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Thermodynamic properties of P-methyl acetophenone with cyclohexylamine, cyclohexanol, and cyclohexane at various temperatures (strong and weak interactions)

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ABSTRACT

The density, viscosity and sound velocity of the binary liquid mixtures of P-methyl acetophenone with cyclohexylamine, cyclohexanol, and cyclohexane are measured over the complete composition range at temperatures of 303.15–313.15 K and at atmospheric pressure of 0.1 M. Excess molar volume, excess isentropic compressibility and viscosity deviation are calculated from the experimental measurements. The sign and magnitude of the derived parameters reveal the nature and type of interactions between the constituent molecules in the binary mixtures. Thermodynamic properties for this work reveal association interactions between dissimilar molecules in the binary systems P-methyl acetophenone + cyclohexylamine and P-methyl acetophenone + cyclohexanol systems, whereas dispersion forces cause the opposite trend in the other binary system P-methyl acetophenone + cyclohexane.

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Density; speed of sound; P-methylacetophenone; cyclohexane; cyclohexylamine; cyclohexanol

1. Introduction

Thermo physical properties of multi-component liquid mixtures are essential for process designing and understanding structural and packing changes of molecules in mixtures. The design and operation of processes that involve non-electrolyte mixtures require knowledge of rigorous models or experimental data to represent the non-ideality of mixtures [1–3].

In the present work, the liquid components selected for the study of molecular interactions are P-methyl acetophenone with cyclohexylamine, cyclohexanol, and cyclohexane. These solvents are well-known organic liquids that have a wide range of uses in chemistry as well as in other industrial settings.

Cyclohexane is widely used as a solvent, polar additive, dilution initiator, structure regulator, and active additive in the synthesis of copolymers, resins, and rubber [4]. Cyclohexanol finds applications as an intermediate substance in the production of nylon and plasticisers. It acts as a stabiliser in soap and detergent making and as a solvent in in the paint and textile industries [5]. Cyclic and linear alcohols are associated through the hydrogen bond in the pure state as well as in mixtures. The degree of association in alkanols containing cyclic alkyl group is very low due to steric factors [6]. In the production of numerous organic molecules used in the chemical, pharmaceutical, and cosmetic industries, cyclic ketones play a significant role as intermediates [7]. A methylated

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acetophenone used in cosmetics and perfumes is P-methyl acetophenone. cyclohexylamine is an organic synthesiser and corrosion inhibitor among cyclic compounds, is used in the production of plasticisers, detergents, pesticides, and emulsifiers [8]

The densities, sound speeds, and viscosities of pure P-methyl acetophenone with cyclohexylamine, cyclohexanol, and cyclohexane as well as those of their binary mixtures over the whole composition range were measured at T = (303.15 K to 313.15) K and at an ambient pressure of 0.1 MPa and are presented in this paper. The thermophysical characteristics of the binary system under study have not been described, according to a review of the literature. These experimental results are used to compute and discuss the values of excess volume, excess isentropic compressibility, and deviation in viscosity, and excess Gibbs free energy of activation of viscous flow in terms of dispersion forces, hydrogen bond formation, and charge transfer complexes.

2. Experimental

2.1 Materials

Their source, ultimate purity, and method of analysis are detailed in Table 1. Table 2 lists the values for density, sound speed and viscosity. These numbers match very well with the data that are available in the literature [9–16].

2.2 Apparatus and procedure

To reduce evaporation losses, all the binary liquid combinations were made by syringing each component into air-tight stopper bottles after weighing the necessary amounts of pure liquids in an electric balance (ER-120A, Afoset, India) with a precision of ±0.1 mg. The mole fraction's level of uncertainty was $\pm 1 \times 10^{-4}$. There have been further descriptions of the procedures and measurement techniques [17].

The density measurements were performed with a Rudolph Research Analytical Digital Density Meter (DDM-2911 Model), equipped with a built-in solid-state thermostat and a resident program with accuracy of temperature of 303.15 K ±0.03 K.

Table 1. List of chemicals with details of source, CAS number, purity and water content.

Name of the chemical	CAS Number	Source	**water content (%)	mass fraction purity
P-methylacetophenone	122-00-9	Sigma Aldrich, India	0.045	0.995
cyclohexane	110-82-7	Sigma Aldrich, India	0.042	0.998
cyclohexylamine	108-91-8	S.D. Fine chemicals	0.042	0.997
cyclohexanol	108-93-0	S.D. Fine chemicals	0.042	0.996

**Karl-Fischer method.

Table 2. Densities, viscosity and speeds of sound data of pure components at 303.15 K and 0.1MPa pressure.

