Dynamic Viscosities of the Binary Systems Cyclohexane and Cyclopentane with Acetone, Butanone, or 2-Pentanone at Three Temperatures T = (293.15, 298.15, and 303.15) K

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Dynamic viscosities, densities, and speeds of sound have been determined over the whole composition range for the binary systems cyclohexane (1) and cyclopentane (1) with acetone (2), butanone (2), or 2-pentanone (2) at T = (293.15, 298.15, and 303.15) K and atmospheric pressure along with the properties of the pure components. Excess molar volumes, isentropic compressibilities, deviations in isentropic compressibility, and viscosity deviations for the binary systems at the above-mentioned temperatures were calculated and fitted to the Redlich−Kister equation to determine the fitting parameters and the root-mean-square deviations. The UNIQUAC equation was used to correlate the experimental viscosity data. Predictions of the dynamic viscosities of this binary mixture from the UNIFAC-VISCO and ASOG-VISCO methods have been determined.

1. Introduction

Viscosity is a very important physical property of fluids in the design of processes with fluid transport not only through pipes but also through pore surfaces and in many process involving mass and energy transfer. Indeed, viscosity is a fundamental characteristic of substance such as adhesives, lubricants, paintings, and so forth. As an extension of our work concerning the dynamic viscosity of binary systems,[1−4] in this article we show experimental dynamic viscosity, density, and speed of sound data for cyclohexane (1) and cyclopentane (1) with acetone (2), butanone (2), or 2-pentanone (2) at T = (293.15, 298.15, and 303.15) K. The results were used to calculate excess molar volumes, isentropic compressibility, deviations in isentropic compressibility, and viscosities over the entire mole fraction range. Viscosity data were correlated using the UNIQUAC[5] equation. The UNIFAC-VISCO[6,7] and ASOG-VISCO[8] methods have been applied to predict the dynamic viscosity.

2. Experimental Section

Chemicals. The pure components were supplied by Fluka (cyclohexane, cyclopentane, and butanone) and Sigma-Aldrich (acetone and 2-pentanone). The components were degassed ultrasonically, dried over type 4 Å molecular sieves that were supplied by Aldrich, and kept in inert argon with a maximum water content of 2×10^{-6} mass fraction. The maximum water content of each liquid was determined using a Metrohm 737 KF coulometer. Their mass fraction purities were >99.8% for cyclohexane and acetone, >99.5% for butanone and 2-pentanone, and >99.0% for cyclopentane.

Apparatus and Procedure. Samples were prepared by mass using a Mettler AX-205 delta range balance with a precision of $\pm 10^{-5}$ g, covering the whole composition range of the mixture.

Kinematic viscosities were determined using a Lauda PVS1 automatic viscosimeter with two Ubbelhode capillary microviscosimeters of 0.4×10^{-3} m and 0.53×10^{-3} m diameter. Gravity fall is the principle of measurement on which this viscosimeter is based. The capillary is maintained in a D20KP Lauda thermostat with a resolution of 0.01 K. The capillaries are calibrated and credited by the company. The uncertainty of the capillary diameter is ±0.005 mm. To verify the calibration, we compared the viscosity of the pure liquids with recently published data (Table 1). The uncertainty of the viscosimeter is ±0.001 mPa·s. The equipment has a PVS1 (processor viscosity system) control unit that is a PC-controlled instrument for the precise measurement of fall time, using standardized glass capillaries, with an accuracy of 0.01s.

The densities and the speeds of sound of the pure liquids and mixtures were measured using an Anton Paar DSA-5000 digital vibrating-tube densimeter. The uncertainty in the density measurement is $\pm 2 \times 10^{-6}$ g·cm^{-3}, and for the speed of sound, it is ±0.1 m·s^{-1}.

Table 1. Comparison of Density, ρ, and Viscosity, η, with Literature Data for Pure Components at T = 298.15 K

	ρ/g·cm^{-3}		$10^3\eta$/Pa·s	
component	exptl	lit	exptl	lit
cyclohexane	0.77392	0.7738[a]	0.887	0.888[a]
		0.77387[c]		0.883[b]
cyclopentane	0.73955	0.74045[c]	0.416	0.416[c]
acetone	0.78541	0.78544[c]	0.306	0.307[c]
butanone	0.79974	0.7997[c]	0.378	0.378[c]
2-pentanone	0.80142	0.8015[c]	0.469	

[a] Petrino et al.[9] [b] Aminabhavi et al.[10] [c] Riddick et al.[11]

3. Results and Discussion

The dynamic viscosity, density, speed of sound, excess molar volume, isentropic compressibility (determined by means of the Laplace equation, $k_s = \rho^{-1}u^{-2}$), and deviation in isentropic compressibility for the systems cyclohexane (1) and cyclopentane (1) with acetone (2), butanone (2), or 2-pentanone (2) at T = (293.15, 298.15, and 303.15) K and atmospheric pressure are reported in Tables 2 to 7. The

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10.1021/je050110r CCC: $30.25
Published on Web 05/28/2005

Table 2. Density, ρ, Speed of Sound, u, Dynamic Viscosity, η, Excess Molar Volume, V^E, Isentropic Compressibility, κ_s, Deviations in Isentropic Compressibility, $\Delta\kappa_s$, and Viscosities Deviation, $\Delta\eta$, of Cyclohexane (1) + Acetone (2)

