Density, Speed of Sound, and Viscosity of Binary Mixtures of Poly(propylene glycol) 400 + Ethanol and + 2-Propanol at Different Temperatures

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The density and speed of sound of the solutions of poly(propylene glycol) 400, in ethanol and 2-propanol at $T = (288.15 \text{ to } 328.15)$ K, and dynamic viscosity of these solutions at $T = (298.15 \text{ to } 328.15)$ K have been measured experimentally over the entire range of compositions and atmospheric pressure. From these experimental data, the excess molar volume, V_m^E, excess molar isentropic compression, $\kappa^E_{s,m}$, and deviation of logarithm of viscosity, $\Delta \ln \eta$, have been determined for each composition. V_m^E, $\kappa^E_{s,m}$, and viscosity data have been adequately fitted to the Redlich−Kister and NRTL models.

Introduction

Knowledge of volumetric and acoustical properties of polymer solutions has been proven to be a very useful tool in evaluating the structural interactions occurring in these solutions. In this respect, the isentropic compressibility and excess molar volume evaluated from sound velocity and density measurements have been used to determine the structure and the nature of molecular interactions in aqueous and nonaqueous solutions of polymers. Knowledge of the viscosity of polymer solutions is important for practical and theoretical purposes. Viscosity of polymer solutions provides an invaluable type of data in polymer research, development, and engineering. Furthermore, the simultaneous investigation of viscosity and volume effects on mixing can be a powerful tool for the characterization of intermolecular interactions present in these mixtures.

In recent years, numerous studies have been carried out on mixtures containing poly(propylene glycols), PPGs. PPG is used in many formulations for polyurethanes. It is used as a rheology modifier,[1] in solid tires, in automobile seats,[2] in foams,[3] and in membranes.[4]

This work is a continuation of our studies on the determination of the density, speed of sound, and dynamic viscosity of the polymer + alcohol systems.[5−7]

Experimental Section

PPG400 was obtained from Fluka. The number average molar mass M_n of this polymer was determined by a cryoscopic osmometer (Osmomat model 030). For this purpose, freezing point depression measurements on PPG400 + H_2O were carried out in different concentrations, and a $\Delta T/K_sC$ vs C curve was plotted (ΔT, C, and K_s are the freezing point depression, concentration of samples, and cryoscopic constant, respectively). The intercept of this curve is $1/M_n$, from which M_n for this polymer was found to be 401 $\text{g}\cdot\text{mol}^{-1}$. Ethanol (minimum mass fraction purity 0.998) and 2-propanol (minimum mass fraction purity 0.995) were obtained from Merck and used without further purification. Double distilled, deionized water was used. The solutions were prepared by mass using an analytical balance (Shimatzu, 321-34553, Shimatzu Co., Japan) with an uncertainty of $\pm 1\cdot10^{-7}$ kg.

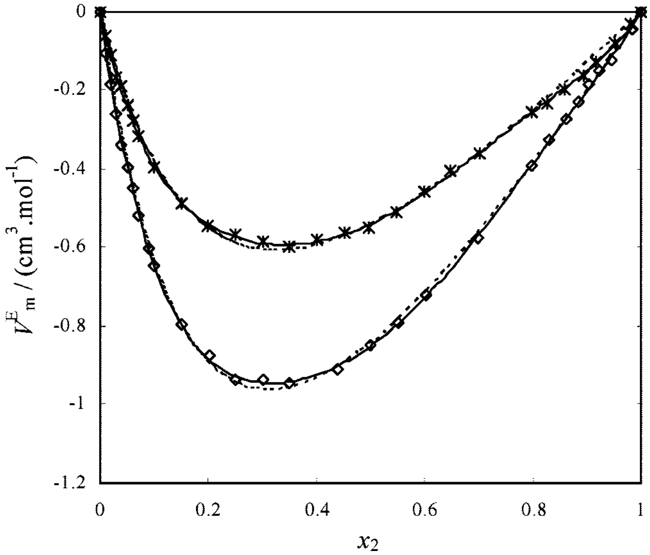

Figure 1. Experimental and calculated excess molar volume, V_m^E, plotted against mole fraction of PPG, x_2, at 298.15 K: ◇, ethanol + PPG400 system; ∗, 2-propanol + PPG400 system; —, Redlich−Kister polynomial; - - -, NRTL model.

Density and speed of sound data were continuously measured using a commercial density and speed of sound measurement apparatus (Anton Paar DSA 5000 densimeter and speed of sound analyzer). Details of the experimental setup and measuring procedure have been given elsewhere.[8] In each measurement, the uncertainty of density and speed of sound were $\pm 3.0\cdot10^{-6}$ $\text{g}\cdot\text{cm}^{-3}$ and ± 0.5 $\text{m}\cdot\text{s}^{-1}$, respectively.

The viscosity was determined by a Setavis Kinematic Viscometer-83541-3, England, as described previously.[9] The uncertainty for the dynamic viscosity determination was estimated to be ± 0.5 %.

Density, speed of sound, and viscosity values of the pure components are given in Table 1 at different temperatures and compared with the literature values.