Component	density (ρ/g·cm^{-3})		Speed of sound (u/m·s^{-1})		Viscosity (η/mPa·s)	
(in K)	Experimental	Literature	Experimental	Literature	Experimental	Literature
P-methyl acetophenone	0.99652* [9]	0.9963* [10]	1434* [9]	1438.0* [11]	1.536* [9]	1.5919* [10]
cyclohexane	0.76916	0.76915 [12]	1229.0	1229.33 [12]	0.821	0.820 [13]
cyclohexylamine	0.85773	0.85771 [14]	1398.2	1397.1 [14]	1.978	1.979 [14]
cyclohexanol	0.94133	0.94132 [14]	1441.5	1442.6 [15]	41.10	41.078 [16]

*308.15 K.

The standard uncertainties are u(x_1) = 1×10^{-4}, u (ρ) $\pm 2 \times 10^{-4}$g.cm^{-3}, u (u) = ±0.6 m.s^{-1}., u (η) = ±0.08mPa·s, u (T) = 0.01 K for density, speed of sound and viscosity, and u (P) = 1 kPa

The ultrasonic speed in pure liquids and in their mixtures was measured by using a multi-frequency ultrasonic interferometer (*M*-82 Model, Mittal Enterprise, New Delhi, India) single-crystal variable-path, operated at 2 MHz, at 303.15 K, 308.15 K, and 313.15 K by using a digital constant temperature water bath.

The viscosities of pure liquids and their mixtures were determined at atmospheric pressure at *T*= (303.15–313.15) K by using an Ubbelohde viscometer

The measurement errors for liquid mixture densities are $\pm 2 \times 10^{-4}$ g.cm^{-3}. Sound speed measurements have a 0.6 m.s^{-1} measuring error. The measurement of viscosity had a precision of ± 0.08 mPa.s. By moving a thermostatic water bath around the cell with a circulating pump, the temperature stability is kept within ± 0.01 K

3. Results and discussion

The experimental data was used in the present study to calculate the excess/deviation parameters (V^E, $\kappa_s{}^E$,Δη, and ΔG^{*E}) for the present mixtures at various temperatures. The details of their equations were described elsewhere [17]. The density, speed of sound, and viscosity for binary mixtures of various mole fractions of P-methyl acetophenone are presented in Table 3 along with V^E, $\kappa_s{}^E$,Δη, and ΔG^{*E} at various temperatures.

The V^E values at 303.15 K are plotted against mole fraction P-methyl acetophenone in Figure 1. The curves for 308.15 and 313.15 K are omitted to avoid congestion of points. It is clear that, for the P-methyl acetophenone + cyclohexane mixture, V^E is positive over the entire composition range, whereas it is negative for the rest of the mixtures.

The observed V^E values are the result of physical and chemical forces and may be broadly recognised as

(i) The breaking of liquid order on mixing with the second component; (ii) Non – specific physical interactions and unfavourable interactions between unlike molecules; (iii) Specific interactions appearing in the mixture between dissimilar molecules by hydrogen bond formation; and, (iv) Specific interactions appearing in the mixture between solvent and co-solvent molecules by dipole-dipole

The first two factors contribute to the expansion of volume and the latter two factors contribute to the reduction of the volume. As a result, positive V^E values indicate that dissociation of associated liquid structure takes place resulting in an expansion of the volume of the mixture, whereas negative values show that the volume reduction factor plays an important role between unlike molecules. This indicates the formation of hydrogen bond complexes. A similar trend was observed [18,19]

Excess molar volume values of P-methyl acetophenone with cyclohexylamine, cyclohexanol, and cyclohexane fall in the order:

$$\text{cyclohexane} < \text{cyclohexylamine} < \text{cyclohexanol}$$

It is hypothesised that in binary liquid mixtures, heteromolecular interaction via attractive forces diminishes from cyclohexanol to cyclohexane with P-methyl acetophenone. Thus, the above arrangement was appropriate.

With the exception of P-methyl acetophenone + cyclohexane, all binary systems' excess isentropic compressibility is negative over the entire composition range and at all experimental temperatures. For the system P-methyl acetophenone + cyclohexane, the opposite trend is found, which may be related to the compact structure, which is induced by the dissociation of dipole-dipole bond molecules. Figure 2 shows that the negative values in the mixtures imply that the force of attraction makes the binary mixture more compact, while dispersion forces are prominent in the P-methyl acetophenone + cyclohexane system [20,21].