	ρ	u	$10^3\eta$	V^E	k_s	$\Delta\kappa_s$	$10^3\Delta\eta$		ρ	u	$10^3\eta$	V^E	k_s	$\Delta\kappa_s$	$10^3\Delta\eta$
x_1	g·cm^{-3}	m·s^{-1}	Pa·s	cm^3·mol^{-1}	TPa^{-1}	TPa^{-1}	Pa·s	x_1	g·cm^{-3}	m·s^{-1}	Pa·s	cm^3·mol^{-1}	TPa^{-1}	TPa^{-1}	Pa·s
							T = 293.15 K								
0.0000	0.79111	1185	0.320	0.000	901	0	0.000	0.5984	0.77383	1212	0.544	1.058	880	48	−0.164
0.0490	0.78810	1182	0.329	0.202	908	13	−0.023	0.7007	0.77387	1225	0.621	0.954	861	41	−0.153
0.0917	0.78555	1180	0.336	0.384	914	23	−0.043	0.8046	0.77459	1241	0.700	0.759	839	31	−0.141
0.1959	0.78098	1181	0.361	0.702	919	41	−0.086	0.9051	0.77604	1258	0.818	0.461	814	18	−0.088
0.2889	0.77795	1184	0.392	0.910	916	49	−0.115	0.9580	0.77727	1269	0.895	0.235	799	9	−0.045
0.4092	0.77547	1193	0.443	1.054	906	53	−0.142	1.0000	0.77862	1279	0.968	0.000	785	0	0.000
0.5009	0.77437	1201	0.486	1.089	895	52	−0.159								
							T = 298.15 K								
0.0000	0.78541	1162	0.306	0.000	942	0	0.000	0.5984	0.76869	1188	0.509	1.089	922	52	−0.145
0.0490	0.78246	1160	0.313	0.207	950	14	−0.021	0.7007	0.76883	1201	0.578	0.981	902	44	−0.135
0.0917	0.77994	1158	0.320	0.394	956	25	−0.039	0.8046	0.76966	1216	0.650	0.779	878	33	−0.123
0.1959	0.77547	1158	0.343	0.720	962	43	−0.077	0.9051	0.77122	1234	0.756	0.473	852	19	−0.076
0.2889	0.77250	1161	0.371	0.937	960	53	−0.103	0.9580	0.77253	1245	0.829	0.240	836	9	−0.034
0.4092	0.77014	1169	0.417	1.084	949	57	−0.126	1.0000	0.77392	1254	0.887	0.000	821	0	0.000
0.5009	0.76913	1178	0.456	1.120	937	56	−0.141								
							T = 303.15 K								
0.0000	0.77966	1140	0.292	0.000	987	0	0.000	0.5984	0.76350	1164	0.477	1.121	967	56	−0.128
0.0490	0.77676	1137	0.299	0.212	995	15	−0.019	0.7007	0.76375	1177	0.540	1.010	945	48	−0.119
0.0917	0.77428	1135	0.305	0.404	1002	27	−0.035	0.8046	0.76470	1192	0.606	0.801	920	36	−0.108
0.1959	0.76990	1135	0.326	0.739	1009	47	−0.068	0.9051	0.76638	1210	0.701	0.486	892	20	−0.065
0.2889	0.76702	1138	0.352	0.962	1007	57	−0.091	0.9580	0.76775	1220	0.762	0.245	875	10	−0.032
0.4092	0.76477	1146	0.394	1.115	996	61	−0.112	1.0000	0.76919	1230	0.816	0.000	860	0	0.000
0.5009	0.76386	1154	0.429	1.152	983	60	−0.125								

Table 3. Density, ρ, Speed of Sound, u, Dynamic Viscosity, η, Excess Molar Volume, V^E, Isentropic Compressibility, κ_s, Deviation in Isentropic Compressibility, $\Delta\kappa_s$, and Viscosity Deviation, $\Delta\eta$, of Cyclohexane (1) + 2-Butanone (2)

	ρ	u	$10^3\eta$	V^E	k_s	$\Delta\kappa_s$	$10^3\Delta\eta$		ρ	u	$10^3\eta$	V^E	k_s	$\Delta\kappa_s$	$10^3\Delta\eta$
x_1	g·cm^{-3}	m·s^{-1}	Pa·s	cm^3·mol^{-1}	TPa^{-1}	TPa^{-1}	Pa·s	x_1	g·cm^{-3}	m·s^{-1}	Pa·s	cm^3·mol^{-1}	TPa^{-1}	TPa^{-1}	Pa·s
							T = 293.15 K								
0.0000	0.80495	1213	0.398	0.000	844	0	0.000	0.6056	0.78101	1229	0.581	0.882	848	40	−0.162
0.0479	0.80206	1212	0.401	0.157	849	8	−0.024	0.7030	0.77932	1238	0.641	0.807	838	35	−0.158
0.0956	0.79943	1211	0.404	0.291	853	15	−0.049	0.8048	0.77818	1249	0.720	0.652	824	28	−0.136
0.1983	0.79432	1210	0.433	0.537	860	28	−0.078	0.9029	0.77783	1262	0.824	0.402	807	16	−0.089
0.3046	0.78989	1212	0.466	0.719	862	36	−0.106	0.9515	0.77802	1270	0.888	0.230	797	9	−0.053
0.4002	0.78639	1215	0.488	0.842	861	41	−0.139	1.0000	0.77862	1279	0.968	0.000	785	0	0.000
0.5028	0.78342	1221	0.530	0.891	856	42	−0.154								
							T = 298.15 K								
0.0000	0.79974	1192	0.378	0.000	880	0	0.000	0.6056	0.77606	1205	0.543	0.904	887	43	−0.143
0.0479	0.79686	1190	0.381	0.160	886	9	−0.021	0.7030	0.77442	1214	0.597	0.826	876	38	−0.139
0.0956	0.79425	1189	0.390	0.297	890	16	−0.037	0.8048	0.77334	1225	0.668	0.667	862	30	−0.119
0.1983	0.78919	1188	0.410	0.549	897	29	−0.069	0.9029	0.77306	1238	0.760	0.411	845	18	−0.077
0.3046	0.78478	1190	0.441	0.737	900	38	−0.092	0.9515	0.77327	1245	0.816	0.236	834	10	−0.046
0.4002	0.78134	1193	0.459	0.861	900	43	−0.123	1.0000	0.77392	1254	0.887	0.000	821	0	0.000
0.5028	0.77841	1198	0.498	0.913	895	45	−0.136								
							T = 303.15 K								
0.0000	0.79448	1171	0.360	0.000	918	0	0.000	0.6056	0.77106	1182	0.510	0.926	928	45	−0.126
0.0479	0.79162	1169	0.363	0.163	925	9	−0.019	0.7030	0.76948	1190	0.558	0.847	917	40	−0.123
0.0956	0.78903	1167	0.370	0.303	930	17	−0.033	0.8048	0.76846	1201	0.622	0.683	903	32	−0.105
0.1983	0.78401	1166	0.388	0.561	938	31	−0.062	0.9029	0.76826	1213	0.705	0.421	884	19	−0.067
0.3046	0.77965	1168	0.419	0.753	941	41	−0.079	0.9515	0.76851	1221	0.754	0.241	873	11	−0.040
0.4002	0.77624	1170	0.433	0.881	941	46	−0.109	1.0000	0.76919	1230	0.816	0.000	860	0	0.000
0.5028	0.77337	1175	0.468	0.934	936	48	−0.121								

excess molar volumes, deviations in isentropic compressibility, and viscosity deviations were calculated with the following equations

$$V^E = \sum_{i=1}^{N} x_i M_i (\rho^{-1} - \rho_i^{-1}) \quad (1)$$

$$\Delta\kappa_s = \kappa_s - \sum_{i=1}^{N} x_i \kappa_{s,i} \quad (2)$$

$$\Delta\eta = \eta - \sum_{i}^{N} x_i \eta_i \quad (3)$$

where ρ and ρ_i are the density of the mixture and the density of the pure components, respectively; κ_s is the isentropic compressibility of the mixture; $\kappa_{s,i}$ is the isentropic compressibility of the pure components; x_i represents the mole fraction of component i; and η and η_i are the dynamic viscosity of the mixture and the pure component, respectively.