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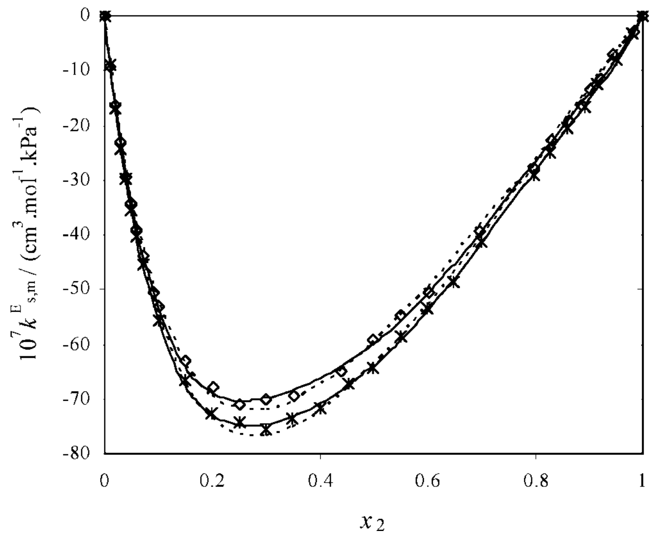

Figure 2. Experimental and calculated excess molar isentropic compression, $\kappa^E_{s,m}$, plotted against mole fraction of PPG, x_2, at 298.15 K: ◇, ethanol + PPG400 system; ∗, 2-propanol + PPG400 system; —, Redlich−Kister polynomial; - - -, NRTL model.

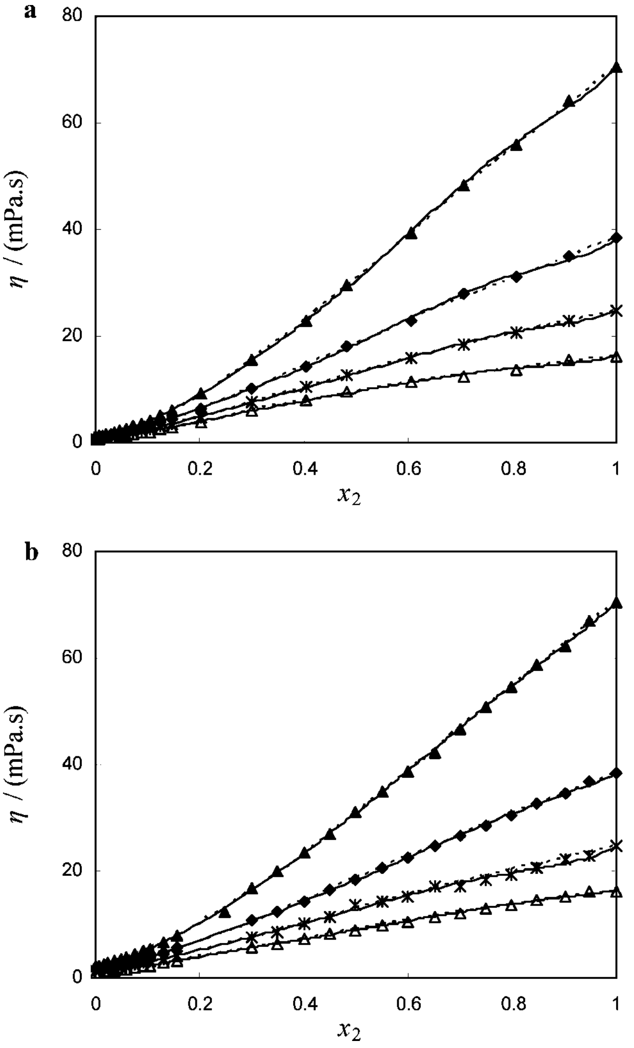

Figure 3. Experimental and calculated viscosity, η, plotted against mole fraction of PPG, x_2, for the ethanol + PPG400 system (a) and the 2-propanol + PPG400 system (b) at different temperatures: ▲, 298.15 K; ◆, 308.15 K; ∗, 318.15 K; △, 328.15 K; —, Redlich−Kister equation; - - -, NRTL model.

Table 1. Density, *d*, Speed of Sound, *u*, and Dynamic Viscosity, η, for Pure Components at T = (288.15 to 328.15) K

component	T / K	d / g·cm^{-3}	u / m·s^{-1}	η / mPa·s
ethanol	288.15	0.79364	1177.47	
	298.15	0.78510	1143.49	1.0930
		0.78522[13]	1143.10[6]	1.077[13]
		0.785085[6]		1.084[14]
	308.15	0.77643	1109.69	0.902
		0.77551[14]	1111[14]	0.903[14]
		0.77726[15]		
	318.15	0.76762	1076.32	0.759
	328.15	0.75860	1043.07	0.644
2-propanol	288.15	0.78912	1173.73	
		0.7891[16]		
	298.15	0.78088	1138.94	2.089
		0.780824[6]	1138.87[6]	2.036[17]
		0.7809[16]	1141[15]	2.045[18]
	308.15	0.77227	1104.04	1.564
		0.77275[15]		1.521[15]
	318.15	0.76330	1068.72	1.192
		0.7635[16]		1.191[16]
	328.15	0.75392	1032.81	0.942
poly(propylene glycol) (PPG400)	288.15	1.01115	1399.74	
		1.011860[5]	1400.58[5]	
	298.15	1.00352	1365.85	70.435
		1.003929[5]	1366.70[5]	
	308.15	0.99554	1332.91	38.266
		0.995937[5]	1333.64[5]	
	318.15	0.98751	1300.72	24.700
	328.15	0.97950	1269.25	16.342

Results and Discussion

The experimental density, *d*, and speed of sound, *u*, data for ethanol + PPG and 2-propanol + PPG systems, as a function of PPG mole fraction, x_2, at T = (288.15 to 328.15) K are collected in Table 2.