Table 3. Density (ρ), excess molar volumes (V^E), speed of sound (u), excess isentropic compressibility (κ_s^E), viscosity (η), deviation in viscosity ($\Delta\eta$) and excess Gibbs energy of activation of viscous flow (G^{*E}) as a function of mole fraction, x_1 of P-methylacetophenone of binary liquid mixtures at T= (303.15 to 313.15) K and 0.1MPa pressure.

x_1	Density(ρ) g·cm^{-3}	V^E cm^3·mol^{-1}	u m.s^{-1}	K_s^E/TPa^{-1}	viscosity (η/mPa·s)	$\Delta\eta$/mPa·s	ΔG^{*E}/J·mol^{-1}
P-methylacetophenone (1)+ cyclohexane (2)							
			303.15 K				
0.0000	0.76916	0.0000	1229.0	0.000	0.821	0.000	0.000
0.0927	0.79489	0.0037	1237.9	3.432	0.859	−0.032	−0.326
0.1808	0.81839	0.0074	1248.1	6.239	0.904	−0.054	−0.459
0.2716	0.84168	0.0105	1260.7	8.507	0.958	−0.069	−0.471
0.3915	0.87111	0.0133	1280.6	10.34	1.039	−0.079	−0.390
0.4999	0.89650	0.0141	1302.1	10.77	1.121	−0.080	−0.272
0.5904	0.91687	0.0135	1322.9	10.22	1.194	−0.076	−0.183
0.6936	0.93923	0.0115	1350.0	8.662	1.283	−0.065	−0.088
0.7918	0.95969	0.0085	1379.4	6.388	1.373	−0.050	−0.039
0.8918	0.97976	0.0045	1413.1	3.485	1.468	−0.031	−0.029
1.0000	1.00065	0.0000	1454.0	0.000	1.581	0.000	0.000
308.15 K							
0.0000	0.76445	0.0000	1204.2	0.000	0.758	0.000	0.000
0.0927	0.79018	0.0064	1212.4	4.814	0.794	−0.037	−0.449
0.1808	0.81370	0.0103	1222.6	8.101	0.840	−0.059	−0.553
0.2716	0.83704	0.0135	1235.4	10.41	0.897	−0.072	−0.488
0.3915	0.86653	0.0158	1255.8	12.07	0.981	−0.081	−0.339
0.4999	0.89198	0.0165	1277.7	12.43	1.065	−0.082	−0.210
0.5904	0.91241	0.0159	1298.7	11.97	1.139	−0.078	−0.124
0.6936	0.93483	0.0143	1325.9	10.61	1.230	−0.068	−0.043
0.7918	0.95537	0.0116	1355.5	8.405	1.319	−0.055	−0.045
0.8918	0.97552	0.0073	1390.1	5.085	1.417	−0.035	−0.060
1.0000	0.99652	0.0000	1434.0	0.000	1.536	0.000	0.000
313.15 K							
0.0000	0.75974	0.0000	1179.4	0.000	0.695	0.000	0.000
0.0927	0.78548	0.0086	1187.3	5.897	0.728	−0.041	−0.591
0.1808	0.80902	0.0131	1197.4	9.630	0.775	−0.064	−0.651
0.2716	0.83239	0.0162	1210.4	12.08	0.835	−0.076	−0.491
0.3915	0.86194	0.0181	1231.1	13.76	0.923	−0.084	−0.261
0.4999	0.88746	0.0188	1253.3	14.19	1.008	−0.085	−0.118
0.5904	0.90794	0.0183	1274.4	13.86	1.084	−0.081	−0.037
0.6936	0.93044	0.0171	1301.8	12.65	1.176	−0.071	0.025
0.7918	0.95104	0.0146	1331.8	10.42	1.266	−0.059	−0.038
0.8918	0.97128	0.0097	1367.5	6.605	1.366	−0.039	−0.088
1.0000	0.99239	0.0000	1414.0	0.000	1.491	0.000	0.000
P-methylacetophenone (1)+ cyclohexylamine (2)							
303.15 K							
0.0000	0.85773	0.0000	1398.2	0.000	1.978	0.000	0.000
0.1019	0.87464	−0.0396	1407.3	−4.690	1.948	0.010	0.200
0.2018	0.89062	−0.0654	1415.6	−7.991	1.916	0.018	0.359
0.3152	0.90808	−0.0814	1424.0	−10.27	1.876	0.024	0.488
0.4115	0.92237	−0.0855	1430.3	−11.06	1.841	0.026	0.558
0.5101	0.93652	−0.0824	1436.0	−10.88	1.802	0.027	0.583
0.6104	0.95046	−0.0730	1440.9	−9.812	1.761	0.025	0.562
0.7006	0.96262	−0.0603	1444.6	−8.193	1.722	0.022	0.499
0.8108	0.97701	−0.0406	1448.4	−5.551	1.671	0.015	0.362
0.9008	0.98842	−0.0220	1451.2	−3.011	1.629	0.009	0.216
1.0000	1.00065	0.0000	1454.0	0.000	1.581	0.000	0.000
308.15K							
0.0000	0.85317	0.0000	1380.2	0.000	1.703	0.000	0.000
0.1019	0.87016	−0.0459	1389.6	−5.320	1.698	0.012	0.208
0.2018	0.88616	−0.0702	1397.7	−8.831	1.690	0.020	0.360
0.3152	0.90366	−0.0860	1405.8	−11.10	1.677	0.027	0.475
0.4115	0.91798	−0.0894	1411.8	−11.82	1.664	0.029	0.533
0.5101	0.93218	−0.0863	1417.2	−11.60	1.648	0.030	0.549
0.6104	0.94617	−0.0773	1422.0	−10.52	1.629	0.028	0.526
0.7006	0.95837	−0.0646	1425.7	−8.927	1.611	0.025	0.468