The binary deviations at several temperatures were fitted to a Redlich−Kister[12] type equation

$$\Delta Q_{12} = x_1 x_2 \sum_{p=0}^{M} B_p (x_1 - x_2)^p \quad (4)$$

where ΔQ_{12} is the excess property, x_1 and x_2 are the mole fractions of components 1 and 2 respectively, B_P is the fitting parameter, and M is the degree of the polynomic expansion, which was optimized using the F test.[13] The fitting parameters are given in Table 8 together with the

Table 4. Density, ρ, Speed of Sound, u, Dynamic Viscosity, η, Excess Molar Volume, V^E, Isentropic Compressibility, κ_s, Deviation in Isentropic Compressibility, $\Delta\kappa_s$, and Viscosities Deviation, $\Delta\eta$, of Cyclohexane (1) + 2-Pentanone (2)

x_1	ρ / g·cm^{-3}	u / m·s^{-1}	$10^3\eta$ / Pa·s	V^E / cm^3·mol^{-1}	k_s / TPa^{-1}	$\Delta\kappa_s$ / TPa^{-1}	$10^3\Delta\eta$ / Pa·s	x_1	ρ / g·cm^{-3}	u / m·s^{-1}	$10^3\eta$ / Pa·s	V^E / cm^3·mol^{-1}	k_s / TPa^{-1}	$\Delta\kappa_s$ / TPa^{-1}	$10^3\Delta\eta$ / Pa·s
							$T = 293.15$ K								
0.0000	0.80626	1233	0.496	0.000	816	0	0.000	0.5982	0.78377	1237	0.625	0.807	833	36	−0.154
0.0483	0.80399	1232	0.500	0.122	820	6	−0.019	0.7002	0.78146	1244	0.680	0.741	827	33	−0.146
0.0981	0.80169	1230	0.506	0.244	824	11	−0.036	0.8051	0.77955	1253	0.748	0.610	817	26	−0.128
0.1932	0.79741	1229	0.516	0.464	830	21	−0.072	0.9024	0.77853	1264	0.847	0.383	804	16	−0.075
0.2960	0.79344	1229	0.537	0.617	835	28	−0.099	0.9503	0.77836	1271	0.898	0.225	796	9	−0.046
0.3957	0.78993	1230	0.562	0.722	837	33	−0.121	1.0000	0.77862	1279	0.968	0.000	785	0	0.000
0.4987	0.78659	1233	0.594	0.793	836	36	−0.137								
							$T = 298.15$ K								
0.0000	0.80142	1213	0.469	0.000	849	0	0.000	0.5982	0.77898	1215	0.591	0.822	870	38	−0.128
0.0483	0.79917	1211	0.473	0.123	853	6	−0.016	0.7002	0.77668	1221	0.632	0.756	864	35	−0.129
0.0981	0.79687	1209	0.477	0.247	858	12	−0.032	0.8051	0.77479	1229	0.694	0.622	854	28	−0.111
0.1932	0.79259	1208	0.486	0.471	865	22	−0.064	0.9024	0.77380	1240	0.781	0.390	841	17	−0.065
0.2960	0.78864	1207	0.504	0.626	870	30	−0.089	0.9503	0.77364	1246	0.826	0.229	832	10	−0.040
0.3957	0.78512	1208	0.528	0.735	873	35	−0.106	1.0000	0.77392	1254	0.887	0.000	821	0	0.000
0.4987	0.78179	1211	0.554	0.807	873	38	−0.124								
							$T = 303.15$ K								
0.0000	0.79658	1192	0.444	0.000	884	0	0.000	0.5982	0.77414	1192	0.548	0.840	909	39	−0.118
0.0483	0.79431	1190	0.447	0.127	889	6	−0.014	0.7002	0.77187	1198	0.594	0.772	903	37	−0.111
0.0981	0.79202	1188	0.452	0.253	894	13	−0.028	0.8051	0.77000	1206	0.645	0.634	894	29	−0.098
0.1932	0.78774	1186	0.458	0.480	902	23	−0.057	0.9024	0.76903	1216	0.724	0.398	880	18	−0.056
0.2960	0.78379	1185	0.476	0.639	908	31	−0.078	0.9503	0.76889	1222	0.762	0.233	871	10	−0.035
0.3957	0.78027	1186	0.498	0.751	911	37	−0.093	1.0000	0.76919	1230	0.816	0.000	860	0	0.000
0.4987	0.77695	1188	0.520	0.823	911	40	−0.109								

Table 5. Density, ρ, Speed of Sound, u, Dynamic Viscosity, η, Excess Molar Volume, V^E, Isentropic Compressibility, κ_s, Deviation in Isentropic Compressibility, $\Delta\kappa_s$, and Viscosity Deviation, $\Delta\eta$, of Cyclopentane (1) + Acetone (2)

