit.	this work	lit.
					Chlorobenzene						
1100.97	1100.90[14] 1101.08[1] 1101.038[19]	0.757	0.759[18]	1.4154	1.4151[14] 1.4154[18]	1249.41		584.94		1.0430	
					1-Hexanol						
815.230	815.2[16] 815.22[17] 815.23[15]	4.594	4.593[16] 4.4029[15]	1.5220	1.5223[14] 1.5221[18]	1287.9	1287[20] 1286.5[8]	742.36	743[20]	0.8861	0.885[20]
					1-Heptanol						
818.732	818.7[16] 818.79[15]	5.944	5.942[16] 6.0016[15]	1.4224	1.4225[14] 1.4225[18]	1313.58	1313[20] 1311[8]	712.11	711[20]	0.8772	0.879[20]
					1-Octanol						
821.826	821.8[16] 821.81[17] 821.82[15]	7.661	7.663[16] 7.5981[15]	1.4279	1.4282[14] 1.4283[18]	1338.02	1339[20] 1332.1[8]	689.85		0.8644	0.865[20]
					1-Nonanol						
824.455	824.4[16] 824.6[18]	9.715	9.715[16] 9.6921[15]	1.4318	1.4319[14] 1.4318[18]	1353.6	1354[20] 1350[8]	669.68		0.8416	0.843[20]
					1-Decanol						
826.762	826.7[18] 826.8[16]	11.825	11.829[16] 11.7968[15]	1.4356	1.4354[14] 1.4354[18]	1364.49	1366[20] 1363.3[8]	654.17		0.8301	0.829[20]

temperature. The temperature control was achieved by the built-in integrated thermostat with cascaded Peltier elements and Pt-100 platinum thermometers. The calibration of the instrument was done at a temperature of interest by dry air and with certified ultrapure water supplied by the manufacturer standards. For all mixtures and pure components, triplicate measurements were performed. The results were average with absolute value of deviations of 2.5×10^{-3} kg·m^{-3} and 0.12 m·s^{-1} in measured density ρ and speed of sound u. The uncertainty was found not to be more than 5×10^{-3} kg·m^{-3} and 0.17 m·s^{-1}, respectively.

Dynamics viscosity η measurements of all pure components and their binary mixtures were determined by using a new advanced digital Anton Paar Stabinger viscometer (model SVM 3000/G2). This instrument is made up of two measuring cells, while the first one is designed for measuring density of the samples based on the relation between oscillation period and density, the other is used for dynamic viscosity measurements. The definite measurement for the dynamic viscosity is calculated by the instrument according to the following expression:

$$\eta = k\omega_2/(w_1 - w_2) \tag{1}$$

where k, w_1, and w_2 are the mean adjustment coefficient and speeds of outer tube and inner rotor of the instrument, respectively.

The whole instrument measuring ranges were adjusted automatically by the aid of a built-in program and four certified standard samples supplied by the manufacturer. The calibration of the instrument was done by a double measurement of the three reference samples S3, S6, and N10 (Canon Instruments Co.) of dynamic viscosity and (33×10^{-1}, 76×10^{-1}, 150×10^{-1}) and (25×10^{-1}, 51×10^{-1}, 94×10^{-1}) mPa·s at (298.15 and 313.15) K, respectively. The average experimental errors in dynamic viscosity measurements were found at (4×10^{-4}, 3×10^{-3}) mPa·s at the temperatures of interest. The estimated uncertainty in dynamic viscosity measurements for all measurements was found not to be more than 34×10^{-4} mPa·s. The temperature of the cells was achieved by a solid-state thermostat and two integrated Pt-100 measuring sensors of temperature reproducibility of $\pm 10^{-2}$ K.

Results and Discussion

The results for the density ρ, viscosities η, and speeds of sound u measurements and the calculated isentropic compressibility k_s ($=1/u^2\rho$) are given in Table 2. To examine the precision of measurement, the experimental data were fitted to polynomial equation of the fourth degree.[21,22] The coefficients with standard errors are listed in Table 3.

This equation reproduces the experimental data; with an average of absolute value of deviations of 2×10^{-3} kg·m^{-3}, 27×10^{-4} mPa·s, and 9×10^{-2} m·s^{-1}, respectively. The excess molar volume V^E was calculated through the following equation:[23]

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

where, V, x, M, and r are the molar volume, mole fraction, molar mass, and density, respectively. The subscripts i and m represent the pure components and the mixture, respectively.

The excess isentropic compressibilities k_s^E were calculated from relations recommended by Benson and Kiyohara[24] and Douheret as reported elsewhere:[5]

$$k_s^E = k_s - k_s^{id} \tag{3}$$

$$k_s^E = k_s - \sum \phi_i \left\{\frac{k_{s,i}^\circ + TV_i^\circ(\alpha_i^\circ)^2}{C_{p,i}^\circ}\right\} - \frac{T(\sum x_i V_i^\circ)(\sum \phi_i \alpha_i^\circ)^2}{\sum x_i C_{p,i}^\circ} \tag{4}$$

$$k_s^{id} = (\phi_1 k_{T,1}^\circ + \phi_2 k_{T,2}^\circ) - \frac{T(\sum x_i V_i^\circ)(\sum \phi_i \alpha_i^\circ)^2}{\sum x_i C_{p,i}^\circ} \tag{5}$$

$$k_s^{id} = \phi_1 \left\{k_{s,1}^\circ + TV_1^\circ \frac{(\alpha_1^\circ)^2}{C_{p,1}^\circ}\right\} + \phi_2 \left\{k_{s,2}^\circ + TV_2^\circ \frac{(\alpha_1^\circ)^2}{C_{p,2}^\circ}\right\} - \frac{T(\sum x_i V_i^\circ)(\sum \phi_i \alpha_i^\circ)^2}{\sum x_i C_{p,i}^\circ} \tag{6}$$

where k_s^{id} is the isentropic compressibility of the ideal solution; T is the temperature; x_i is the mole fraction of the pure

Table 2. Experimental Values of Density ρ, Viscositie η, Speed of Sound Refractive Index for {Chlorobenzene (1) + 1-Alkanol (2)} Binary Mixtures at Different Temperatures