Values of the excess molar volume, V^E_m, and excess molar isentropic compression, $\kappa^E_{s,m}$, were calculated by the following equations

$$V^E_m = \sum_{i=1}^{2} x_i M_i \left[\frac{1}{d} - \frac{1}{d_i}\right] \tag{1}$$

$$\kappa^E_{s,m} = \sum_{i=1}^{2} x_i M_i \left[\frac{1}{(du)^2} - \frac{1}{(d_i u_i)^2}\right] \tag{2}$$

where x is the mole fraction; M is the molar mass; and subscripts 1 and 2 stand for solvent and polymer, respectively. The calculated V^E_m and $\kappa^E_{s,m}$ values for ethanol + PPG and 2-propanol + PPG systems have been plotted versus the mole fraction of polymer, x_2, in Figures 1 and 2 at 298.15 K as examples, respectively. Figures 1 and 2 show that both the V^E_m and $\kappa^E_{s,m}$ are negative and become more negative when temperature increases. The negative values of V^E_m and $\kappa^E_{s,m}$ for studied mixtures can be explained as a cumulative manifestation of the various types of intermolecular interactions between the components.

The deviation of logarithm of viscosity can be calculated as

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

where η_i is the dynamic viscosity of the pure component i. The experimental dynamic viscosity, η, data for ethanol + PPG and 2-propanol + PPG systems, as a function of PPG mole fraction,

Table 2. Density and Speed of Sound of Binary Mixtures Containing Ethanol + PPG400 and 2-Propanol + PPG400 at Different Temperatures