(*Continued*)

Table 3. (Continued).

x_1	Density(ρ) g·cm^{-3}	V^E cm^3·mol^{-1}	u m.s^{-1}	K_s^E/TPa^{-1}	viscosity (η/mPa·s)	Δη/mPa·s	ΔG*^{E}/J·mol^{-1}
0.8108	0.97282	−0.0453	1429.4	−6.260	1.586	0.019	0.351
0.9008	0.98427	−0.0263	1431.9	−3.542	1.564	0.011	0.209
1.0000	0.99652	0.0000	1434.0	0.000	1.536	0.000	0.000
313.15K							
0.0000	0.84861	0.0000	1361.6	0.000	1.618	0.000	0.000
0.1019	0.86567	−0.0523	1371.2	−5.951	1.619	0.014	0.246
0.2018	0.88170	−0.0749	1379.3	−9.671	1.616	0.023	0.414
0.3152	0.89923	−0.0907	1387.1	−11.93	1.607	0.029	0.533
0.4115	0.91359	−0.0932	1392.9	−12.58	1.598	0.032	0.588
0.5101	0.92783	−0.0901	1398.1	−12.31	1.586	0.033	0.609
0.6104	0.94187	−0.0816	1402.8	−11.23	1.572	0.032	0.591
0.7006	0.95411	−0.0689	1406.5	−9.660	1.558	0.029	0.543
0.8108	0.96863	−0.0501	1410.2	−6.968	1.537	0.022	0.420
0.9008	0.98012	−0.0306	1412.5	−4.072	1.517	0.014	0.258
1.0000	0.99239	0.0000	1414.0	0.000	1.491	0.000	0.000
P-methylacetophenone (1)+ cyclohexanol (2)							
303.15K							
0.0000	0.94133	0.0000	1441.5	0.000	41.10	0.000	0.000
0.1112	0.94981	−0.0460	1443.3	−0.557	36.71	0.011	6.269
0.2218	0.95762	−0.0723	1445.2	−1.073	32.35	0.020	12.13
0.3215	0.96422	−0.0846	1446.9	−1.437	28.42	0.025	17.02
0.4115	0.96984	−0.0879	1448.3	−1.647	24.86	0.027	21.00
0.5103	0.97569	−0.0847	1449.8	−1.727	20.96	0.028	24.77
0.6244	0.98207	−0.0744	1451.1	−1.610	16.45	0.026	27.98
0.7206	0.98716	−0.0603	1452.1	−1.346	12.64	0.022	29.21
0.8118	0.99177	−0.0433	1452.8	−0.977	9.034	0.016	28.21
0.9108	0.99655	−0.0239	1453.5	−0.484	5.115	0.009	22.03
1.0000	1.00065	0.0000	1454.0	0.000	1.581	0.000	0.000
308.15K							
0.0000	0.93724	0.0000	1416.2	0.000	27.95	0.000	0.000
0.1112	0.94575	−0.0504	1418.7	−0.638	25.02	0.014	5.425
0.2218	0.95356	−0.0779	1421.2	−1.161	22.11	0.023	10.46
0.3215	0.96014	−0.0890	1423.4	−1.507	19.48	0.028	14.60
0.4115	0.96575	−0.0912	1425.3	−1.702	17.11	0.030	17.93
0.5103	0.97160	−0.0884	1427.3	−1.775	14.50	0.031	21.00
0.6244	0.97798	−0.0780	1429.3	−1.669	11.48	0.029	23.47
0.7206	0.98307	−0.0642	1430.7	−1.424	8.941	0.026	24.17
0.8118	0.98767	−0.0478	1432.0	−1.066	6.526	0.019	22.87
0.9108	0.99245	−0.0271	1433.1	−0.554	3.902	0.010	17.09
1.0000	0.99652	0.0000	1434.0	0.000	1.536	0.000	0.000
313.15K							
0.0000	0.93315	0.0000	1390.9	0.000	14.80	0.000	0.000
0.1112	0.94168	−0.0548	1394.1	−0.718	13.34	0.017	3.945
0.2218	0.94950	−0.0836	1397.2	−1.249	11.87	0.026	7.529
0.3215	0.95606	−0.0935	1400.0	−1.578	10.55	0.031	10.41
0.4115	0.96166	−0.0945	1402.3	−1.756	9.357	0.034	12.64
0.5103	0.96751	−0.0920	1404.8	−1.822	8.042	0.034	14.58
0.6244	0.97388	−0.0815	1407.4	−1.728	6.523	0.033	15.92
0.7206	0.97897	−0.0682	1409.4	−1.501	5.239	0.029	15.94
0.8118	0.98358	−0.0523	1411.1	−1.155	4.019	0.023	14.48
0.9108	0.98834	−0.0302	1412.7	−0.625	2.693	0.015	9.980
1.0000	0.99239	0.0000	1414.0	0.000	1.491	0.000	0.000