x_1	ρ / g·cm^{-3}	u / m·s^{-1}	$10^3\eta$ / Pa·s	V^E / cm^3·mol^{-1}	k_s / TPa^{-1}	$\Delta\kappa_s$ / TPa^{-1}	$10^3\Delta\eta$ / Pa·s	x_1	ρ / g·cm^{-3}	u / m·s^{-1}	$10^3\eta$ / Pa·s	V^E / cm^3·mol^{-1}	k_s / TPa^{-1}	$\Delta\kappa_s$ / TPa^{-1}	$10^3\Delta\eta$ / Pa·s
							$T = 293.15$ K								
0.0000	0.79111	1185	0.320	0.000	901	0	0.000	0.6026	0.75316	1180	0.357	0.821	954	63	−0.035
0.0453	0.78650	1182	0.318	0.183	910	10	−0.007	0.6876	0.75020	1188	0.367	0.761	945	55	−0.035
0.0935	0.78240	1178	0.319	0.315	921	22	−0.012	0.7950	0.74730	1199	0.385	0.604	930	42	−0.030
0.1869	0.77530	1173	0.319	0.519	938	40	−0.023	0.9016	0.74540	1214	0.408	0.343	910	23	−0.020
0.2786	0.76900	1170	0.324	0.689	949	53	−0.029	0.9511	0.74490	1224	0.419	0.177	897	11	−0.014
0.3922	0.76235	1170	0.333	0.821	958	64	−0.034	1.0000	0.74452	1232	0.439	0.000	885	0	0.000
0.5170	0.75640	1175	0.344	0.864	958	65	−0.037								
							$T = 298.15$ K								
0.0000	0.78541	1162	0.306	0.000	942	0	0.000	0.6026	0.74773	1155	0.338	0.857	1002	68	−0.034
0.0453	0.78090	1159	0.308	0.181	953	11	−0.003	0.6876	0.74490	1162	0.347	0.789	994	60	−0.034
0.0935	0.77680	1155	0.304	0.319	965	24	−0.012	0.7950	0.74210	1174	0.365	0.626	978	46	−0.029
0.1869	0.76960	1149	0.304	0.544	984	44	−0.023	0.9016	0.74030	1188	0.390	0.357	956	26	−0.015
0.2786	0.76340	1147	0.309	0.714	996	58	−0.028	0.9511	0.73990	1198	0.397	0.180	942	12	−0.013
0.3922	0.75678	1146	0.318	0.855	1006	69	−0.031	1.0000	0.73955	1206	0.416	0.000	929	0	0.000
0.5170	0.75090	1150	0.327	0.902	1007	71	−0.036								
							$T = 303.15$ K								
0.0000	0.77966	1140	0.292	0.000	987	0	0.000	0.6026	0.74224	1130	0.321	0.896	1054	73	−0.032
0.0453	0.77520	1136	0.290	0.183	999	13	−0.007	0.6876	0.73950	1137	0.332	0.824	1047	66	−0.030
0.0935	0.77110	1132	0.291	0.327	1013	26	−0.010	0.7950	0.73680	1148	0.347	0.656	1030	51	−0.027
0.1869	0.76390	1126	0.289	0.565	1033	48	−0.022	0.9016	0.73520	1162	0.370	0.366	1007	29	−0.014
0.2786	0.75780	1123	0.294	0.735	1047	63	−0.026	0.9511	0.73490	1171	0.377	0.177	992	15	−0.012
0.3922	0.75115	1122	0.303	0.892	1058	75	−0.029	1.0000	0.73454	1180	0.394	0.000	977	0	0.000
0.5170	0.74540	1126	0.311	0.936	1059	77	−0.034								

root-mean-square deviations (eq 5)

$$\sigma = \left\{ \sum_{i}^{n_{dat}} \frac{(z_{exptl} - z_{calcd})^2}{n_{dat}} \right\}^{1/2} \quad (5)$$

where z_{exptl}, z_{calcd}, and n_{dat} are the values of the experimental and calculated property and the number of experimental data, respectively.

Figures 1 and 2 show the fitted curves as well as excess and deviation values of the studied systems at $T = (293.15, 298.15, \text{and } 303.15)$ K. All systems present similar behavior for these physical properties, and because of this, only some of them are represented. In these Figures, we can observe that the excess molar volume is positive over the entire composition range, with a maximum over $x_1 = 0.5$ for cyclohexane (1) with acetone (2) and over $x_1 = 0.6$ for the other system. All systems present a minimun in the speed of sound and a maximum in the isoentropic compressibility. These values of the physical properties—a maximum in the excess molar volumes and in the adiabatic compressibility and a minimum in the speed of sound—indicate that there is a weak intermolecular interaction between unlike molecules, in this case, London dispersion forces.

In Figure 2, for viscosity deviations, the sign is negative for cyclohexane (1) with butanone (2), and the minimum lies at approximately $x_1 = 0.6$ mole fraction. The behavior of the other systems is similar, except for cyclopentane (1)

Table 6. Density, ρ, Speed of Sound, u, Dynamic Viscosity, η, Excess Molar Volume, V^E, Isentropic Compressibility, κ_s, Deviation in Isentropic Compressibility, $\Delta\kappa_s$, and Viscosity Deviation, $\Delta\eta$, of Cyclopentane (1) + 2-Butanone (2)

x_1	ρ / g·cm^{-3}	u / m·s^{-1}	$10^3\eta$ / Pa·s	V^E / cm^3·mol^{-1}	k_s / TPa^{-1}	$\Delta\kappa_s$ / TPa^{-1}	$10^3\Delta\eta$ / Pa·s	x_1	ρ / g·cm^{-3}	u / m·s^{-1}	$10^3\eta$ / Pa·s	V^E / cm^3·mol^{-1}	k_s / TPa^{-1}	$\Delta\kappa_s$ / TPa^{-1}	$10^3\Delta\eta$ / Pa·s
					$T = 293.15$ K										
0.0000	0.80495	1213	0.398	0.000	844	0	0.000	0.6189	0.76270	1200	0.394	0.504	911	42	−0.029
0.0472	0.80167	1211	0.397	0.034	851	5	−0.003	0.6838	0.75893	1202	0.398	0.497	912	40	−0.028
0.0981	0.79782	1207	0.395	0.106	860	12	−0.007	0.8034	0.75269	1210	0.407	0.402	908	31	−0.024
0.1929	0.79079	1202	0.394	0.234	875	23	−0.012	0.9061	0.74813	1220	0.419	0.229	899	18	−0.017
0.2932	0.78366	1199	0.390	0.344	888	32	−0.020	0.9499	0.74657	1225	0.426	0.105	892	10	−0.011
0.3753	0.77806	1198	0.390	0.413	896	37	−0.023	1.0000	0.74452	1232	0.439	0.000	885	0	0.000
0.4966	0.77013	1198	0.393	0.486	905	41	−0.026								
					$T = 298.15$ K										
0.0000	0.79974	1192	0.378	0.000	880	0	0.000	0.6189	0.75751	1176	0.374	0.527	955	45	−0.028
0.0472	0.79644	1189	0.377	0.037	887	5	−0.003	0.6838	0.75377	1178	0.377	0.517	956	42	−0.027
0.0981	0.79260	1186	0.375	0.111	897	13	−0.007	0.8034	0.74758	1185	0.387	0.420	953	33	−0.022
0.1929	0.78556	1180	0.372	0.244	914	24	−0.014	0.9061	0.74308	1194	0.397	0.238	944	19	−0.015
0.2932	0.77843	1177	0.370	0.358	928	34	−0.019	0.9499	0.74156	1200	0.405	0.110	937	10	−0.009
0.3753	0.77284	1175	0.370	0.430	938	40	−0.022	1.0000	0.73955	1206	0.416	0.000	929	0	0.000
0.4966	0.76491	1174	0.373	0.509	948	43	−0.024								
					$T = 303.15$ K										
0.0000	0.79448	1171	0.360	0.000	918	0	0.000	0.6189	0.75227	1152	0.355	0.551	1002	48	−0.026
0.0472	0.79118	1168	0.358	0.039	927	6	−0.003	0.6838	0.74856	1154	0.359	0.540	1004	45	−0.025
0.0981	0.78734	1164	0.358	0.115	937	13	−0.005	0.8034	0.74242	1160	0.367	0.438	1001	36	−0.021
0.1929	0.78029	1158	0.354	0.254	955	26	−0.013	0.9061	0.73799	1169	0.377	0.249	992	20	−0.014
0.2932	0.77317	1154	0.353	0.372	971	36	−0.017	0.9499	0.73651	1174	0.383	0.115	985	11	−0.009
0.3753	0.76757	1152	0.352	0.449	982	42	−0.021	1.0000	0.73454	1180	0.394	0.000	977	0	0.000
0.4966	0.75963	1151	0.354	0.533	994	46	−0.023								