x_1	ρ / kg·m^{-3}	η / mPa·s	u / m·s^{-1}	k_s / TPa^{-1}	x_1	ρ / kg·m^{-3}	η / mPa·s	u / m·s^{-1}	k_s / TPa^{-1}	x_1	ρ / kg·m^{-3}	η / mPa·s	u / m·s^{-1}	k_s / TPa^{-1}	x_1	ρ / kg·m^{-3}	η / mPa·s	u / m·s^{-1}	k_s / TPa^{-1}
Chlorobenzene (1) + 1-Hexanol (2)																			
T = 298.15 K										T = 303.15 K									
0.0000	815.230	4.594	1304.72	720.58	0.6542	987.534	1.184	1264.34	633.46	0.0000	812.118	3.887	1287.90	742.36	0.6542	982.986	1.079	1246.56	654.68
0.1144	842.629	3.576	1297.70	704.72	0.7457	1015.514	1.008	1260.86	619.41	0.1144	839.289	3.096	1280.61	726.53	0.7457	1010.711	0.935	1243.07	640.30
0.2338	872.274	2.746	1289.83	689.10	0.8353	1044.185	0.873	1259.29	603.91	0.2338	868.705	2.414	1272.45	710.96	0.8353	1039.122	0.824	1241.54	624.33
0.3573	904.193	2.107	1281.57	673.37	0.9171	1071.621	0.788	1260.91	586.94	0.3573	900.355	1.870	1264.01	695.16	0.9171	1066.267	0.752	1243.23	606.78
0.4628	932.670	1.699	1274.79	659.77	1.0000	1100.975	0.757	1267.96	565.11	0.4628	928.591	1.515	1257.10	681.45	1.0000	1095.104	0.714	1249.41	584.97
0.5568	959.077	1.417	1269.25	647.22						0.5568	954.767	1.274	1251.57	668.64					
T = 308.15 K										T = 313.15 K									
0.0000	808.482	3.359	1271.14	765.50	0.6542	977.948	0.997	1228.92	677.08	0.0000	804.811	2.914	1254.45	789.59	0.6542	973.227	0.896	1211.62	699.93
0.1144	835.421	2.695	1263.57	749.71	0.7457	1005.424	0.870	1225.40	662.36	0.1144	831.574	2.350	1246.54	773.90	0.7457	1000.531	0.780	1207.89	685.04
0.2338	864.604	2.123	1255.39	733.88	0.8353	1033.552	0.772	1224.30	645.49	0.2338	860.561	1.865	1238.45	757.63	0.8353	1028.463	0.692	1206.56	667.90
0.3573	895.988	1.665	1246.68	718.10	0.9171	1060.412	0.711	1225.80	627.60	0.3573	891.747	1.478	1229.79	741.47	0.9171	1055.093	0.637	1208.18	649.30
0.4628	923.985	1.369	1239.73	704.17	1.0000	1089.081	0.677	1230.87	606.06	0.4628	919.571	1.223	1222.88	727.19	1.0000	1083.665	0.617	1212.63	627.55
0.5568	949.942	1.165	1233.94	691.38						0.5568	945.388	1.044	1216.68	714.56					
Chlorobenzene (1) + 1-Heptanol (2)																			
T = 298.15 K										T = 303.15 K									
0.0000	818.732	5.944	1327.32	693.28	0.6827	988.992	1.273	1269.10	627.79	0.0000	815.287	5.069	1313.58	712.11	0.6827	984.268	1.160	1253.80	646.29
0.1306	846.348	4.469	1316.71	681.50	0.7682	1016.226	1.073	1264.60	615.32	0.1306	842.689	3.832	1299.95	702.23	0.7682	1011.304	0.984	1248.72	634.14
0.2566	874.819	3.335	1305.54	670.65	0.8521	1044.880	0.918	1262.71	600.24	0.2566	870.964	2.896	1289.02	691.01	0.8521	1039.687	0.850	1245.44	620.09
0.3866	906.448	2.453	1293.83	659.02	0.9255	1071.666	0.817	1263.81	584.22	0.3866	902.362	2.164	1277.56	678.99	0.9255	1066.234	0.764	1245.55	604.53
0.4947	934.739	1.911	1283.99	648.91	1.0000	1100.975	0.757	1267.96	565.11	0.4947	930.425	1.709	1268.16	668.30	1.0000	1095.104	0.714	1249.41	584.97
0.5878	960.727	1.557	1275.95	639.34						0.5878	956.224	1.406	1260.67	658.01					
T = 308.15 K										T = 313.15 K									
0.0000	811.737	4.333	1293.86	735.89	0.6827	979.252	1.059	1234.96	669.57	0.0000	808.162	3.726	1277.15	758.61	0.6827	974.575	0.953	1217.92	691.78
0.1306	838.900	3.311	1283.28	723.85	0.7682	1006.020	0.915	1230.09	656.93	0.1306	835.146	2.872	1266.52	746.47	0.7682	1001.128	0.822	1212.94	678.94
0.2566	866.926	2.532	1272.12	712.79	0.8521	1034.115	0.816	1227.58	641.70	0.2566	862.967	2.219	1255.62	735.00	0.8521	1029.023	0.723	1209.90	663.88
0.3866	898.052	1.922	1260.38	700.96	0.9255	1060.416	0.733	1227.98	625.38	0.3866	893.905	1.705	1243.84	723.07	0.9255	1055.079	0.662	1209.66	647.70
0.4947	925.892	1.543	1250.19	691.02	1.0000	1089.081	0.677	1230.87	606.06	0.4947	921.550	1.378	1233.59	713.08	1.0000	1083.665	0.617	1212.63	627.55
0.5878	951.470	1.283	1242.05	681.28						0.5878	946.950	1.135	1225.34	703.33					
Chlorobenzene (1) + 1-Octanol (2)																			
T = 298.15 K										T = 303.15 K									
0.0000	821.826	7.661	1347.82	669.82	0.7073	990.466	1.363	1272.70	623.32	0.0000	818.230	6.402	1338.02	689.85	0.7073	985.680	1.243	1260.00	639.03
0.1423	848.715	5.448	1334.07	662.04	0.7885	1017.455	1.132	1266.98	612.27	0.1423	844.912	4.640	1317.49	681.86	0.7885	1012.469	1.040	1253.37	628.72
0.2807	877.644	3.870	1319.12	654.81	0.8662	1045.681	0.956	1264.00	598.56	0.2807	873.625	3.352	1303.37	673.81	0.8662	1040.472	0.885	1248.70	616.39
0.4121	908.104	2.788	1303.67	647.93	0.9331	1072.016	0.841	1264.03	583.83	0.4121	903.886	2.455	1289.57	665.27	0.9331	1066.598	0.782	1247.49	602.46
0.5237	936.698	2.116	1291.06	640.48	1.0000	1100.975	0.757	1267.96	565.11	0.5237	932.283	1.890	1277.85	656.89	1.0000	1095.104	0.714	1249.41	584.97
0.6158	962.489	1.692	1281.24	632.91						0.6158	957.910	1.528	1268.56	648.71					
T = 308.15 K										T = 313.15 K									
0.0000	814.737	5.425	1314.27	710.58	0.7073	980.694	1.119	1245.73	657.08	0.0000	810.098	4.628	1297.60	733.13	0.7073	975.500	1.037	1230.69	676.82
0.1423	841.161	3.981	1302.61	700.65	0.7885	1007.212	0.956	1238.65	647.11	0.1423	836.375	3.436	1285.80	723.20	0.7885	1001.950	0.891	1223.45	666.77
0.2807	869.616	2.919	1289.52	691.53	0.8662	1034.919	0.833	1233.39	635.16	0.2807	864.727	2.562	1273.24	713.33	0.8662	1029.566	0.760	1217.84	654.88
0.4121	899.625	2.174	1275.95	682.76	0.9331	1060.818	0.752	1230.90	622.20	0.4121	894.659	1.934	1260.35	703.65	0.9331	1055.421	0.681	1214.32	642.59
0.5237	927.793	1.678	1263.83	674.80	1.0000	1089.081	0.677	1230.87	606.06	0.5237	922.757	1.528	1248.92	694.77	1.0000	1083.665	0.617	1212.63	627.55
0.6158	953.186	1.366	1254.63	666.49						0.6158	948.078	1.267	1239.56	686.48					