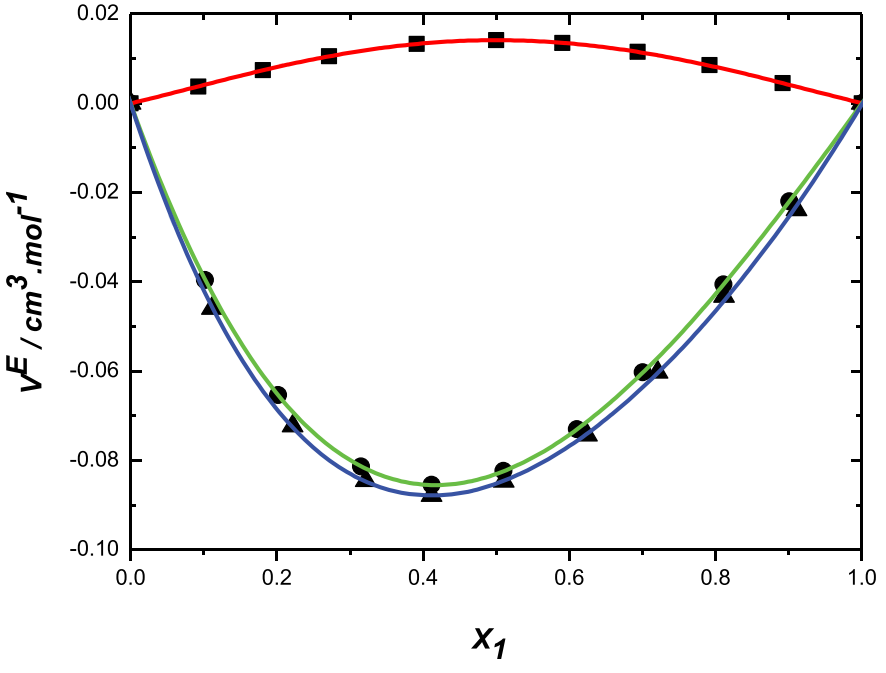

Figure 1. Curves of excess molar volume (V^E) with mole fraction for the binary mixtures of P-methyl acetophenone with cyclohexane (■); cyclohexylamine (●) and cyclohexanol (▲) at 303.15 K.

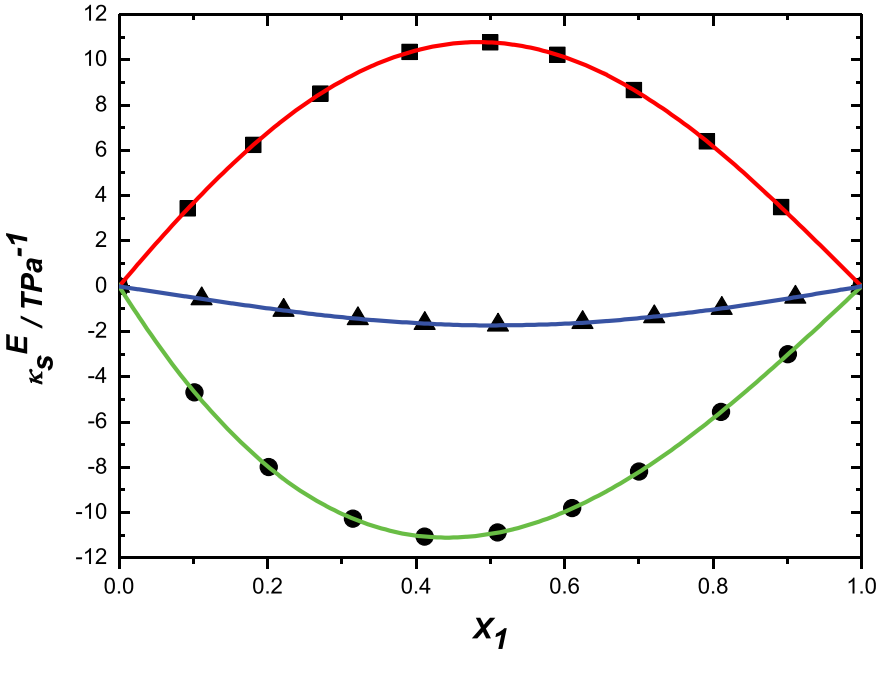

Figure 2. Curves of excess isentropic compressibility with mole fraction for the binary mixtures of P-methyl acetophenone with cyclohexane (■);cyclohexylamine (●) and cyclohexanol (▲) at 303.15 K.