x_2	d ($g\cdot cm^{-3}$)	u ($m\cdot s^{-1}$)	x_2	d ($g\cdot cm^{-3}$)	u ($m\cdot s^{-1}$)	x_2	d ($g\cdot cm^{-3}$)	u ($m\cdot s^{-1}$)	x_2	d ($g\cdot cm^{-3}$)	u ($m\cdot s^{-1}$)
Ethanol + PPG400			2-Propanol + PPG400			Ethanol + PPG400			2-Propanol + PPG400		
$T = 288.15$ K						$T = 318.15$ K					
0.0101	0.80910	1191.13	0.0101	0.80085	1184.61	0.0101	0.78319	1090.62	0.0101	0.77509	1080.08
0.0202	0.82267	1203.58	0.0199	0.81134	1194.54	0.0202	0.79688	1103.50	0.0199	0.78566	1090.57
0.0301	0.83465	1214.84	0.0301	0.82471	1204.43	0.0301	0.80896	1115.27	0.0301	0.79585	1100.81
0.0400	0.84566	1225.54	0.0399	0.83022	1212.84	0.0400	0.82008	1126.60	0.0399	0.80465	1109.58
0.0500	0.85540	1235.28	0.0500	0.83887	1221.31	0.0500	0.82990	1136.43	0.0500	0.81335	1118.40
0.0600	0.86440	1244.18	0.0601	0.84688	1229.16	0.0600	0.83899	1145.92	0.0601	0.82140	1126.44
0.0705	0.87312	1253.25	0.0702	0.85430	1236.68	0.0705	0.84781	1155.27	0.0702	0.82887	1134.41
0.0905	0.88737	1268.18	0.1000	0.87340	1256.17	0.0905	0.86220	1170.52	0.1000	0.84821	1154.51
0.0998	0.89340	1274.45	0.1510	0.89914	1282.37	0.0998	0.86826	1176.62	0.1510	0.87411	1181.42
0.1497	0.91887	1301.79	0.2001	0.91806	1301.83	0.1497	0.89399	1204.63	0.2001	0.89320	1201.74
0.2005	0.93701	1321.60	0.2500	0.93314	1317.71	0.2005	0.91257	1224.36	0.2500	0.90849	1217.70
0.2506	0.95072	1336.87	0.3006	0.94561	1331.02	0.2506	0.92644	1239.82	0.3006	0.92106	1231.33
0.3000	0.96106	1347.92	0.3495	0.95551	1341.20	0.3000	0.93678	1250.57	0.3495	0.93107	1241.72
0.3509	0.96980	1357.63	0.4003	0.96416	1350.27	0.3509	0.94563	1260.10	0.4003	0.93979	1251.28
0.4391	0.98107	1369.57	0.4515	0.97147	1358.01	0.4391	0.95703	1272.26	0.4515	0.94721	1258.82
0.4991	0.98678	1375.13	0.4983	0.97729	1364.34	0.4991	0.96281	1277.47	0.4983	0.95313	1265.37
0.5514	0.99113	1379.93	0.5492	0.98281	1369.93	0.5514	0.96711	1281.94	0.5492	0.95870	1270.89
0.6015	0.99462	1383.74	0.6008	0.98759	1375.17	0.6015	0.97068	1285.70	0.6008	0.96357	1276.29
0.6982	1.00008	1389.16	0.6488	0.99157	1379.58	0.6982	0.97626	1290.75	0.6488	0.96760	1280.62
0.7996	1.00459	1393.61	0.7008	0.99541	1383.30	0.7996	0.98085	1295.14	0.7008	0.97153	1284.39
0.8313	1.00580	1394.88	0.7991	1.00167	1389.90	0.8313	0.98209	1296.31	0.7991	0.97784	1291.17
0.8637	1.00697	1395.96	0.8274	1.00320	1391.49	0.8637	0.98330	1297.05	0.8274	0.97946	1292.60
0.8856	1.00772	1396.73	0.8598	1.00489	1393.28	0.8856	0.98404	1298.05	0.8598	0.98115	1294.66
0.9023	1.00825	1397.10	0.8930	1.00656	1395.06	0.9023	0.98457	1298.29	0.8930	0.98284	1296.10
0.9230	1.00891	1397.77	0.9162	1.00761	1395.95	0.9230	0.98525	1299.03	0.9162	0.98394	1297.15
0.9458	1.00962	1398.25	0.9524	1.00923	1397.46	0.9458	0.98599	1299.27	0.9524	0.98556	1299.05
0.9831	1.01071	1399.41	0.9805	1.01040	1398.89	0.9831	0.98707	1300.43	0.9805	0.98673	1299.97
$T = 298.15$ K						$T = 328.15$ K					
0.0101	0.80058	1157.37	0.0101	0.79261	1149.88	0.0101	0.77422	1057.54	0.0101	0.76578	1044.69
0.0202	0.81419	1169.77	0.0199	0.80313	1160.19	0.0202	0.78798	1070.84	0.0199	0.77639	1055.10
0.0301	0.82620	1181.20	0.0301	0.81326	1170.09	0.0301	0.80011	1082.81	0.0301	0.78671	1065.45
0.0400	0.83725	1192.36	0.0399	0.82202	1178.63	0.0400	0.81125	1093.98	0.0399	0.79555	1074.56
0.0500	0.84701	1201.94	0.0500	0.83067	1187.20	0.0500	0.82114	1104.18	0.0500	0.80423	1083.49
0.0600	0.85603	1211.25	0.0601	0.83868	1194.98	0.0600	0.83024	1113.49	0.0601	0.81235	1091.97