Table 2. (Continued)

x_1	ρ / kg·m^{-3}	η / mPa·s	u / m·s^{-1}	k_s / TPa^{-1}	x_1	ρ / kg·m^{-3}	η / mPa·s	u / m·s^{-1}	k_s / TPa^{-1}	x_1	ρ / kg·m^{-3}	η / mPa·s	u / m·s^{-1}	k_s / TPa^{-1}	x_1	ρ / kg·m^{-3}	η / mPa·s	u / m·s^{-1}	k_s / TPa^{-1}
Chlorobenzene (1) + 1-Nonanol (2)																			
T = 298.15 K											T = 303.15 K								
0.0000	824.478	9.715	1365.48	650.52	0.7273	991.186	1.455	1281.16	614.66	0.0000	821.044	7.927	1353.60	669.68	0.7273	986.433	1.325	1265.39	633.10
0.1529	850.648	6.576	1350.52	644.54	0.8031	1017.422	1.192	1273.96	605.58	0.1529	846.995	5.560	1332.63	664.83	0.8031	1012.442	1.097	1257.72	624.39
0.3008	879.504	4.488	1333.30	639.59	0.8744	1044.709	0.999	1268.98	594.41	0.3008	875.625	3.876	1315.77	659.65	0.8744	1039.485	0.924	1252.00	613.71
0.4379	910.112	3.135	1316.18	634.26	0.9370	1071.143	0.864	1267.06	581.55	0.4379	906.014	2.752	1299.52	653.58	0.9370	1065.724	0.802	1249.06	601.50
0.5505	938.617	2.329	1302.22	628.28	1.0000	1100.675	0.757	1267.96	565.11	0.5505	934.309	2.070	1286.02	647.18	1.0000	1095.104	0.714	1249.41	584.97
0.6413	964.273	1.828	1291.12	622.12						0.6413	959.757	1.646	1275.10	640.87					
T = 308.15 K											T = 313.15 K								
0.0000	817.582	6.664	1331.78	689.61	0.7273	981.393	1.205	1246.29	656.01	0.0000	814.098	5.645	1315.00	710.35	0.7273	976.738	1.094	1229.77	676.96
0.1529	843.265	4.745	1315.54	685.22	0.8031	1007.142	1.014	1238.45	647.36	0.1529	839.584	4.074	1299.38	705.45	0.8031	1002.280	0.919	1221.83	668.31
0.3008	871.650	3.365	1298.50	680.41	0.8744	1033.954	0.869	1232.97	636.20	0.3008	867.761	2.935	1282.02	701.14	0.8744	1028.877	0.775	1215.64	657.70
0.4379	901.759	2.433	1281.73	675.02	0.9370	1059.964	0.764	1231.47	622.21	0.4379	897.663	2.152	1264.94	696.22	0.9370	1054.697	0.676	1213.28	644.23
0.5505	929.764	1.858	1267.66	669.30	1.0000	1089.081	0.677	1230.87	606.06	0.5505	925.493	1.658	1250.99	690.44	1.0000	1083.665	0.617	1212.63	627.55
0.6413	954.969	1.493	1256.35	663.42						0.6413	950.508	1.346	1239.81	684.44					
Chlorobenzene (1) + 1-Decanol (2)																			
T = 298.15 K											T = 303.15 K								
0.0000	826.762	11.825	1380.01	635.12	0.7456	992.108	1.517	1288.54	607.07	0.0000	822.853	9.754	1364.99	654.17	0.7456	987.138	1.388	1270.53	627.52
0.1664	852.913	7.762	1362.60	631.49	0.8174	1017.953	1.243	1280.10	599.43	0.1664	848.821	6.542	1343.91	652.29	0.8174	1012.826	1.147	1262.60	619.28
0.3220	881.587	5.123	1344.36	627.61	0.8857	1045.673	1.017	1273.34	589.82	0.3220	877.329	4.407	1325.02	649.20	0.8857	1040.317	0.949	1256.08	609.24
0.4609	911.692	3.484	1326.97	622.93	0.9426	1071.478	0.865	1269.48	579.15	0.4609	907.247	3.058	1307.21	645.02	0.9426	1065.894	0.808	1252.20	598.37
0.5731	939.879	2.539	1311.74	618.36	1.0000	1100.675	0.757	1267.96	565.11	0.5731	935.236	2.262	1292.44	640.11	1.0000	1095.104	0.714	1249.41	584.97
0.6619	965.236	1.967	1299.54	613.47						0.6619	960.447	1.771	1280.90	634.60					
T = 308.15 K											T = 313.15 K								
0.0000	819.427	8.135	1346.10	673.50	0.7456	982.146	1.273	1249.54	652.08	0.0000	815.983	6.842	1329.31	693.53	0.7456	977.488	1.156	1230.12	676.03
0.1664	845.166	5.554	1326.00	672.95	0.8174	1007.558	1.045	1240.84	644.54	0.1664	841.509	4.751	1308.57	693.97	0.8174	1002.683	0.968	1222.07	667.73
0.3220	873.388	3.814	1306.37	670.89	0.8857	1034.748	0.868	1234.63	633.99	0.3220	869.536	3.323	1288.14	693.05	0.8857	1029.639	0.809	1216.52	656.23
0.4609	903.044	2.695	1288.07	667.45	0.9426	1060.077	0.756	1231.03	622.55	0.4609	898.972	2.388	1269.12	690.63	0.9426	1054.838	0.702	1213.40	644.02
0.5731	930.800	2.021	1272.93	663.07	1.0000	1089.081	0.677	1230.87	606.06	0.5731	926.509	1.816	1253.35	687.10	1.0000	1083.665	0.617	1212.63	627.55
0.6619	955.749	1.597	1260.79	658.24						0.6619	951.271	1.454	1241.08	682.49					

Table 3. Coefficients and Standard Deviation of Equation 3 for Density ρ, Viscosities η, and Speed of Sound {Chlorobenzene (1) + 1-Alkanol (2)} Binary Mixtures at Different Temperatures