In the current experiment, negative κ_s^E values indicate that hydrogen bonds are present between the components of the liquid mixtures, whereas positive values show that hydrogen bonds are absent.

Excess isentropic compressibility values of P-methyl acetophenone with cyclic compounds follow the order:

$$\text{cyclohexane} < \text{cyclohexanol} < \text{cyclohexylamine}$$

Figure 3 shows that the Excess viscosity values are found to be negative for liquid systems with dispersion, induction, and dipolar forces present, whereas the presence of specific interactions in liquid mixtures that lead to the formation of complexes and hydrogen bonds tends to make excess viscosity positive [22].

With the exception of P-methyl acetophenone with cyclohexane, all binary systems' deviation viscosity is positive over the whole composition range and at all testing temperatures.

According to Table 3, the association between the P-methyl acetophenone and cyclohexylamine, cyclohexanol through intermolecular hydrogen bonds between the dissimilar molecules is responsible for the positive values of deviation in viscosity, while the negative values of $\Delta\eta$ would imply that the mixtures are less viscous than the corresponding ideal mixture.

Deviation in viscosity values for all binary mixtures:

$$\text{cyclohexanol} > \text{cyclohexylamine} > \text{cyclohexane}$$

All binary mixtures at experimental temperatures have a positive ΔG^{*E} over the whole range of composition. The curves in Figure 4 indicate that ΔG^{*E} values are positive for all the binary mixtures over the entire mole fraction range and at each investigated temperature. The observed

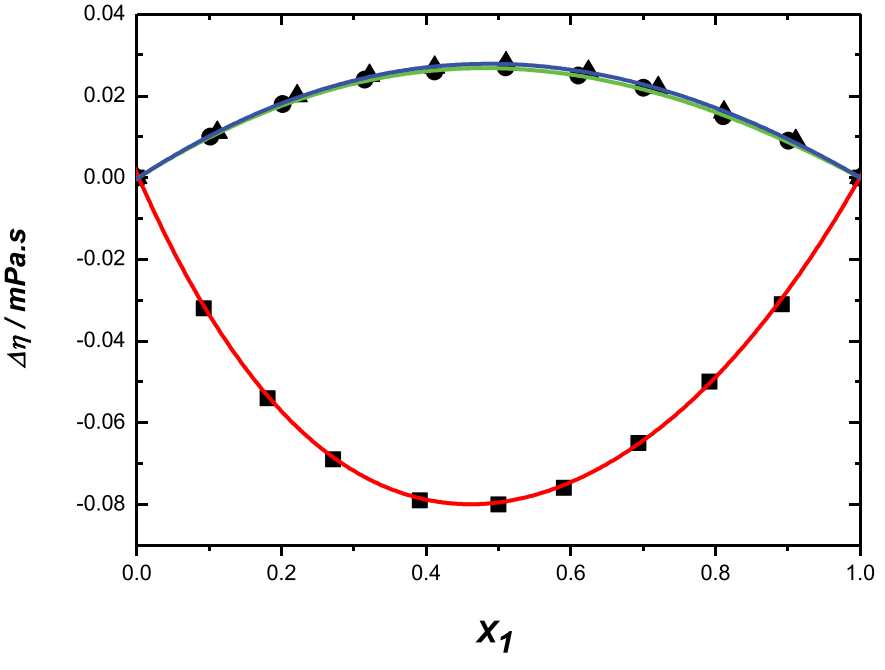

Figure 3. Curves of deviation in viscosity (Δη) with mole fraction for the binary mixtures of P-methyl acetophenone with cyclohexane (■); cyclohexylamine (●) and cyclohexanol (▲) at 303.15 K.