0.0705	0.86479	1220.45	0.0702	0.84611	1202.97	0.0705	0.83909	1122.91	0.0702	0.81984	1099.89
0.0905	0.87909	1235.48	0.1000	0.86533	1222.31	0.0905	0.85354	1138.34	0.1000	0.83928	1120.26
0.0998	0.88512	1241.52	0.1510	0.89109	1248.69	0.0998	0.85966	1144.72	0.1510	0.86534	1147.93
0.1497	0.91066	1268.99	0.2001	0.91006	1265.55	0.1497	0.88554	1172.59	0.2001	0.88451	1168.31
0.2005	0.92915	1288.86	0.2500	0.92523	1284.18	0.2005	0.90413	1192.47	0.2500	0.89992	1184.85
0.2506	0.94291	1304.36	0.3006	0.93770	1297.76	0.2506	0.91806	1207.88	0.3006	0.91253	1198.21
0.3000	0.95323	1315.02	0.3495	0.94765	1307.76	0.3000	0.92851	1218.63	0.3495	0.92263	1209.08
0.3509	0.96188	1324.64	0.4003	0.95630	1317.20	0.3509	0.93736	1228.54	0.4003	0.93139	1218.60
0.4391	0.97321	1336.74	0.4515	0.96366	1324.57	0.4391	0.94880	1240.37	0.4515	0.93888	1226.61
0.4991	0.97905	1342.23	0.4983	0.96953	1331.07	0.4991	0.95461	1245.53	0.4983	0.94482	1232.93
0.5514	0.98331	1346.71	0.5492	0.97503	1336.44	0.5514	0.95896	1250.37	0.5492	0.95041	1238.91
0.6015	0.98682	1350.57	0.6008	0.97986	1341.80	0.6015	0.96248	1253.83	0.6008	0.95533	1244.04
0.6982	0.99239	1355.68	0.6488	0.98384	1346.22	0.6982	0.96816	1259.24	0.6488	0.95940	1248.45
0.7996	0.99693	1360.31	0.7008	0.98774	1349.74	0.7996	0.97276	1263.29	0.7008	0.96338	1252.62
0.8313	0.99814	1361.14	0.7991	0.99407	1356.45	0.8313	0.97400	1264.44	0.7991	0.96976	1259.20
0.8637	0.99934	1362.42	0.8274	0.99557	1357.83	0.8637	0.97524	1265.59	0.8274	0.97137	1260.98
0.8856	1.00008	1363.12	0.8598	0.99728	1359.59	0.8856	0.97598	1266.20	0.8598	0.97307	1262.93
0.9023	1.00060	1363.33	0.8930	0.99894	1361.50	0.9023	0.97655	1266.71	0.8930	0.97471	1264.36
0.9230	1.00128	1364.18	0.9162	0.99999	1362.31	0.9230	0.97725	1267.40	0.9162	0.97588	1265.44
0.9458	1.00202	1364.37	0.9524	1.00160	1364.21	0.9458	0.97800	1267.71	0.9524	0.97751	1267.20
0.9831	1.00308	1365.55	0.9805	1.00275	1365.12	0.9831	0.97904	1269.00	0.9805	0.97870	1269.00
$T = 308.15$ K											
0.0101	0.79196	1123.88	0.0101	0.78402	1115.08						
0.0202	0.80561	1136.45	0.0199	0.79455	1125.56						
0.0301	0.81765	1148.00	0.0301	0.80470	1135.60						
0.0400	0.82873	1159.36	0.0399	0.81348	1144.25						
0.0500	0.83852	1169.01	0.0500	0.82215	1152.92						
0.0600	0.84758	1178.50	0.0601	0.83017	1160.73						
0.0705	0.85636	1187.78	0.0702	0.83762	1168.79						
0.0905	0.87070	1202.89	0.1000	0.85688	1188.57						
0.0998	0.87676	1209.07	0.1510	0.88269	1214.99						
0.1497	0.90238	1236.77	0.2001	0.90170	1235.16						
0.2005	0.92091	1256.57	0.2500	0.91692	1250.85						
0.2506	0.93471	1271.95	0.3006	0.92950	1264.47						
0.3000	0.94506	1282.84	0.3495	0.93941	1274.57						
0.3509	0.95384	1292.17	0.4003	0.94808	1284.13						
0.4391	0.96509	1304.19	0.4515	0.95548	1291.49						
0.4991	0.97095	1309.60	0.4983	0.96137	1298.08						
0.5514	0.97524	1314.09	0.5492	0.96690	1303.44						
0.6015	0.97875	1317.96	0.6008	0.97174	1308.91						
0.6982	0.98435	1322.99	0.6488	0.97574	1313.12						
0.7996	0.98891	1327.42	0.7008	0.97965	1316.80						
0.8313	0.99014	1328.54	0.7991	0.98593	1323.59						
0.8637	0.99135	1329.25	0.8274	0.98753	1324.89						
0.8856	0.99208	1330.32	0.8598	0.98927	1326.74						
0.9023	0.99260	1330.44	0.8930	0.99092	1328.67						
0.9230	0.99328	1331.31	0.9162	0.99199	1329.37						
0.9458	0.99402	1331.45	0.9524	0.99360	1331.34						
			0.9805	0.99476	1332.18						