	b_0	b_1	b_2	b_3	b_4	σ	b_0	b_1	b_2	b_3	b_4	σ
Chlorobenzene (1) + 1-Hexanol (2)												
	$T = 298.15$ K						$T = 303.15$ K					
ρ/kg·m^{-3}	815.250	234.540	39.826	−2.88	14.205	0.005	812.120	233.290	35.480	4.810	9.394	0.006
η/mPa·s	4.598	−10.258	11.709	−7.752	2.456	0.004	3.890	−7.770	6.880	−2.660	0.377	0.003
u/m·s^{-1}	1304.90	−71.75	59.20	−153.5	128.73	0.140	1287.70	−72.31	46.82	−125.27	111.84	0.22
	$T = 308.15$ K						$T = 313.15$ K					
ρ/kg·m^{-3}	808.490	231.000	37.212	1.365	10.987	0.007	804.830	229.080	39.010	−1.569	12.261	0.004
η/mPa·s	3.363	−6.558	5.997	−2.672	0.544	0.004	2.917	−5.614	5.458	−3.071	0.923	0.002
u/m·s^{-1}	1271.20	−69.52	20.37	−75.56	84.28	0.08	1254.50	−71.48	27.67	−87.14	89.17	0.07
Chlorobenzene (1) + 1-Heptanol (2)												
	$T = 298.15$ K						$T = 303.15$ K					
ρ/kg·m^{-3}	818.760	202.710	62.640	−10.27	27.086	0.007	815.300	201.680	59.160	−4.152	23.087	0.004
η/mPa·s	5.948	−12.858	11.600	−4.527	0.583	0.002	5.070	−10.800	10.292	−4.969	1.119	0.003
u/m·s^{-1}	1327.30	−81.50	2.57	−80.11	99.67	0.05	1313.60	−118.38	138.16	−251.37	167.22	0.16
	$T = 308.15$ K						$T = 313.15$ K					
ρ/kg·m^{-3}	811.760	199.400	61.510	−8.973	25.300	0.005	808.190	197.660	63.490	−12.960	27.200	0.007
η/mPa·s	4.334	−8.860	8.097	−3.590	0.703	0.004	3.727	−7.379	6.710	−3.298	0.857	0.002
u/m·s^{-1}	1293.90	−79.10	−11.08	−56.22	83.40	0.07	1277.20	−80.60	2.21	−81.44	95.25	0.06
Chlorobenzene (1) + 1-Octanol (2)												
	$T = 298.15$ K						$T = 303.15$ K					
ρ/kg·m^{-3}	821.860	176.960	81.480	−24.79	45.380	0.005	818.250	176.050	77.876	−17.880	40.740	0.006
η/mPa·s	7.662	−18.110	19.143	−10.45	2.514	0.003	6.404	−14.345	14.360	−7.489	1.775	0.003
u/m·s^{-1}	1347.80	−96.56	−2.43	−102.3	121.10	0.15	1337.90	−170.84	262.70	−420.88	240.43	0.16
	$T = 308.15$ K						$T = 313.15$ K					
ρ/kg·m^{-3}	814.770	173.810	80.590	−22.98	42.830	0.006	810.130	172.310	84.090	−28.320	45.380	0.004
η/mPa·s	5.424	−11.540	10.600	−4.730	0.923	0.003	4.628	−9.640	9.466	−5.239	1.400	0.004
u/m·s^{-1}	1314.30	−81.16	−9.51	−82.37	89.35	0.14	1297.60	−82.74	2.97	−84.02	78.71	0.12
Chlorobenzene (1) + 1-Nonanol (2)												
	$T = 298.15$ K						$T = 303.15$ K					
ρ/kg·m^{-3}	824.520	155.570	99.980	−49.65	70.137	0.005	821.090	153.610	103.380	−56.326	73.213	0.006
η/mPa·s	9.714	−24.418	28.321	−17.92	5.070	0.003	7.929	−18.040	17.720	−8.861	1.960	0.004
u/m·s^{-1}	1365.49	−99.65	5.55	−133.3	129.53	0.26	1353.60	−160.82	204.55	−364.65	216.48	0.15
	$T = 308.15$ K						$T = 313.15$ K					
ρ/kg·m^{-3}	817.600	151.950	103.700	−58.23	73.908	0.008	814.150	150.280	105.950	−62.570	75.720	0.007
η/mPa·s	6.665	−14.535	13.809	−6.811	1.552	0.003	5.647	−11.925	11.447	−6.298	1.741	0.004
u/m·s^{-1}	1331.90	−112.50	51.24	−190.3	150.64	0.25	1315.10	−106.49	22.08	−141.43	123.10	0.27
Chlorobenzene (1) + 1-Decanol (2)												
	$T = 298.15$ K						$T = 303.15$ K					
ρ/kg·m^{-3}	826.790	137.350	120.520	−86.84	102.650	0.003	822.920	135.770	123.700	−93.127	105.570	0.006
η/mPa·s	11.826	−29.150	30.990	−17.07	4.158	0.004	9.755	−22.840	22.980	−12.004	2.816	0.004
u/m·s^{-1}	1380.10	−111.63	58.59	215.27	155.90	0.19	1365.00	−135.26	81.47	−187.83	126.09	0.11
	$T = 308.15$ K						$T = 313.15$ K					
ρ/kg·m^{-3}	819.500	133.880	126.370	−98.77	107.840	0.004	816.060	132.410	127.990	−102.46	109.400	0.006
η/mPa·s	8.139	−18.317	18.180	−10.0	2.660	0.003	6.843	−14.716	13.960	−7.365	1.889	0.003
u/m·s^{-1}	1346.20	−137.70	121.37	−294.5	194.90	0.19	1329.35	−132.56	66.79	−206.56	155.47	0.09

component in the mixture; $C^{\circ}_{p,i}$, V°_i, and α°_i are the molar isobaric heat capacity, molar volume, and isobaric expansion coefficient of pure component i, respectively. ϕ_i is the ideal volume fraction of pure component i in the mixture and is defined by the relation

$$\phi_i = x_i V_i / (\sum x_i V^{\circ}_i) \tag{7}$$

The values of the heat capacities $C^{\circ}_{p,i}$/J·mol^{-1}·K^{-1} for the pure component at the temperature range (298.15 to 313.15) K were taken from the DIPPR database,[18] shown in Table 4. The thermal expansion coefficient defined as $\alpha = V^{-1}\,(\mathrm{d}V/\mathrm{d}T)_p = -\rho^{-1}\,(\mathrm{d}\rho/\mathrm{d}T)_p$, listed in Table 5, was calculated from the experimental ρ data of each pure component using A_i, the coefficients of[5]

$$\rho = \sum_{i=1}^{m=3} A_i (T - 273.15)^{i-1} \tag{8}$$

The deviation of the measured speeds of sound from their values in an ideal mixture u^{D} were calculated from the following equations as reported in Pal and Singh:[25]

$$u^{\mathrm{D}} = u - u^{\mathrm{id}} \tag{9}$$

$$u^{\mathrm{id}} = V^{\mathrm{id}}_{\mathrm{m}} \{ (\sum x_i M_i) k^{\mathrm{id}}_{\mathrm{s}} \}^{-0.5} \tag{10}$$

−ophere u^{id}, $V^{\mathrm{id}}_{\mathrm{m}}$, $k^{\mathrm{id}}_{\mathrm{s}}$, x_i, and M_i are the calculated speed sound, molar volume, and isentropic compressibility of the ideal solution, the mole fraction, and molar mass of the pure component, respectively

The viscosity deviations Δh from a linear dependence on mole fraction were calculated according to the literature suggestions[26] through the following relation:

$$\Delta\eta = \eta_m - \sum_{i=1}^{n} (x_i \eta_i) \tag{11}$$

where x and η are the molar mass and dynamic viscosity, respectively. The subscripts i and m represent the pure components and the mixture respectively.

The excess molar volumes V^{E}, excess molar isentropic compressibility $k^{\mathrm{E}}_{\mathrm{s}}$, deviations of the speed of sound u^{D}, and viscosity deviation $\Delta\eta$ for binary mixtures were fitted by the method of least-squares to a Redlich−Kister[8] polynomial type

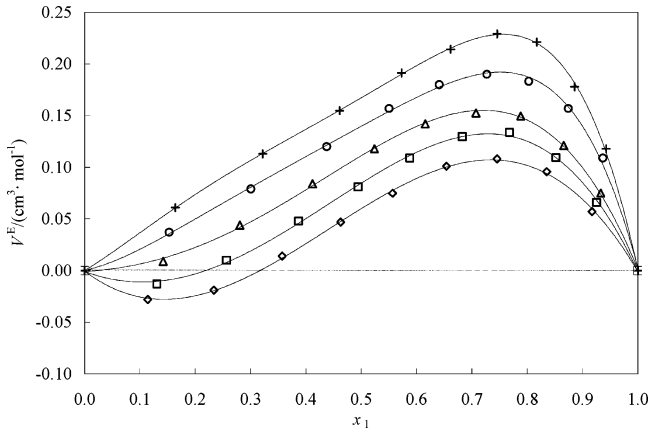

Figure 1. Excess molar volumes V^E for the binary mixtures: ◇, chlorobenzene + 1-hexanol; □, + 1-heptanol; Δ, + 1-octanol; ○, + 1-nonanol; +, + 1-decanol at 298.15 K. Solid line (Redlich−Kister equation).[8]

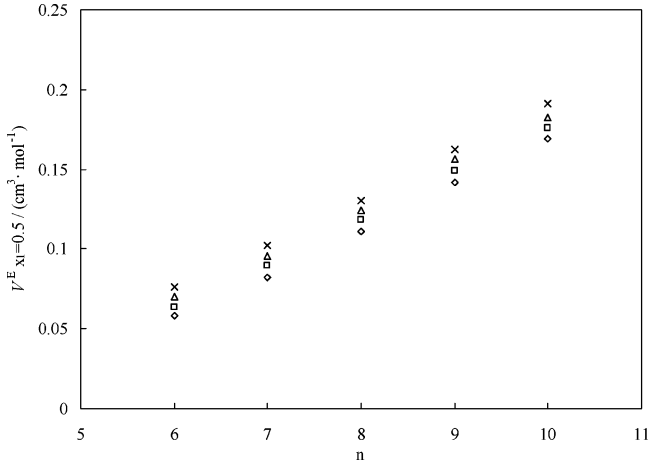

Figure 2. Equimolar excess molar volume V^E $x_1 = 0.5$, as a function of number of carbon atoms n for 1-alkanol of {chlorobenzene (1) + 1-alkanol (2)} binary mixtures at ◇, 298.15 K; □, 303.15 K; Δ, 308.15 K; and ×, 313.15 K.