Table 7. Density, ρ, Speed of Sound, u, Dynamic Viscosity, η, Excess Molar Volume, V^E, Isentropic Compressibilities, κ_s, Deviation in Isentropic Compressibility, $\Delta\kappa_s$, and Viscosity Deviation, $\Delta\eta$, of Cyclopentane (1) + 2-Pentanone (2)

x_1	ρ / g·cm^{-3}	u / m·s^{-1}	$10^3\eta$ / Pa·s	V^E / cm^3·mol^{-1}	k_s / TPa^{-1}	$\Delta\kappa_s$ / TPa^{-1}	$10^3\Delta\eta$ / Pa·s	x_1	ρ / g·cm^{-3}	u / m·s^{-1}	$10^3\eta$ / Pa·s	V^E / cm^3·mol^{-1}	k_s / TPa^{-1}	$\Delta\kappa_s$ / TPa^{-1}	$10^3\Delta\eta$ / Pa·s
					$T = 293.15$ K										
0.0000	0.80626	1233	0.496	0.000	816	0	0.000	0.6097	0.76725	1211	0.436	0.422	889	31	−0.025
0.0411	0.80385	1231	0.490	0.022	821	2	−0.003	0.6934	0.76209	1212	0.433	0.395	893	30	−0.024
0.0966	0.80008	1227	0.481	0.114	830	8	−0.009	0.7996	0.75571	1216	0.429	0.319	895	25	−0.021
0.1985	0.79357	1222	0.471	0.215	845	15	−0.014	0.9054	0.74964	1222	0.429	0.181	893	15	−0.015
0.3214	0.78570	1216	0.458	0.313	861	23	−0.020	0.9515	0.74727	1227	0.433	0.080	889	8	−0.009
0.3876	0.78143	1214	0.452	0.357	869	26	−0.022	1.0000	0.74452	1232	0.439	0.000	885	0	0.000
0.5026	0.77420	1211	0.443	0.389	880	30	−0.025								
					$T = 298.15$ K										
0.0000	0.80142	1213	0.469	0.000	849	0	0.000	0.6097	0.76225	1187	0.414	0.438	930	32	−0.023
0.0411	0.79900	1210	0.463	0.023	854	2	−0.004	0.6934	0.75708	1188	0.410	0.410	936	31	−0.022
0.0966	0.79523	1206	0.455	0.117	865	8	−0.009	0.7996	0.75070	1191	0.407	0.331	939	26	−0.020
0.1985	0.78867	1200	0.445	0.222	880	16	−0.013	0.9054	0.74463	1197	0.406	0.190	937	15	−0.015
0.3214	0.78076	1194	0.433	0.324	898	24	−0.018	0.9515	0.74228	1202	0.410	0.084	933	8	−0.008
0.3876	0.77648	1192	0.428	0.370	907	27	−0.020	1.0000	0.73955	1206	0.416	0.000	929	0	0.000
0.5026	0.76921	1189	0.419	0.404	920	31	−0.023								
					$T = 303.15$ K										
0.0000	0.79658	1192	0.444	0.000	884	0	0.000	0.6097	0.75721	1164	0.392	0.456	975	34	−0.021
0.0411	0.79413	1189	0.440	0.026	890	2	−0.002	0.6934	0.75203	1164	0.390	0.428	981	33	−0.020
0.0966	0.79034	1185	0.431	0.122	901	8	−0.008	0.7996	0.74564	1167	0.387	0.346	985	27	−0.017
0.1985	0.78374	1179	0.422	0.232	919	16	−0.012	0.9054	0.73959	1172	0.386	0.199	985	16	−0.013
0.3214	0.77579	1172	0.410	0.337	938	25	−0.017	0.9515	0.73726	1176	0.389	0.088	981	8	−0.007
0.3876	0.77149	1169	0.406	0.385	948	28	−0.018	1.0000	0.73454	1180	0.394	0.000	977	0	0.000
0.5026	0.76419	1166	0.398	0.422	963	33	−0.021								

with acetone (2) where the minimum lies at approximately $x_1 = 0.5$ mole fraction.

4. Correlation and Prediction

The UNIQUAC[5] equation is used to calculate the excess molar free energy of activation for flow, ΔG^{*E}, which is related to the viscosity by

$$\ln(\nu M) = \sum_i x_i \ln(\nu_i M_i) + \frac{\Delta G^{*E}}{RT} \tag{6}$$

where ν is the kinematic viscosity and M and M_i are the molecular weights of the mixture and the pure component, respectively.

The correlation has been performed with experimental data using the UNIQUAC equation to calculate the excess molar free energy, minimizing the following objective function

$$\mathrm{OF} = \frac{1}{N}\sum_{i=1}^{N} \frac{|\eta_{i,\mathrm{exptl}} - \eta_{i,\mathrm{calcd}}|}{\eta_{i,\mathrm{exptl}}} \tag{7}$$

where N is the number of experimental data and $\eta_{i,\mathrm{exptl}}$ and $\eta_{i,\mathrm{calcd}}$ are the experimental and calculated dynamic viscosities, respectively. The fitting parameters (τ_{12}, τ_{21}) together with the objective function (OF) are reported in Table 9.

Figure 3 shows the viscosity data correlated by the UNIQUAC equation for the binary systems cyclohexane (1)

Table 8. Fitting Parameters and Root-Mean-Square Deviation, σ, for Binary Mixtures at T = (273.15, 298.15, and 303.15) K