Table 3. Dynamic Viscosity and Density of Binary Mixtures Containing Ethanol + PPG400 and 2-Propanol + PPG400 at Different Temperatures

x_2	η (mPa·s)	d (g·cm^{-3})	x_2	η (mPa·s)	d (g·cm^{-3})	x_2	η (mPa·s)	d (g·cm^{-3})	x_2	η (mPa·s)	d (g·cm^{-3})
Ethanol + PPG400			2-Propanol + PPG400			Ethanol + PPG400			2-Propanol + PPG400		
T = 298.15 K						T = 318.15 K					
0.0059	1.187	0.79461	0.0078	2.252	0.79006	0.0059	0.843	0.77717	0.0078	1.303	0.77253
0.0125	1.336	0.80394	0.0163	2.536	0.79935	0.0125	0.922	0.78656	0.0163	1.468	0.78186
0.0199	1.444	0.81379	0.0224	2.754	0.80565	0.0199	1.023	0.79648	0.0258	1.645	0.79158
0.0278	1.700	0.82358	0.0361	3.083	0.81874	0.0278	1.143	0.80633	0.0361	1.784	0.80136
0.0370	1.942	0.83400	0.0477	3.477	0.82874	0.0370	1.277	0.81681	0.0477	1.961	0.81140
0.0470	2.236	0.84416	0.0604	3.892	0.83891	0.0470	1.480	0.82704	0.0604	2.221	0.82163
0.0576	2.468	0.85404	0.075	4.399	0.84951	0.0576	1.669	0.83698	0.075	2.487	0.83229
0.0705	3.155	0.86475	0.0906	5.018	0.85972	0.0705	1.761	0.84776	0.0906	2.796	0.84257
0.0885	3.568	0.87782	0.1046	5.436	0.86799	0.0885	2.251	0.86092	0.1046	3.049	0.85089
0.1035	4.147	0.88730	0.1304	6.713	0.88154	0.1035	2.481	0.87047	0.1304	3.605	0.86451
0.1248	4.939	0.89903	0.1550	7.909	0.89282	0.1248	3.039	0.88227	0.1550	4.123	0.87585
0.1483	6.122	0.91002	0.2488	12.445	0.92492	0.1483	3.489	0.89332	0.3005	7.628	0.92102
0.2010	9.173	0.92935	0.3005	16.781	0.93767	0.2010	4.859	0.91278	0.3498	8.672	0.93111
0.3003	15.451	0.95334	0.3498	20.011	0.94769	0.3003	7.485	0.93696	0.3996	10.245	0.93968
0.4037	22.820	0.96910	0.3996	23.586	0.95619	0.4037	10.394	0.95284	0.4476	11.577	0.94674
0.4826	29.520	0.97756	0.4476	27.029	0.96319	0.4826	12.758	0.96136	0.4994	13.497	0.95325
0.6051	39.413	0.98706	0.4994	31.027	0.96964	0.6051	15.842	0.97092	0.5504	14.182	0.95880
0.7063	48.328	0.99278	0.5504	34.983	0.97513	0.7063	18.541	0.97666	0.5996	15.100	0.96347
0.8070	55.757	0.99722	0.5996	38.639	0.97975	0.8070	20.548	0.98115	0.6502	17.293	0.96773
0.9083	64.191	1.00083	0.6502	42.231	0.98397	0.9083	22.962	0.98479	0.7004	17.200	0.97150
			0.7004	46.517	0.98770				0.7492	18.419	0.97479
			0.7492	50.723	0.99097				0.7977	19.367	0.97777
			0.7977	54.740	0.99391				0.8466	20.747	0.98049
			0.8466	58.666	0.99660				0.9018	22.098	0.98326
			0.9018	62.363	0.99934				0.9491	22.724	0.98542
			0.9491	66.945	1.00146						
T = 308.15 K						T = 328.15 K					
0.0059	1.002	0.78596	0.0078	1.697	0.78147	0.0059	0.704	0.76808	0.0078	1.043	0.76323
0.0125	1.11	0.79532	0.0163	1.886	0.79077	0.0125	0.799	0.77764	0.0163	1.129	0.77258
0.0199	1.253	0.80521	0.0224	1.976	0.79708	0.0199	0.866	0.78759	0.0224	1.247	0.77896
0.0278	1.397	0.81502	0.0361	2.322	0.81019	0.0278	0.971	0.79745	0.0361	1.374	0.79224
0.0370	1.575	0.82548	0.0477	2.585	0.82021	0.0370	1.083	0.80799	0.0477	1.515	0.80232
0.0470	1.799	0.83567	0.0604	2.895	0.83040	0.0470	1.226	0.81827	0.0604	1.725	0.81256
0.0576	2.04	0.84558	0.0750	3.246	0.84103	0.0576	1.362	0.82823	0.0750	1.887	0.82327
0.0705	2.352	0.85632	0.0906	3.648	0.85127	0.0705	1.627	0.83903	0.0906	2.130	0.8336
0.0885	2.806	0.86943	0.1046	3.966	0.85955	0.0885	1.887	0.85226	0.1046	2.364	0.84198
0.1035	3.198	0.87894	0.1304	4.784	0.87312	0.1035	2.049	0.86188	0.1304	2.763	0.85569
0.1248	3.771	0.89071	0.1550	5.602	0.88442	0.1248	2.524	0.87379	0.1550	3.134	0.86708
0.1483	4.568	0.90173	0.3005	10.660	0.92943	0.1483	2.917	0.88488	0.3005	5.582	0.91252
0.2010	6.358	0.92112	0.3498	12.294	0.93947	0.2010	3.800	0.90434	0.3498	6.409	0.92267
0.3003	10.165	0.94520	0.3996	14.301	0.94799	0.3003	6.034	0.92866	0.3996	7.351	0.93128
0.4037	14.340	0.96099	0.4476	16.490	0.95500	0.4037	7.862	0.94464	0.4476	8.137	0.93838
0.4826	18.215	0.96948	0.4994	18.335	0.96148	0.4826	9.493	0.95317	0.4994	8.872	0.94494
0.6051	22.924	0.97900	0.5504	20.746	0.96699	0.6051	11.301	0.96272	0.5504	9.885	0.95053
0.7063	27.825	0.98473	0.5996	22.568	0.97164	0.7063	12.535	0.96852	0.5996	10.620	0.95524
0.8070	31.209	0.98920	0.6502	24.777	0.97587	0.807	13.780	0.97308	0.6502	11.525	0.95953
0.9083	35.063	0.99283	0.7004	26.564	0.97963	0.9083	15.407	0.97677	0.7004	12.149	0.96333
			0.7492	28.524	0.98291				0.7492	13.008	0.96666
			0.7977	30.616	0.98587				0.7977	13.729	0.96965
			0.8466	32.631	0.98857				0.8466	14.445	0.97239
			0.9018	34.635	0.99133				0.9018	15.286	0.97519
			0.9491	36.732	0.99346				0.9491	16.037	0.97737

x_2, at T = (298.15 to 328.15) K are collected in Table 3. Plots of viscosity values versus polymer mole fraction are shown in Figure 3 for ethanol + PPG and 2-propanol + PPG systems. The results of $\Delta \ln \eta$ values calculated from eq 3 indicate that the deviation of logarithm of viscosity values is positive for the ethanol + PPG and 2-propanol + PPG systems over the entire composition range and over the four temperatures investigated.

Correlation. All the calculated values were correlated with the composition data by means of the Redlich−Kister polynomial, which for binary mixtures is

$$Q_{ij} = x_i x_j \sum_{k \geq 0} A_k (x_i - x_j)^k \tag{4}$$

where Q_{ij} is V_m^E, $\kappa^E{}_{s,m}$, or $\Delta \ln \eta$ and x_i is the mole fraction of component i. $A_k$is the polynomial coefficient, and k is the number of the polynomial coefficient. The adjustable parameters A_k determined by fitting the experimental values to eq 4 along with standard deviations of V_m^E, $\kappa^E{}_{s,m}$, and $\Delta \ln \eta$ are given in Tables 4 and 5 for the ethanol + PPG and 2-propanol + PPG systems, respectively. The full lines in Figures 1 to 3 correspond to the Redlich−Kister polynomials. On the basis of standard deviations reported in Tables 6 and 7, we concluded that the performance of the Redlich−Kister polynomial in the correlation of V_m^E, $\kappa^E{}_{s,m}$, and $\Delta \ln \eta$ values is good.