equation:

$$Y = x_1 x_2 \sum_{j=1}^{p} a_{j-1}(x_1 - x_2)^{j-1} \tag{12}$$

where Y is V^E, $\Delta\eta$, u^D, or k_s^E, and x_1 and x_2 are the mole fractions of pure components 1 and 2, respectively. a_{j-1} is the polynomial coefficient, and p is the polynomial degree. The degree of eq 12 was optimized by applying the F-test;[27] the correlated results are shown in Table 6 in which the tabulated standard deviation σ was defined as

$$\sigma = ((\sum_{i=1}^{n}{}^2(Y_{exp} - Y_{cal}))\}/\{(n - j)\}) \tag{13}$$

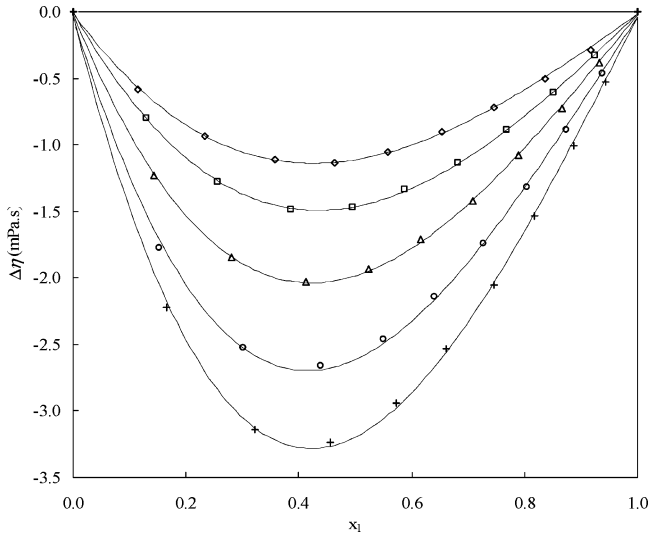

Figure 3. Viscosity deviation $\Delta\eta$ for the binary mixtures: ◇, chlorobenzene + 1-hexanol; □, + 1-heptanol; Δ, + 1-octanol; ○, + 1-nonanol; +, + 1-decanol} at 298.15 K. Solid line (Redlich−Kister equation).[8]

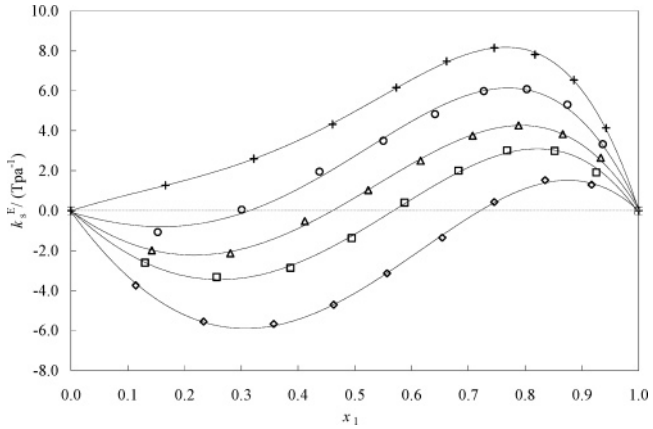

Figure 4. Deviation in isentropic compressibility k_s^E as a function of x_1 for the binary mixtures: ◇, chlorobenzene + 1-hexanol; □, + 1-heptanol; Δ, + 1-octanol; ○, + 1-nonanol; +, + 1-decanol} at 298.15 K. Solid line (Redlich−Kister equation.[8]

where n is the number of data points and j is the number of the coefficients. The subscripts exp and cal denote experimental and correlated values, respectively.

Figure 1 shows that the dependency of excess molar volumes V^E on the composition of {chlorobenzene + 1-alkanol} binary mixtures at 298.15 K. A sigmoidal trend could be seen on the behavior of {chlorobenzene + 1-hexanol or 1-heptanol}, and the values vary from negative to positive with the increase of chlorobenzene mole fraction. The remaining binary mixtures exhibit positive deviation for the entire mole fraction. Such a behavior could be a result of several opposing effects as was suggested by Treszczanowicz and Benson.[28] The negative excess molar volumes changes in mixtures rich in alcohol could be attributed to predominant interaction between the −OH group

Table 4. Values of Heat Capacities ($C_{p,i}^{\circ}$) at T = (298.15 to 313.15) K and Critical Temperatures (T_c) of Pure Components

	$C_{p,i}^{\circ}$/J·mol^{-1}K^{-1}				
	T = 298.15 K	T = 303.15 K	T = 308.15 K	T = 313.15 K	T_c
chlorobenzene	150.47	150.98	151.67	152.60	632.35
1-hexanol	241.64	246.52	251.47	256.48	610.30
1-heptanol	273.24	275.37	289.83	295.35	630.10
1-octanol	308.39	313.60	320.12	325.98	652.50
1-nonanol	336.33	342.40	348.18	354.40	670.70
1-decanol	371.10	375.40	380.40	384.50	687.30

Table 5. Isobaric Expansion Coefficients of Pure Components at T = (298.15 to 313.15) K

	α/kK^{-1}			
	T = 298.15 K	T = 303.15 K	T = 308.15 K	T = 313.15 K
chlorobenzene	1.0410	1.0430	1.0460	1.0480
1-hexanol	0.8747	0.8861	0.9078	0.9297
1-heptanol	0.8533	0.8732	0.8908	0.9100
1-octanol	0.8362	0.8644	0.8803	0.8969
1-nonanol	0.8202	0.8416	0.8633	0.8851
1-decanol	0.8112	0.8301	0.8550	0.8758

Table 6. Redlich−Kister Coefficients a_i and Standard Deviations σ for Excess and Deviations Functions of {Chlorobenzene (1) + 1-Alkanol (2)} Binary Mixtures from T = (298.15 to 313.15) K