Cyclohexane (1) + Acetone (2)						
			$T = 293.15$ K			
V^E/cm^3·mol^{-1}	$B_o = 4.3473$	$B_1 = 0.0372$	$B_2 = 0.8776$	$B_3 = 0.7388$		$\sigma = 0.004$
$\Delta\kappa_s$/TPa^{-1}	$B_o = 207.60$	$B_1 = -47.05$	$B_2 = 52.59$			$\sigma = 0.27$
$10^3\Delta\eta$/Pa·s	$B_o = -0.6241$	$B_1 = -0.2720$	$B_2 = -0.2255$			$\sigma = 0.003$
			$T = 298.15$ K			
V^E/cm^3·mol^{-1}	$B_o = 4.4732$	$B_1 = 0.0381$	$B_2 = 0.8759$	$B_3 = 0.7636$		$\sigma = 0.004$
$\Delta\kappa_s$/TPa^{-1}	$B_o = 223.35$	$B_1 = -50.77$	$B_2 = 53.10$			$\sigma = 0.30$
$10^3\Delta\eta$/Pa·s	$B_o = -0.5551$	$B_1 = -0.2209$	$B_2 = -0.1779$			$\sigma = 0.003$
$T = 303.15$ K						
V^E/cm^3·mol^{-1}	$B_o = 4.6030$	$B_1 = 0.0513$	$B_2 = 0.8773$	$B_3 = 0.7605$		$\sigma = 0.004$
$\Delta\kappa_s$/TPa^{-1}	$B_o = 240.87$	$B_1 = -53.95$	$B_2 = 55.08$			$\sigma = 0.32$
$10^3\Delta\eta$/Pa·s	$B_o = -0.4932$	$B_1 = -0.1889$	$B_2 = -0.1496$			$\sigma = 0.002$
Cyclohexane (1) + Butanone (2)						
			$T = 293.15$ K			
V^E/cm^3·mol^{-1}	$B_o = 3.5532$	$B_1 = 0.6401$	$B_2 = 0.6253$			$\sigma = 0.008$
$\Delta\kappa_s$/TPa^{-1}	$B_o = 167.38$	$B_1 = 1.83$	$B_2 = 22.24$			$\sigma = 0.26$
$10^3\Delta\eta$/Pa·s	$B_o = -0.6073$	$B_1 = -0.3028$	$B_2 = -0.2290$			$\sigma = 0.003$
$T = 298.15$ K						
V^E/cm^3·mol^{-1}	$B_o = 3.6378$	$B_1 = 0.6576$	$B_2 = 0.6330$			$\sigma = 0.008$
$\Delta\kappa_s$/TPa^{-1}	$B_o = 177.94$	$B_1 = 3.15$	$B_2 = 24.55$			$\sigma = 0.30$
$10^3\Delta\eta$/Pa·s	$B_o = -0.5379$	$B_1 = -0.2726$	$B_2 = -0.1682$			$\sigma = 0.002$
			$T = 303.15$ K			
V^E/cm^3· mol^{-1}	$B_o = 3.7258$	$B_1 = 0.6802$	$B_2 = 0.6336$			$\sigma = 0.008$
$\Delta\kappa_s$/TPa^{-1}	$B_o = 189.92$	$B_1 = 4.47$	$B_2 = 26.09$			$\sigma = 0.33$
$10^3\Delta\eta$/Pa·s	$B_o = -0.4758$	$B_1 = -0.2366$	$B_2 = -0.1376$			$\sigma = 0.003$
Cyclohexane (1) + 2-Pentanone (2)						
			$T = 293.15$ K			
V^E/cm^3· mol^{-1}	$B_o = 3.1642$	$B_1 = 0.6363$	$B_2 = 0.6503$	$B_3 = 0.5010$		$\sigma = 0.006$
$\Delta\kappa_s$/TPa^{-1}	$B_o = 142.98$	$B_1 = 30.40$	$B_2 = 21.83$			$\sigma = 0.29$
$10^3\Delta\eta$/Pa·s	$B_o = -0.5624$	$B_1 = -0.2894$	$B_2 = -0.1573$			$\sigma = 0.002$
			$T = 298.15$ K			
V^E/cm^3· mol^{-1}	$B_o = 3.1642$	$B_1 = 0.6363$	$B_2 = 0.6503$	$B_3 = 0.5010$		$\sigma = 0.006$
$\Delta\kappa_s$/TPa^{-1}	$B_o = 142.98$	$B_1 = 30.40$	$B_2 = 21.83$			$\sigma = 0.29$
$10^3\Delta\eta$/Pa·s	$B_o = -0.5624$	$B_1 = -0.2894$	$B_2 = -0.1573$			$\sigma = 0.002$
$T = 303.15$ K						
V^E/cm^3·mol^{-1}	$B_o = 3.2895$	$B_1 = 0.6859$	$B_2 = 0.6587$	$B_3 = 0.4935$		$\sigma = 0.006$
$\Delta\kappa_s$/TPa^{-1}	$B_o = 157.98$	$B_1 = 33.78$	$B_2 = 25.54$			$\sigma = 0.32$
$10^3\Delta\eta$/Pa·s	$B_o = -0.4357$	$B_1 = -0.2212$	$B_2 = -0.1375$			$\sigma = 0.002$
Cyclopentane (1) + Acetone (2)						
			$T = 293.15$ K			
V^E/cm^3· mol^{-1}	$B_o = 3.4163$	$B_1 = 0.2107$	$B_2 = 0.5120$	$B_3 = -0.1856$		$\sigma = 0.009$
$\Delta\kappa_s$/TPa^{-1}	$B_o = 263.82$	$B_1 = -3.07$	$B_2 = -11.43$			$\sigma = 0.64$
$10^3\Delta\eta$/Pa·s	$B_o = -0.1462$	$B_1 = -0.0114$	$B_2 = -0.0384$	$B_3 = -0.0643$	$B_4 = -0.0513$	$\sigma = 0.001$
			$T = 298.15$ K			
V^E/cm^3· mol^{-1}	$B_o = 3.5684$	$B_1 = 0.1849$	$B_2 = 0.4376$	$B_3 = -0.0848$		$\sigma = 0.008$
$\Delta\kappa_s$/TPa^{-1}	$B_o = 282.57$	$B_1 = -3.09$	$B_2 = 1.16$			$\sigma = 0.66$
$10^3\Delta\eta$/Pa·s	$B_o = -0.1382$	$B_1 = -0.0178$	$B_2 = -0.0839$	$B_3 = -0.0335$	$B_4 = 0.0596$	$\sigma = 0.002$
			$T = 303.15$ K			
V^E/cm^3·mol^{-1}	$B_o = 3.7217$	$B_1 = 0.2615$	$B_2 = 0.3765$	$B_3 = -0.2088$		$\sigma = 0.008$
$\Delta\kappa_s$/TPa^{-1}	$B_o = 307.82$	$B_1 = -0.57$	$B_2 = 14.09$			$\sigma = 0.54$
$10^3\Delta\eta$/Pa·s	$B_o = -0.1305$	$B_1 = -0.0141$	$B_2 = -0.0384$	$B_3 = -0.0204$	$B_4 = -0.080$	$\sigma = 0.001$
Cyclopentane (1) + Butanone (2)						
			$T = 293.15$ K			
V^E/cm^3· mol^{-1})	$B_o = 1.9246$	$B_1 = 0.8046$	$B_2 = 0.7548$	$B_3 = 0.1242$	$B_4 = -1.3161$	$\sigma = 0.005$
$\Delta\kappa_s$/TPa^{-1})	$B_o = 165.09$	$B_1 = 38.12$	$B_2 = 46.95$	$B_3 = 13.75$	$B_4 = -56.43$	$\sigma = 0.16$
$10^3\Delta\eta$/Pa·s)	$B_o = -0.1085$	$B_1 = -0.0418$	$B_2 = -0.0218$	$B_3 = -0.0508$	$B_4 = -0.0235$	$\sigma = 0.001$
			$T = 298.15$ K			
V^E/cm^3·mol^{-1}	$B_o = 2.0122$	$B_1 = 0.8491$	$B_2 = 0.7419$	$B_3 = 0.1033$	$B_4 = -1.3062$	$\sigma = 0.006$
$\Delta\kappa_s$/TPa^{-1}	$B_o = 175.23$	$B_1 = 41.39$	$B_2 = 49.53$	$B_3 = 11.48$	$B_4 = -65.94$	$\sigma = 0.20$
$10^3\Delta\eta$/Pa·s	$B_o = -0.1022$	$B_1 = -0.0360$	$B_2 = -0.0448$	$B_3 = -0.0331$	$B_4 = 0.0148$	$\sigma = 0.001$
			$T = 303.15$ K			
V^E/cm^3· mol^{-1}	$B_o = 2.1059$	$B_1 = 0.8902$	$B_2 = 0.7171$	$B_3 = 0.1070$	$B_4 = -1.2832$	$\sigma = 0.006$
$\Delta\kappa_s$/TPa^{-1}	$B_o = 187.30$	$B_1 = 45.72$	$B_2 = 51.51$	$B_3 = 13.85$	$B_4 = -67.41$	$\sigma = 0.20$
$10^3\Delta\eta$/Pa·s	$B_o = -0.0954$	$B_1 = -0.0344$	$B_2 = -0.0319$	$B_3 = -0.0389$	$B_4 = 0.0016$	$\sigma = 0.001$