The V_m^E, $\kappa^E{}_{s,m}$, and dynamic viscosity, η, values of the studied systems were also correlated with the corresponding equation of the NRTL model. The NRTL equation for the excess molar volume and excess molar isentropic compression of solvent + polymer solutions has been taken from our previous work.[6]

In the correlation of the V_m^E and $\kappa^E{}_{s,m}$ values of the investigated systems with the NRTL model,[6] the smallest standard deviations were obtained using the value of 0.4 for the nonrandomness factor. To correlate V_m^E and $\kappa^E{}_{s,m}$ data of a polymer solution with the NRTL model, its two parameters (τ_{12} and τ_{21}) are required which can be obtained from fitting of the vapor−liquid equilibrium, VLE, data to Chen's NRTL model[10]

Table 4. Parameters of the Redlich−Kister Polynomial, Equation 4, along with Standard Deviations, *σ*, of Binary Mixtures Containing Ethanol + PPG400 at Different Temperatures

T/K	A_0	A_1	A_2	A_3	A_4	σ	
			V^E_m ($cm^3 \cdot mol^{-1}$)				
						$\sigma(V^E_m)$	$10^3\sigma(d)/(g \cdot cm^{-3})$
288.15	−3.349	1.757	−0.513	1.926	−2.116	0.01	0.06
298.15	−3.406	1.954	−0.947	1.759	−1.694	0.01	0.04
308.15	−3.519	2.091	−1.083	1.814	−1.717	0.01	0.05
318.15	−3.673	2.202	−0.926	1.896	−2.111	0.01	0.06
328.15	−3.787	2.432	−0.840	1.795	−2.591	0.01	0.06
			$\kappa^E_{s,m}/(cm^3 \cdot mol^{-1} \cdot kPa^{-1})$				
						$10^7\sigma(\kappa^E_{s,m})$	$\sigma(u)/(m \cdot s^{-1})$
288.15	−209.46	132.58	−81.58	166.81	−160.61	0.56	0.45
298.15	−239.74	151.61	−97.36	190.33	−183.77	0.66	0.47
308.15	−272.23	173.28	−114.50	224.63	−213.05	0.78	0.51
318.15	−307.77	198.58	−119.49	260.74	−264.10	0.94	0.55
328.15	−346.49	228.67	−128.50	308.88	−321.24	1.10	0.61
			$\Delta \ln \eta/(mPa \cdot s)$				
						$\sigma(\Delta \ln \eta)$	$\sigma(\eta)/(mPa \cdot s)$
298.15	4.982	−2.831	2.526	−2.006		0.02	0.31
308.15	4.576	−2.490	2.619	−2.742		0.02	0.26
318.15	4.389	−2.544	2.430	−2.306		0.02	0.15
328.15	4.305	−2.755	2.484	−2.366		0.02	0.16

Table 5. Parameters of the Redlich−Kister Polynomial, Equation 4, along with Standard Deviations, *σ*, of Binary Mixtures Containing 2-Propanol + PPG400 at Different Temperatures

T/K	A_0	A_1	A_2	A_3	A_4	σ	
			$V^E_m/(cm^3 \cdot mol^{-1})$				
						$\sigma(V^E_m)$	$10^3\sigma(d)/(g \cdot cm^{-3})$
288.15	−2.112	1.251	−0.223	0.649	−1.550	0.01	0.03
298.15	−2.163	1.252	−0.371	0.665	−1.508	0.01	0.03
308.15	−2.223	1.391	−0.482	0.643	−1.483	0.01	0.03
318.15	−2.320	1.437	−0.490	0.868	−1.577	0.01	0.03
328.15	−2.425	1.516	−0.690	1.154	−1.504	0.01	0.04
			$\kappa^E_{s,m}/(cm^3 \cdot mol^{-1} \cdot kPa^{-1})$				
						$10^7\sigma(\kappa^E_{s,m})$	$\sigma(u)/(m \cdot s^{-1})$
288.15	−222.33	147.11	−93.21	161.89	−147.74	0.48	0.30
298.15	−255.79	168.73	−98.98	177.07	−192.58	0.54	0.32
308.15	−291.36	194.04	−114.23	202.66	−225.40	0.65	0.34
318.15	−333.15	223.10	−133.67	243.44	−260.77	0.72	0.35
328.15	−383.37	258.57	−162.90	304.36	−297.65	0.91	0.39
			$\Delta \ln \eta/(mPa \cdot s)$				
						$\sigma(\Delta \ln \eta)$	$\sigma(\eta)/(mPa \cdot s)$
298.15	3.735	−2.005	1.293	−0.794		0.02	0.29
308.15	3.456	−1.913	1.642	−1.177		0.01	0.17
318.15	3.446	−1.875	1.338	−1.993		0.02	0.28
328.15	3.284	−1.946	1.898	−1.221		0.01	0.09

Table 6. Parameters of the NRTL Model along with Standard Deviations, $\sigma(V^E_m)$, for Ethanol + PPG400 and 2-Propanol + PPG400 Systems at Different Temperatures