	a_0	a_1	a_2	a_3	σ	a_0	a_1	a_2	a_3	σ
				Chlorobenzene (1) + 1-Hexanol (2)						
			T = 298.15 K					T = 303.15 K		
V^E/cm^3·mol^{-1}	0.2411	−0.659	0.0007	0.0080	0.0008	0.2640	−0.6565	0.0142	−0.0238	0.0005
$\Delta\eta$/mPa·s	−4.3847	−1.544	−0.5982	0.4519	0.0004	−3.5492	−1.0697	−0.0822	0.4221	0.0006
k_s^E/TPa^{-1}	−16.446	−29.364	23.706	−20.665	0.0007	−15.871	−30.523	19.414	−16.912	0.0005
u^D/m·s^{-1}	15.321	28.086	−14.075	3.499	0.0003	14.092	28.893	−16.703	3.822	0.0002
			T = 308.15 K					T = 313.15 K		
V^E/cm^3·mol^{-1}	0.2771	−0.676	0.0803	−0.0204	0.0001	0.3061	−0.6585	0.0846	−0.0605	0.0009
$\Delta\eta$/mPa·s	−2.9623	−0.891	−0.1690	0.4700	0.0004	−2.4696	−0.7154	−0.2189	0.3776	0.0005
k_s^E/TPa^{-1}	−12.789	−33.132	13.894	−5.392	0.0003	−11.212	−36.796	16.770	3.037	0.0003
u^D/m·s^{-1}	11.578	29.525	−16.223	3.813	0.0003	9.284	30.988	−16.198	−1.926	0.0004
				Chlorobenzene (1) + 1-Heptanol (2)						
			T = 298.15 K					T = 303.15 K		
V^E/cm^3·mol^{-1}	0.3403	−0.602	0.0983	−0.1584	0.0004	0.3596	−0.6468	0.1701	−0.1166	0.0006
$\Delta\eta$/mPa·s	−5.8462	−1.847	−0.1140	0.6135	0.0005	−4.8049	−1.4733	−0.2592	0.3967	0.0007
k_s^E/TPa^{-1}	−4.727	−34.532	11.694	4.573	0.0022	−3.569	−34.042	13.039	1.932	0.0002
u^D/m·s^{-1}	4.695	34.060	−13.091	−2.772	0.0004	3.265	35.300	−13.809	−4.142	0.0006
			T = 308.15 K					T = 313.15 K		
V^E/cm^3·mol^{-1}	0.3834	−0.616	0.2342	−0.2376	0.0007	0.4958	−0.4463	0.1300	−0.5723	0.0009
$\Delta\eta$/mPa·s	−3.9545	−1.097	−0.2147	0.1065	0.0003	−3.2614	−0.7820	−0.2106	−0.0371	0.0039
k_s^E/TPa^{-1}	−2.339	−35.657	15.593	3.733	0.0002	−0.992	−36.458	17.099	2.247	0.0005
u^D/m·s^{-1}	2.226	33.811	−15.891	−1.232	0.0009	0.599	32.793	−17.187	2.465	0.0006
				Chlorobenzene (1) + 1-Octanol (2)						
			T = 298.15 K					T = 303.15 K		
V^E/cm^3·mol^{-1}	0.4446	−0.604	0.2423	−0.0844	0.0005	0.4723	−0.5584	0.2894	−0.1870	0.0008
$\Delta\eta$/mPa·s	−7.8670	−2.769	−0.6128	0.2080	0.0004	−6.2464	−2.0623	−0.4188	0.3469	0.0003
k_s^E/TPa^{-1}	2.578	−32.161	10.994	−4.089	0.0005	4.472	−33.736	12.456	−2.497	0.0002
u^D/m·s^{-1}	−3.819	27.394	−15.877	8.483	0.0002	−5.833	26.944	−17.698	10.528	0.0003
			T = 308.15 K					T = 313.15 K		
V^E/cm^3·mol^{-1}	0.4978	−0.516	0.3680	−0.2667	0.0005	0.5207	−0.4802	0.4598	−0.3000	0.0005
$\Delta\eta$/mPa·s	−5.1366	−1.365	−0.2807	−0.1777	0.0008	−4.0573	−1.2847	−0.316	0.1284	0.0015
k_s^E/TPa^{-1}	6.8542	−32.497	15.537	−7.698	0.0006	9.179	−30.532	16.548	−11.576	0.0004
u^D/m·s^{-1}	−7.502	26.848	−21.125	13.709	0.0003	−9.374	26.747	−23.737	17.516	0.0005
				Chlorobenzene (1) + 1-Nonanol (2)						
			T = 298.15 K					T = 303.15 K		
V^E/cm^3·mol^{-1}	0.5602	−0.566	0.5146	−0.4148	0.0001	0.5922	−0.5465	0.6180	−0.5299	0.0004
$\Delta\eta$/mPa·s	−10.297	−3.820	−1.291	−0.268	0.0008	−7.873	−2.549	−0.463	0.298	0.0007
k_s^E/TPa^{-1}	10.952	−31.995	14.187	−10.297	0.0007	13.739	−31.583	18.396	−12.733	0.0003
u^D/m·s^{-1}	−12.037	33.229	−16.824	17.124	0.0004	−14.481	32.221	−19.104	19.982	0.0005
			T = 308.15 K					T = 313.15 K		
V^E/cm^3·mol^{-1}	0.6453	−0.5960	0.6850	−0.432	0.0007	0.6759	−0.5559	0.7447	−0.5600	0.0007
$\Delta\eta$/mPa·s	−6.299	−1.880	−0.383	0.055	0.0004	−5.0589	−1.4924	−0.414	0.328	0.0009
k_s^E/TPa^{-1}	16.917	−30.832	24.281	−10.584	0.0002	20.841	−28.467	26.146	−17.647	0.0009
u^D/m·s^{-1}	−16.745	30.506	−18.358	24.629	0.0006	−19.501	27.005	−19.510	37.933	0.0002
				Chlorobenzene (1) + 1-Decanol (2)						
			T = 298.15 K					T = 303.15 K		
V^E/cm^3·mol^{-1}	0.670	−0.5880	0.6432	−0.6531	0.0003	0.6913	−0.6165	0.7504	−0.6599	0.0005
$\Delta\eta$/mPa·s	0.669	−0.592	0.650	−0.651	0.0005	−9.916	−3.297	−0.713	0.428	0.0008
k_s^E/TPa^{-1}	21.944	−32.025	20.510	5.639	0.0002	24.493	−25.840	24.735	−17.805	0.0004
u^D/m·s^{-1}	−22.004	20.622	−20.758	17.664	0.0008	−24.111	21.183	−27.420	23.536	0.0003
			T = 308.15 K					T = 313.15 K		
V^E/cm^3·mol^{-1}	0.7277	−0.548	0.8137	−1.0020	0.0009	0.7666	−0.4825	0.8519	−1.2842	0.0005
$\Delta\eta$/mPa·s	−7.867	−2.426	−0.611	0.343	0.0009	−6.227	−1.830	−0.451	0.128	0.0006
k_s^E/TPa^{-1}	27.031	−22.967	30.157	−27.637	0.0005	30.024	−21.505	33.477	−38.421	0.0003
u^D/m·s^{-1}	−26.288	20.912	−30.530	28.417	0.0006	−29.065	17.749	−33.175	41.166	0.0005

of an alcohol and electronegative Cl atom on the benzene ring through hydrogen bonding. The positive excess molar volumes change in chlorobenzene-rich region suggest that may be due to the effect of rupture hydrogen bonded between unlike molecules, and the dominant effect will be physical interaction consisting mainly of dispersion forces. The increase in excess molar volume with increasing chain length of 1-alkanols implies that dipole−dipole interactions are weak in higher 1-alkanols

Table 7. Values of Molar Volume V_m, Molar Volume at Absolute Zero V_0, Free Length L_f, Surface Area Y, Collision Factor S, and Space Filling Factor r_f of the Pure Components at 298.15 K

component	V_m / cm³·mol⁻¹	V_0 / cm³·mol⁻¹	L_f / Å	Y / cm·²mol⁻¹	S	r_f
chlorobenzene	102.26	84.45	0.4626	87.605	3.100	2.667
1-hexanol	125.34	102.50	0.5113	77.002	3.191	2.546
1-heptanol	141.93	117.23	0.5250	95.790	3.521	2.461
1-octanol	158.46	131.94	0.5370	103.647	3.416	2.319
1-nonanol	174.97	143.53	0.5735	109.625	3.890	2.301
1-decanol	191.46	157.00	0.5921	116.373	4.021	2.010

Table 8. Comparison of Equimolar Experimental Speeds of Sound in Binary Mixtures with Those Estimated from the CFT and FLT at T = 298.15 K

	u_{exp} / m·s⁻¹	u_{CFT} / m·s⁻¹	σ %	u_{FLT} / m·s⁻¹	σ %
chlorobenzene (1) + 1-hexanol (2)	1272.60	1275.09	0.1950	1289.40	1.3200
chlorobenzene (1) + 1-heptanol (2)	1283.53	1286.94	0.2650	1312.50	2.2570
chlorobenzene (1) + 1-octanol (2)	1293.73	1296.40	0.2060	1321.60	2.1540
chlorobenzene (1) + 1-nonanol (2)	1308.23	1306.77	0.1120	1332.60	1.8628
chlorobenzene (1) + 1-decanol (2)	1318.56	1323.10	0.2310	1342.60	1.8200