Table 8. (Continued)

Cyclopentane (1) + 2-Pentanone (2)

			T = 293.15 K			
V^E/cm^3·mol^{-1}	B_o = 1.5781	B_1 = 0.5668	B_2 = 0.7107	B_3 = −0.0704	B_4 = −1.0770	σ =0.008
$\Delta\kappa_s$/TPa^{-1}	B_o = 120.51	B_1 = 48.62	B_2 = 10.55			σ = 0.30
R10$^3\Delta\eta$/Pa·s	B_o = −0.0952	B_1 = −0.0219	B_2 = −0.0558	B_3 = −0.0383		σ = 0.001
			T = 298.15 K			
V^E/cm^3·mol^{-1}	B_o = 1.6374	B_1 = 0.5920	B_2 = 0.7302	B_3 = −0.0484	B_4 = −1.1019	σ = 0.008
$\Delta\kappa_s$/TPa^{-1}	B_o =124.80	B_1 =51.44	B_2 = 9.84			σ = 0.36
10$^3\Delta\eta$/Pa·s	B_o = −0.0876	B_1 = −0.0211	B_2 = −0.0564	B_3 = −0.0354		σ = 0.001
			T = 303.15 K			
V^E/cm^3·mol^{-1}	B_o = 1.7066	B_1 = 0.6220	B_2 = 0.7420	B_3 = −0.0632	B_4 = −1.0934	σ = 0.008
$\Delta\kappa_s$/TPa^{-1}	B_o = 130.83	B_1 = 56.39	B_2 = 12.21			σ = 0.39
10$^3\Delta\eta$/Pa·s	B_o = −0.0801	B_1 = −0.0142	B_2 = −0.0425	B_3 = −0.0395		σ = 0.001

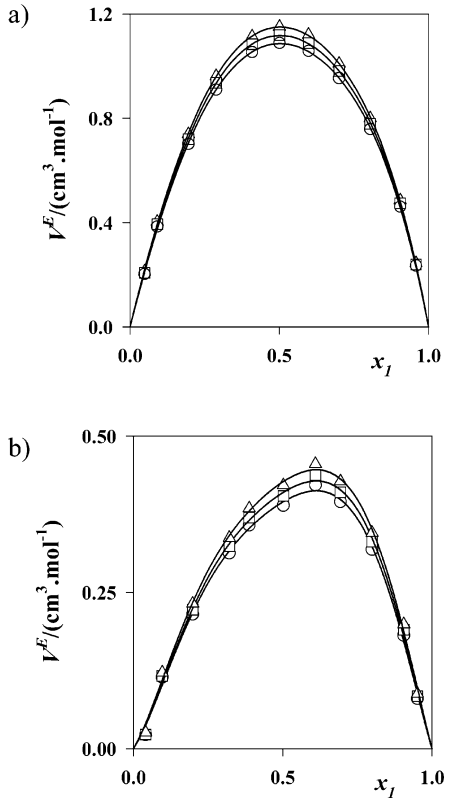

Figure 1. Excess molar volume, V^E, from the Redlich−Kister equation plotted against mole fraction at T = 293.15 K (○), T = 298.15 K (□), and T = 313.15 K (△) for the binary mixtures (a) cyclohexane (1) + acetone (2) and (b) cyclopentane (1) + 2-pentanone (2).

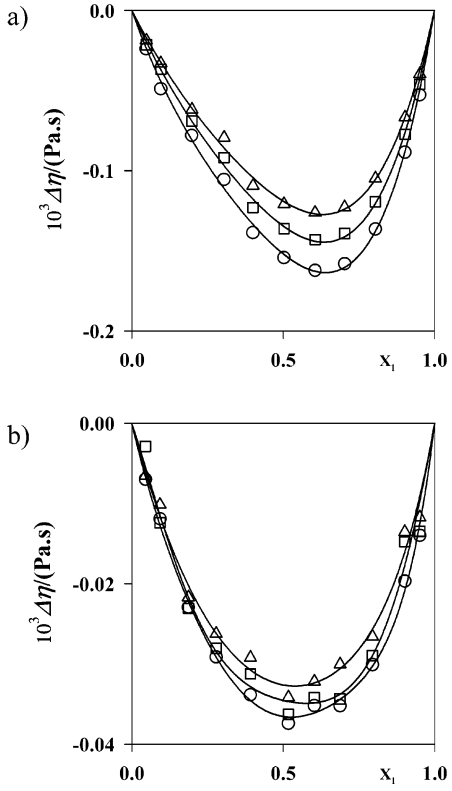

Figure 2. Viscosity deviations, $\Delta\eta$, from the Redlich−Kister equation plotted against mole fraction at T = 293.15 K (○), T = 298.15 K (□), and T = 313.15 K (△) for the binary mixtures (a) cyclohexane (1) + butanone (2) and (b) cyclopentane (1) + acetone (2).

with acetone (2) and cyclopentane (1) with butanone (2). It can be seen that this equation fit the experimental data fairly well at several temperatures. The other systems present similar behavior.