T/K	$10^4 \cdot \tau^V_{12}$	$10^4 \cdot \tau^V_{21}$	$\sigma(V^E_m)$ $(cm^3 \cdot mol^{-1})$	$10^3\sigma(d)$ $(g \cdot cm^{-3})$
		Ethanol + PPG400		
288.15	−5.627	−0.174	0.02	0.11
298.15	−6.107	0.806	0.01	0.07
308.15	−6.623	1.530	0.01	0.06
318.15	−7.127	2.358	0.01	0.08
328.15	−2.846	−4.822	0.01	0.06
		2-Propanol + PPG400		
288.15	−5.347	2.017	0.01	0.06
298.15	−5.523	2.457	0.01	0.06
308.15	−6.275	2.769	0.01	0.05
318.15	−5.551	0.882	0.01	0.04
328.15	−9.253	8.603	0.01	0.06

Table 7. Parameters of the NRTL Model along with Standard Deviations, $\sigma(\kappa^E_{s,m})$, for Ethanol + PPG400 and 2-Propanol + PPG400 Systems at Different Temperatures

T/K	τ^κ_{12}	τ^κ_{21}	$10^7\sigma(\kappa^E_{s,m})$ $(cm^3 \cdot mol^{-1} \cdot kPa^{-1})$	$\sigma(u)$ $(m \cdot s^{-1})$
		Ethanol + PPG400		
288.15	0.067	−0.048	0.73	0.44
298.15	0.079	−0.063	0.92	0.55
308.15	0.096	−0.081	1.03	0.57
318.15	0.113	−0.103	1.19	0.62
328.15	0.175	−0.134	0.79	0.34
		2-Propanol + PPG400		
288.15	0.106	−0.095	0.85	0.51
298.15	0.121	−0.115	1.22	0.65
308.15	0.177	−0.163	1.15	0.53
318.15	0.257	−0.214	0.91	0.36
328.15	0.224	−0.258	1.93	0.80

for the systems studied. The values for τ_{12} and τ_{21} parameters at different temperatures have been taken from our previous work.[11]

In the case of the NRTL equation, the required parameters (τ^{v}_{ij} and τ^{κ}_{ij}) were obtained from fitting of V^E_m and $10^7\kappa^E_{s,m}$ data with the results collected in Tables 6 and 7, respectively.

Table 8. Parameters of the NRTL Model along with Standard Deviations, $\sigma(\eta)$, for Ethanol + PPG400 and 2-Propanol + PPG400 Binary Systems at Different Temperatures

T/K	τ^{η}_{12}	τ^{η}_{21}	$\sigma(\eta)$/(mPa.s)
	Ethanol + PPG400		
298.15	−1.970	0.396	0.20
308.15	−2.267	1.635	0.15
318.15	−1.599	0.598	0.07
328.15	−0.989	0.192	0.11
	2-Propanol + PPG400		
298.15	−1.686	0.538	0.25
308.15	−1.967	1.579	0.13
318.15	−1.700	1.402	0.41
328.15	−1.492	1.254	0.10

The dynamic viscosity data have been correlated with the segment-based Eyring−NRTL viscosity model, proposed recently by Novak et al.[12] In the correlation of the dynamic viscosity of the investigated systems with the Eyring−NRTL model,[12] the smallest standard deviations were obtained using the value of 0.25 for the nonrandomness factor. The two parameters of the segment-based Eyring−NRTL viscosity model, τ^{η}_{12} and τ^{η}_{21}, were obtained by using the dynamic viscosity data from Table 3, and these parameters are collected in Table 8 for the ethanol + PPG and 2-propanol + PPG systems.

To see the performances of the Redlich−Kister and NRTL models, comparison between the experimental and calculated $V^{\mathrm{E}}_{\mathrm{m}}$, $\kappa^{\mathrm{E}}_{\mathrm{s,m}}$, and η values is shown, respectively, in Figures 1 to 3. As can be seen from these figures and standard deviations reported in Tables 4 to 8, the performance of the NRTL model with only two parameters in the correlation of $V^{\mathrm{E}}_{\mathrm{m}}$ or $\kappa^{\mathrm{E}}_{\mathrm{s,m}}$ values is similar to that of the Redlich−Kister equation with five adjustable parameters. The quality of fitting of η values with the NRTL model with only two parameters is better than the Redlich−Kister polynomial with four adjustable parameters.

Conclusion

Experimental density, speed of sound, and dynamic viscosity data were obtained for ethanol + PPG and 2-propanol + PPG systems over the entire range of compositions at different temperatures. The excess molar volume and excess molar isentropic compression values, calculated from these experimental data, are negative, whereas deviations of logarithm of viscosity values are positive. The Redlich−Kister polynomial and NRTL model were applied successfully for the correlation of $V^{\mathrm{E}}_{\mathrm{m}}$, $\kappa^{\mathrm{E}}_{\mathrm{s,m}}$, and $\Delta \ln \eta$ values. The quality of fitting of excess volume or excess molar isentropic compression values for the studied systems with the NRTL model with only two parameters is similar to that of the Redlich−Kister polynomial with five parameters. In the case of correlation of viscosity values, it was found that the performance of the NRTL model is better than the Redlich−Kister polynomial.

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