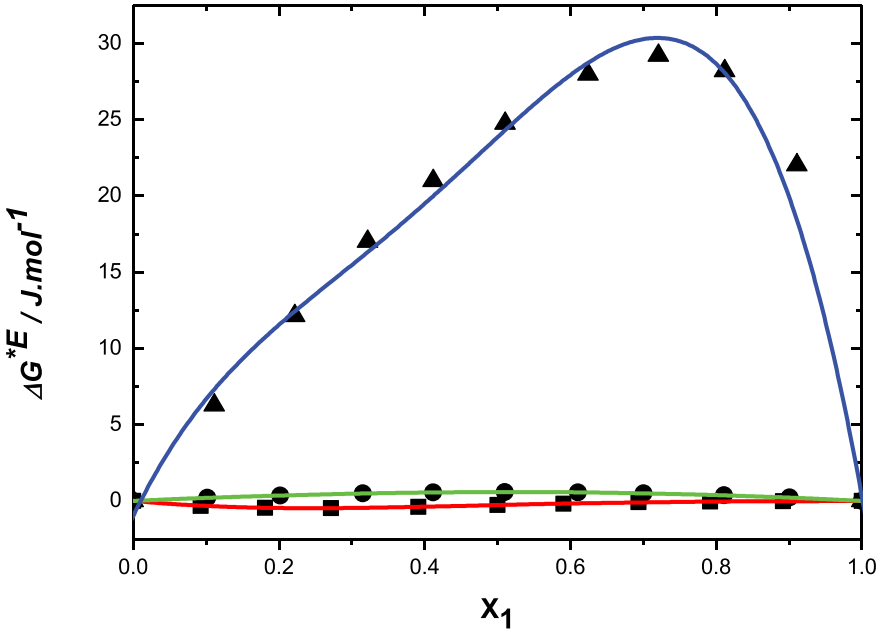

Figure 4. Curves of excess Gibbs energy of activation of viscous flow (ΔG^{*E}) with mole fraction for the binary mixtures of P-methyl acetophenone with cyclohexane (■); cyclohexylamine (●) and cyclohexanol (▲) at 303.15 K.

positive trends in (ΔG^{*E}) values indicate that the chemical forces between dissimilar molecules are dominant over the physical forces of the binary mixture components.

Excess/deviation functions (V^E, $\kappa_s^{E,}$ and $\Delta\eta$) data are fitted to a Redlich-Kister polynomial equation [23].

$$Y^E = x_1 x_2 \sum_{i=0}^{j=n-1} A_i (1 - 2x_1)^i \tag{1}$$

$$\sigma(Y^E) = \left[\sum (Y^E_{exp} - Y^E_{cal})^2/(m - n)\right]^{1/2} \tag{2}$$

Where m is the total number of experimental points and n is the number of parameters. The coefficients, A_i, and corresponding standard deviation values (σ) are presented in Table 4.

3.1 Partial molar properties

The interpretations of excess partial molar properties ($\overline{V}^E_{m,1}$,$\overline{V}^E_{m,2}$,$\overline{K}^E_{s,m,1}$and $\overline{K}^E_{s,m,2}$) and excess partial molar properties at infinite dilution($\overline{V}^{\circ E}_{m,1}$, $\overline{V}^{\circ E}_{m,2}\overline{K}^{\circ E}_{s,m,1}$and $\overline{K}^{\circ E}_{s,m,2}$) of components 2 have previously been described [17].

Tables 5 and 6 show that the negative values may be attributed to the attractive forces through the hetero-molecular association between the components of the mixtures, resulting in the formation of associated complexes through hydrogen bond interactions [24]. Positive values show dispersive forces and different component sizes in binary mixtures.

Table 4. Coefficients of Redlich – Kister equation and standard deviation (σ) values for liquid mixtures of P-methylacetophenone with cyclohexane, cyclohexylamine and cyclohexanol at *T*= (303.15–313.15) K.

T/K	A_0	A_1	A_2	σ
P-methylacetophenone + cyclohexane				
V^E/cm^3·mol^{-1}				
303.15	0.057	0.001	−0.017	0.001
308.15	0.065	0.001	0.016	0.001
313.15	0.074	0.001	0.042	0.002
κ_s^E/TPa^{-1}				
303.15	43.07	−3.160	−7.293	0.001
308.15	49.71	−2.595	8.162	0.002
313.15	56.76	−0.428	19.61	0.003
Δη/mPa• s				
303.15	−0.319	0.064	−0.008	0.001
308.15	−0.331	0.066	−0.063	0.001
313.15	−0.333	0.048	−0.169	0.001
P-methylacetophenone + cyclohexylamine				
V^E/cm^3·mol^{-1}				
303.15	−0.332	0.117	−0.012	0.001
308.15	−0.345	0.124	−0.078	0.001
313.15	−0.357	0.132	−0.146	0.002
κ_s^E/TPa^{-1}				
303.15	−43.78	10.98	2.004	0.003
308.15	−46.64	11.60	−3.562	0.002
313.15	−49.49	12.23	−9.145	0.002
Δη/mPa• s				
303.15	0.108	−0.006	−0.006	0.001
308.15	0.120	−0.005	0.011	0.001
313.15	0.132	0.003	0.034	0.001
P-methylacetophenone + cyclohexanol				
V^E/cm^3·mol^{-1}				
303.15	−0.339	0.113	−0.062	0.001
308.15	−0.353	0.119	−0.108	0.001
313.15	−0.366	0.124	−0.153	0.001
κ_s^E/TPa^{-1}				
303.15	−6.905	−0.274	1.742	0.002
308.15	−7.097	−0.261	0.728	0.002
313.15	−7.287	−0.255	−0.292	0.003
Δη/mPa• s				
303.15	0.112	−0.004	−0.002	0.001
308.15	0.125	−0.009	0.013	0.001
313.15	0.135	0.002	0.059	0.001