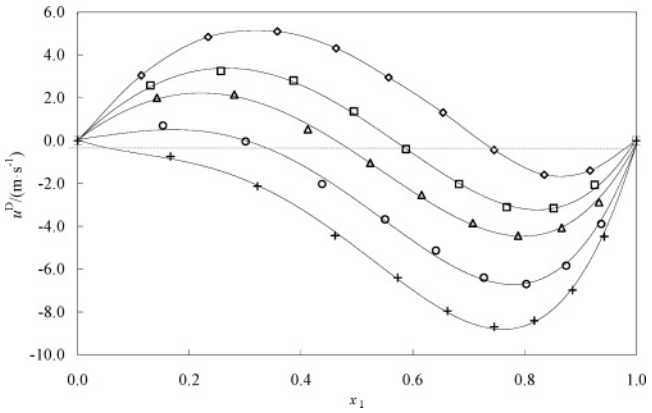

Figure 5. Deviation of the speeds of sound u^D from their ideal values for the binary mixtures: ◇, chlorobenzene + 1-hexanol; □, + 1-heptanol; Δ, + 1-octanol; ○, + 1-nonanol; +, + 1-decanol} at 298.15 K. Solid line (Redlich−Kister.[8]

owing to the decrease in their polarizability as suggested by Mecke,[29] which is quite evident in the behavior of the {chlorobenzene (1) + 1-decanol (2)} binary mixture.

Figure 2 presents the equimolar excess molar volume $V^E_{(x=0.5)}$ of {chlorobenzene (1) + 1-alkanol (2)} against a number of carbon atoms of 1-alkanol. As the chain length of 1-alkanol increases, the excess molar volume values increase with the same dependency and systematic variation and so does it with the increase in temperature.

The comparison of equimolar excess molar volumes $V^E_{(x=0.5)}$ values (0.0438, 0.0377, 0.035) cm³·mol⁻¹ of binary liquid mixtures, composed of haloalkane {1-chlorobutane + 1-hexanol-, or 1-heptanol, or 1-octanol},[30] with $V^E_{(x=0.5)}$ values (0.058, 0.0825, 0.1107) cm³·mol⁻¹ of halobenzene {chlorobenzene + 1-hexanol, or 1-heptanol, or 1-octanol} binary mixtures of the systems under studies at temperature 298.15 K, shows opposite behavior for dependency of excess molar volumes on the chain length of alcohol, suggesting that the shape, type, and molecular size of the solvent molecule will effect the behavior of haloalkane or halobenzene + 1-alkanol binary liquid mixtures. The author[30] suggests that this opposite behavior may be due to a lower steric interaction among the long alcohol carbon chains in order to admit the molecules of $CH_3(CH_2)_3Cl$ into their environment.

To estimate the viscosity of liquid mixtures in terms of pure component values, the experimental viscosity data of the binary mixtures were fitted to semiempirical relations proposed by Grunberg and Nissan,[9] McAllister's three- and four-body models,[10] and the equation of Heric and Brewer.[11] Our analysis shows the suitability of all four relations for representing the viscosities of the systems with an average of absolute values of deviations (3×10^{-2}, 7×10^{-3}, 4×10^{-3}, 5.5×10^{-3}), respectively. The best correlation method gives relatively low standard deviation is found to be the McAllister four-body model.

The deviations in viscosity $\Delta\eta$ at 298.15 K throughout over whole the mixtures compositions are negative as shown in Figure 3, a systematic dependence of $\Delta\eta$ on the chain length could be seen. The negative values of viscosity deviation decrease in the following sequence: 1-hexanol >1-heptanol >1-octanol >1-nonanol >1-decanol.

The speed of sound for the five binary mixtures at 298.15 K were evaluated from both free length theory (FLT) and collision factor theory (CFT) formulations. The pertinent relations in these calculations and their theoretical basis were described by Schaaffs,[12] Jacobson,[13] and Nutsch-Kuhnkies.[31] Values of molar volume V_m, molar volume at absolute zero V_0, free Length L_f, surface area Y, collision factor S, and space filling factor r_f of the pure components at 298.15 K are given in Table 7.

The experimental speeds of sound u data at equimolar compositions ($x_1 = 0.5$) of the binary mixtures under studies at 298.15 K are compared with calculated values using aforementioned theories (Table 8). The values of standard percentage deviations σ of u estimating from CFT are in the range from 0.195 to 0.231 for the five binary mixtures investigated while the corresponding values for FLT are from 2.25 to 1.32, with an average absolute value of deviation of 0.20 and 1.88, respectively This indicates that Schaaffs' collision factor theory is suitable for predication of speed sound data.

Figure 4 shows the behavior and dependence of excess isentropic compressibilities k^E_s on the mole fraction of chlorobenzene at 298.15 K. While the {chlorobenzene (1) + 1-decanol (2)}binary mixture reveals a positive deviation in its behavior, the remaining binary mixtures exhibit a sigmoidal kind of behavior, and the values vary from negative to positive. The negative values of k^E_s for all the aforementioned system indicate that each mixture is less compressible than the corresponding ideal mixture, and the positive values indicate the mixture is more compressible and that excess isentropic compressibilities vary as follows: 1-decanol >1-nonanol >1-octanol >1-heptanol >1-hexanol. As temperature increases, the

absolute values of k_s^E decrease with the same dependencies and systematic variation, but these results are not presented to avoid overcrowding the curves.

The opposite behavior could be seen for the deviation of the speed of sound from there ideal values at 298.15 K throughout the whole mixtures compositions as shown in Figure 5. The u^D exhibits a negative deviation for {chlorobenzene + 1-decanol} and a sigmoidal behavior of {chlorobenzene + 1-hexanol, or 1-heptanol, or 1-octanol, or 1-nonanol}, with values varying from positive to negative and decreasing as follows: 1-hexanol > 1-heptanol > 1-octanol > 1-nonanol}. As the temperature increases, the u^D values decrease with the same dependencies and systematic variation.

Conclusions

In this study we report experimental data of density ρ, viscosity η, and speed of sound u of {chlorobenzene + 1-alkanol) binary mixtures at (298.15 to 313.15) K and atmospheric pressure as well as the calculated excess and deviation functions. The excess molar volumes of {chlorobenzene + 1-hexanol or 1-heptanol} as well as the excess isentropic compressibilities of {chlorobenzene + 1-hexanol, or 1-heptanol, or 1-octanol, or 1-nonanol} showed a sigmoidal trend behavior. These values vary from negative to positive with the increase of chlorobenzene mole fraction. The remaining binary mixtures exhibit positive deviation for the entire mole fraction, respectively. While the equimolar excess molar volumes increase, the u^D values decrease as the chain length of 1-alkanol increases. The viscosity deviation decrease in the following sequence: 1-hexanol > 1-heptanol > 1-octanol > 1-nonanol > 1-decanol. The best correlation method to represent the viscosity for the systems of our study is found to be the McAllister four-body model.

Literature Cited

(1) Tanaka, R.; Nakamichi, T. Excess molar volumes and excess molar heat capacities of (benzonitrial + chlorobenzene, or benzene, or toluene) at the temperature of 298.15 K and 303.15 K. *J. Chem. Thermodyn.* **1997**, *29*, 221−227.

(2) Touriño, A.; Hervello, M.; Gayol, A.; Marino, G.; Iglesias, M. Excess molar volumes of the ternary mixtures chlorobenzene + *n*-hexane + linear aliphatic alkane (C_{11}−C_{12}) at 298.15 K. *J. Mol. Liq.* **2005**, *122*, 87−94.