UNIFAC-VISCO and ASOG-VISCO methods have been applied to predict the dynamic viscosities.

Table 10 shows the average absolute deviation of dynamic viscosity (AAD) resulting from the prediction using UNIFAC-VISCO and ASOG-VISCO methods for the binary mixtures cyclohexane and cyclopentane with ketones at T = (293.15, 298.15, and 303.15) K.

Figure 4 shows the experimental dynamic viscosities and the predicted values by applying the UNIFAC-VISCO and ASOG-VISCO methods for the binary mixtures cyclohexane (1) with 2-pentanone (2) and cyclopentane (1) with acetone (2). The other systems have not been represented because they present similar behavior. It can be observed that the UNIFAC-VISCO method predicts the experimental behavior of these mixtures better than the ASOG-VISCO method.

Table 9. UNIQUAC Parameters and the Objective Function, OF

systems	τ_{12}/J·mol^{-1}	τ_{21}/J·mol^{-1}	OF
cyclohexane (1) + acetone (2)	−144.30	207.16	0.005
cyclohexane (1) + butanone (2)	−384.41	383.11	0.005
cyclohexane (1) + 2-pentanone (2)	−403.97	387.84	0.003
cyclopentane (1) + acetone (2)	−17.29	134.42	0.005
cyclopentane (1) + butanone (2)	−272.18	276.54	0.003
cyclopentane (1) + 2-pentanone (2)	−223.25	225.64	0.003

5. Conclusions

In this work, the dynamic viscosities, densities, and speeds of sound of the binary systems cyclohexane (1) and cyclopentane (1) with acetone (2), butanone (2), or 2-pentanone (2) at T = (293.15, 298.15, and 303.15) K and atmospheric pressure have been determined.

The excess molar volumes and viscosity deviations were calculated, and these data were fitted to the Redlich−Kister equation to test the quality of the experimental values.

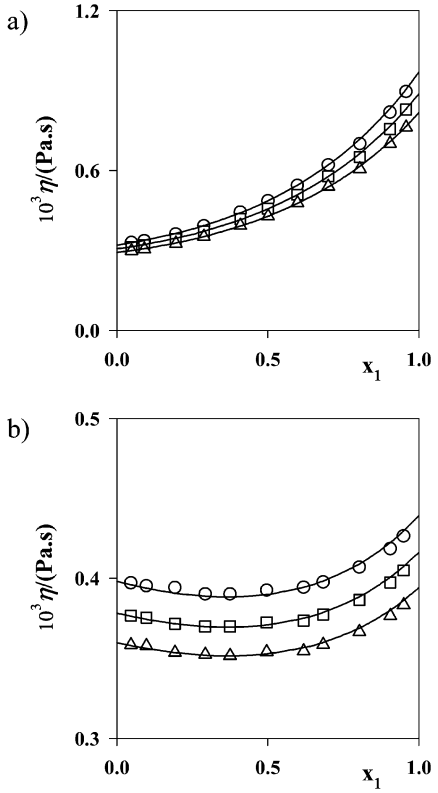

Figure 3. Dynamic viscosity, η, from the UNIQUAC equation plotted against mole fraction at $T = 293.15$ K (○), $T = 298.15$ K (□), and $T = 313.15$ K (△) for the binary mixtures (a) cyclohexane (1) + acetone (2) and (b) cyclopentane (1) + butanone (2).

Table 10. Average Absolute Deviation (AAD) of Dynamic Viscosity Resulting from the Prediction Using the UNIFAC-VISCO and ASOG-VISCO Methods for Binary Mixtures of Cyclohexane (1) + Cyclopentane (1), + Acetone (2), and + Butanone (2), and 2-Pentanone (2) at Several Temperatures

systems	*T*/K	AAD UNIFAC-VISCO	AAD ASOG-VISCO
cyclohexane (1) + acetone (2)	293.15	2.13	9.08
	298.15	1.69	8.77
	303.15	1.23	8.37
cyclohexane (1) + butanone (2)	293.15	4.27	10.91
	298.15	3.57	10.23
	303.15	3.08	9.77
cyclohexane (1) + 2-pentanone (2)	293.15	5.04	10.70
	298.15	4.58	10.18
	303.15	4.16	9.72
cyclopentane (1) + acetone (2)	293.15	1.31	5.64
	298.15	1.18	5.57
	303.15	1.15	5.52
cyclopentane (1) + butanone (2)	293.15	0.77	4.31
	298.15	0.88	4.29
	303.15	0.94	4.19
cyclopentane (1) + 2-pentanone (2)	293.15	1.51	3.84
	298.15	1.52	3.83
	303.15	1.61	3.58

The correlation of the experimental data had been determined using the UNIQUAC equation. These equation fit the experimental data fairly well.

A prediction of the dynamic viscosity of these mixtures from the UNIFAC-VISCO and ASOG-VISCO methods has been made. For these systems, the UNIFAC-VISCO method obtains better results than the ASOG-VISCO method.

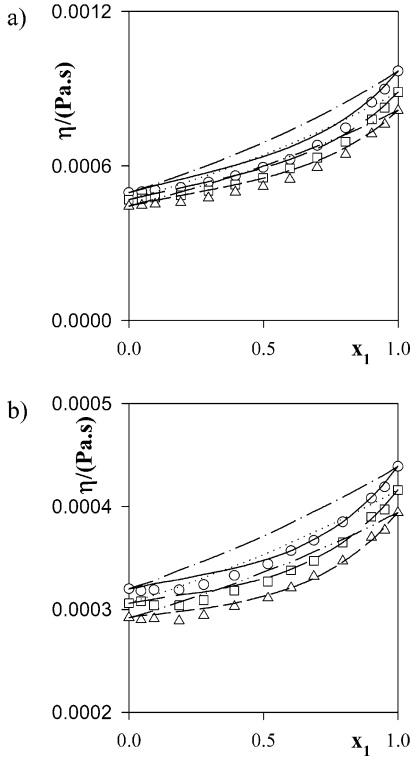

Figure 4. Predicted values of the dynamic viscosity, η, from the UNIFAC-VISCO and ASOG-VISCO methods plotted against mole fraction at $T = 293.15$ K (○, experimental data; — UNIFAC-VISCO method; – · – ASOG-VISCO method); $T = 298.15$ K (□, experimental data; – –, UNIFAC–VISCO method; ···, ASOG-VISCO method), and $T = 303.15$ K (△, experimental data; – –, UNIFAC-VISCO method; – · · –, ASOG-VISCO method) for the binary mixtures (a) cyclohexane (1) + 2-pentanone (2) and (b) cyclopentane (1) + acetone (2).

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Received for review March 21, 2005. Accepted April 28, 2005.

JE050110R