Table 5. The values of $\bar{V}^{\circ}_{m,1}$, $\bar{V}^{*}_{m,1}$, $\bar{V}^{\circ E}_{m,1}$, $\bar{V}^{\circ}_{m,2}$, *and* $\bar{V}^{\circ E}_{m,2}$ of the components for P-methylacetophenone with cyclohexane, cyclohexylamine and cyclohexanol of binary mixtures at *T*= (303.15–313.15) K.

T/K	$\bar{V}^{\circ}_{m,1}$	$\bar{V}^{*}_{m,1}$	$\bar{V}^{\circ E}_{m,1}$	$\bar{V}^{\circ}_{m,2}$	$V^{*}_{m,2}$	$\bar{V}^{\circ E}_{m,2}$
(cm^3·mol^{-1})						
P-methylacetophenone (1) + cyclohexane (2)						
303.15	134.12	134.08	0.040	105.00	104.96	0.039
308.15	134.72	134.64	0.081	105.64	105.56	0.080
313.15	135.32	135.20	0.117	106.29	106.18	0.115
P-methylacetophenone (1) + cyclohexylamine (2)						
303.15	133.86	134.08	−0.228	115.16	115.62	−0.461
308.15	134.34	134.64	−0.299	115.69	116.24	−0.547
313.15	134.83	135.20	−0.370	116.23	116.86	−0.635
P-methylacetophenone (1) + cyclohexanol (2)						
303.15	133.79	134.08	−0.288	105.89	106.40	−0.515
308.15	134.30	134.64	−0.342	106.29	106.86	−0.579
313.15	134.80	135.20	−0.395	106.69	107.33	−0.643

Table 6. The values of $\bar{K}^{\circ}_{s,m,1}$, $K^{*}_{s,m,1}$, $\bar{K}^{\circ E}_{s,m,1}$, $\bar{K}^{\circ}_{s,m,2}$ *and* $\bar{K}^{\circ E}_{s,m,2}$ of the components for P-methylacetophenone with cyclohexane, cyclohexylamine and cyclohexanol of binary mixtures at T= (303.15–313.15) K.

T/K	$\bar{K}^{\circ}_{s,m,1}$	$K^{*}_{s,m,1}$	$\bar{K}^{\circ E}_{s,m,1}$	$\cdot\bar{K}^{\circ}_{s,m,2}$	$K^{*}_{s,m,2}$	$\bar{K}^{\circ E}_{s,m,2}$
TPa^{-1}						
P-methylacetophenone (1) + cyclohexane (2)						
303.15	50.12	6.338	43.78	51.02	9.418	41.61
308.15	80.27	6.570	73.70	76.77	9.931	66.84
313.15	108.05	6.814	101.24	96.83	10.48	86.34
P-methylacetophenone (1) + cyclohexylamine (2)						
303.15	−36.28	6.338	−42.61	−56.81	6.895	−63.70
308.15	−46.80	6.570	−53.37	−68.26	7.152	−75.41
313.15	−57.47	6.814	−64.29	−79.88	7.428	−87.31
P-methylacetophenone (1) + cyclohexanol (2)						
303.15	−2.46	6.338	−8.799	−2.274	5.440	−7.714
308.15	−4.12	6.570	−10.69	−3.875	5.685	−9.560
313.15	−5.80	6.814	−12.61	−5.511	5.946	−11.46

4. Conclusions

The densities, sound speeds and viscosities of binary mixtures of P-methyl acetophenone with cyclohexylamine, cyclohexanol, and cyclohexane over the entire composition range at temperatures of 303.15, 308.15, and 313.15 K with a 5 K interval are experimentally measured and reported in this paper. At all measured temperatures, the excess molar volume and excess isentropic compressibility are found to be negative for systems cyclohexylamine and cyclohexanol with P-methyl acetophenone, whereas the opposite trend is seen for systems cyclohexane with P-methyl acetophenone. The attractive forces through the hetero-association interaction between the components of the mixtures, resulting in the formation of associated complexes through hydrogen bond interactions, may be responsible for the negative values of excess molar volume, excess isentropic compressibility, and positive values of deviation in viscosity, including excess Gibbs energy of activation of viscous flow. The hydrogen bonds formed by dissimilar molecules in binary liquid mixtures were used to assess the data in terms of molecular interactions.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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