(3) Prasad, D. H. L.; Viswanathan, S.; Anand, R. M. Densities and viscosities of binary liquid mixtures of anisole or methyl *tert*-butyl ether with benzene, chlorobezene, benzonitrial, and nitrobenzene. *J. Chem. Eng. Data* **2000**, *45*, 764−770.

(4) Oswal, S. L.; Patel, B. M.; Patel, A. M.; Ghael, N. Y. Densities, speeds of sound, isentropic compressibilities, and refractive indices of binary mixtures of methyl methacrylate with hydrocarbons, haloalkanes and alkyl amins. *Fluid Phase Equilib.* **2003**, *206*, 313−329.

(5) Oswal, S. L.; Patel, I. N. Speed of sound, isentropic compressibility and refractive index of binary mixtures of alkyl ehanoates with chloroalkanes at 303.15 K. *J. Mol. Liq.* **2005**, *116*,99−107.

(6) Nayak, J. N.; Aralogupi, M. I.; Aminabhavi, T. M. Density, viscosity, refractive index and speed of sound in the binary mixtuyes of ethyl chloroacetate with aromatic liquids at 298.15, 303.15, and 303.15 K. *J. Chem. Eng. Data* **2002**, *47*, 964−969.

(7) Tejraj, M.; Aminabhavi, T. M.; Banerjee, K. Density, viscosity, refractive index in binary mixtures of 1-chloronaphalene with benzene methylbenzene, 1,4-dimethylbenzene, 1,3,5-trimethylbenzene, and methoxybenzene at 298.15, 303.15, and 308.15 K. *J. Chem. Eng. Data* **1999**, *44*, 547−552.

(8) Redlich, O.; Kister, A. T. Algebraic representation of thermodynamic properties and the classification of solutions. *Ind. Eng. Chem.* **1948**, *40*, 345−348.

(9) Grunberg, L.; Nissan, A. H. Mixture law for viscosity. *Nature* **1949**, *164*, 799−800.

(10) McAllister, R. A. The viscosity of liquid mixtures. *AIChE J.* **1960**, *6*, 427−431.

(11) Heric, E.L.; Brewer, J. G. Viscosity of some binary liquid nonelectrolyte mixtures. *J. Chem. Eng. Data* **1967**, *12* (4), 574−583.

(12) Schaffs, W. *Molekularakustich*; Springer-Verlag: Berlin, 1963; Chapters XI and XII.

(13) Jacobson, B. Intermolecular free length in the liquid state. I. Adiabatic and isothermal compressibilities. *Acta Chem. Scand. A* **1952**, *8*, 1485−1498.

(14) Riddick, J. A.; Bunger, W. B.; Sakano, T. K. *Organic Solvents Physical Properties and Methods of Purifications, Techniques in Chemistry*; John Wiley; New York, 1986; Vol. II.

(15) Al-Jimaz, A. S.; Al-Kandary, J. A.; Abdu-Latif, A. M. Viscosities and densities for binary mixtures of phenetole with 1-pentanol, 1-hexanol, 1-heptanol, 1-octanol, 1-nonanol, and 1-decanol at different temperatures. *Fluid Phase Equilib.* **2004**, *218*, 247−260.

(16) Shan, Z.; Asfour, A. A. Viscosities and densities of nine binary 1-alkanol systems at 293.15 K and 298.15 K. *J. Chem. Eng. Data* **1999**, *44*, 118−123.

(17) Dewan, R. K.; Mehta, S. K.; Paraqshar, R.; Bala, K. Topological investigations on the association of alkanols: excess volume of pyridine−alkanol (C1−C10) mixtures. *J. Chem. Soc. Faraday Trans.* **1991**, *87* (10), 1561−1568.

(18) DIPPR Project 801. Evaluated Thermophysical Properties of Pure Chemical Database. T. P. Laboratory Brigham Young University, February 2003.

(19) Ŝerbanović, S. P.; Kijevčanin., M. L.; Radović, I. R.; Djordjević, B. D. Effect of temperature on the excess molar volumes of some alcohol + aromatic mixtures and modeling by cubic EOS mixing rules. *Fluid Phase Equilib.* **2006**, *239*, 69−82.

(20) Oswal, S. L.; Prajapati, K. D.; Ghael, N. Y.; Ijardar, S. P. Speeds of sound, isentropic compressibilities, and excess molar volumes of alkanol + cycloalkane at 303.15 K. II. Results for alkan-2-ols + cyclohexane and alkane-1-ol, + methylcyclohexane and theoretical interpretation. *Fluid Phase Equilib.* **2004**, *218*, 131−140.

(21) Kinart, C. M.; Kinart, W. J.; Ćwiklińska, A. 2-Methoxyethanol + tetrahydrofuran binary liquid system. viscosities, densities, excess molar volumes and excess Gibbs activation energies of viscous flow at various temperatures. *J. Therm. Anal. Calorim.* **2002**, *68*, 307−317.

(22) George, J.; Sastry, N. V. Partial excess molar volumes, partial excess isentropic compressibilities and relative permittivities of water + 1,2-diol derivative and water + 1,2-dimethoxyethane at different temperatures. *Fluid Phase Equilib.* **2004**, *216*, 307−321.

(23) Aminabhavi, T. M.; Aralaguppi, M. I.; Bindu, G.; Khinnavar, R. S. Densities, shear viscosities, refractive indices, and speeds of sound of bis(2-methoxyethyl) ether with hexane, heptane, octane, and 2,2,4-trimethylpentane in the temperature interval 298.15 to 318.15 K. *J. Chem. Eng. Data* **1994**, *39*, 522−528.

(24) Benson, G. C.; Kiyohara, O. Evaluation of excess isentropic compressibities and isochoric heat capacities. *J. Chem. Thermodyn.* **1979**, *11*, 1061−1064.

(25) Pal, A.; Singh, Y. P. The speed of sound and isentropic functions of $\{x\mathrm{H(CH_2)}_v(\mathrm{OC_2H_4})_2\mathrm{OH} + (1-x)(\mathrm{C_4H_9})_2\mathrm{O}\}$, ($v = 1$, 2, and 4) at the temperature 298.15 K. *J. Chem. Thermodyn.* **1996**, *28*, 1197−1205.

(26) Aminabhavi, T. M.; Phyada, H. T. S.; Khinnaaver, R. S.; Bindu, G.; Hansen, K. C. Densities, refractive indices, speed of sound, and shear viscosities of diethylene glycol dimethyl ether with ethyl acetate, methyl benzoate, ethyl benzoate and diethyl succinate in the temperature range from 298.15 to 318.15 K. *J. Chem. Eng. Data* **1994**, *39*, 251−260.

(27) Bevington, P. *Data Reduction and Error Analysis for the Physical Sciences*; McGraw-Hill: New York, 1969

(28) Tresczanowicz, A. J.; Benson, G. C. Excess volumes of alkanol + alkane binary systems in terms of an association model with a Flory contribution term. *Fluid Phase Equilib.* **1985**, *23*, 117−135.

(29) Mecke, R. Infra-red spectra of hydroxylic compounds. *Discuss. Faraday Soc.* **1950**, *9*, 161−177.

(30) Santana, P.; Balseiro, J.; Jiménez, E.; Franjo, C.; Legido, J. L.; Romaní, L.; Paz, Andrade, M. I. Measurments and analysis of excess molar enthalpies and excess molar volumes of the binary systems $\{x\mathrm{CH_3(CH_2)_3Cl} + (1-x)\mathrm{CH_3(CH_2)}_{n-1}\mathrm{OH}\}$ ($n = 4$ to 8) at $T = 298.15$ K. *J. Chem. Thermodyn.* **1999**, *31*, 547−554.

(31) Nutsch-Kuhnkies, R. Sound velocities of binary mixtures and solutions. *J. Chem. Thermodyn.* **1979**, *11*, 861−873.

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