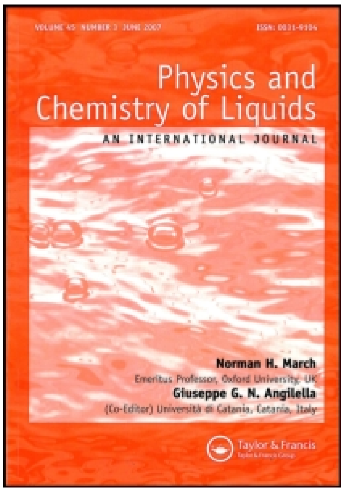

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V. Syamala[a]; D. Raja Sekhar[a]; K. Sivakumar[b]; P. Venkateswarlu[a]
[a] Department of Chemistry, Sri Venkateswara University, Tirupati, India [b] Department of Chemistry, SV Arts College, Tirupati, India

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Speed of sound, isentropic compressibilities and viscosities of ternary non-electrolyte solutions at 303.15 K

V. Syamala[a], D. Raja Sekhar[a], K. Sivakumar[b] and P. Venkateswarlu[a]*

[a]*Department of Chemistry, Sri Venkateswara University, Tirupati, India;* [b]*Department of Chemistry, SV Arts College, Tirupati, India*

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Measurements of ultrasonic speeds, isentropic compressibilities and viscosities were carried out for six ternary mixtures namely dimethylsulphoxide (1) + 1,2-dichlorobenzene (2) + 1-alkanols (3) at 303.15 K. The 1-alkanols include 1-propanol, 1-butanol, 1-pentanol, 1-hexanol, 1-heptanol and 1-octanol. The ultrasonic speeds of these ternary mixtures were also evaluated on the basis of Jacobson's free length theory and Schaaff's collision factor theory. From the viscosity data, deviations in viscosity and interaction parameters for various models were also calculated. An attempt has also been made to explain the nature of intermolecular interactions in the light of deviation in isentropic compressibilities and interaction parameter.

Keywords: speed of sound; interferometer; viscosities; ternary mixtures

1. Introduction

The present study is a continuation of our earlier research [1–3] on thermodynamic properties of binary and ternary liquid mixtures. In recent years, measurements of ultrasonic velocity have been adequately employed in understanding the nature of molecular systems and physicochemical behaviour in liquid mixtures [4]. The non-rectilinear behaviour of ultrasonic velocity and compressibility of liquid mixtures with changing mole fraction is attributed to difference in size of the molecules and the strength of interactions. Lagemann [5] was the first to point out the ultrasonic velocity approach for the qualitative estimation of the interaction in liquids.

The present article is focused on an investigation of the molecular interactions in ternary liquid mixtures with special reference to the behaviour of ultrasonic velocity, isentropic compressibility (k_{s123}), deviation in isentropic compressibility (k'_{s123}), viscosities (η_{123}) and deviation in viscosities ($\Delta \ln \eta$) have also been computed. Moreover, viscosities of the mixtures were theoretically calculated using the empirical relations proposed in the literature [6]. The excess volumes have been estimated to explain the intermolecular interactions occurring in the liquid mixtures. Further, the ultrasonic sound velocity has been analysed in terms of free length theory (FLT) of Jacobson [7] and collision factor theory (CFT) developed by Schaaff's [8].

Dimethylsulphoxide (DMSO), 1,2-dichlorobenzene (1,2-dcb) and 1-alkanols were chosen to study the above thermodynamic properties. The 1-alkanols include 1-propanol;

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*Corresponding author. Email: prof_pv@yahoo.co.in

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1-butanol, 1-pentanol, 1-hexanol, 1-heptanol and 1-octanol. All the chemicals that were used in the present investigation are industrially important.

The properties of DMSO have been the subject of considerable interest because of its versatility and plasticiser. It is a highly polar self-associated [9] liquid and has the ability to participate in hydrogen bonding. Alkanols are also strongly self-associated liquids through hydrogen bonding. 1,2-dcb is used as an intermediate for dyes and certain agricultural chemicals.

The investigation of the thermodynamic properties of ternary liquid mixtures containing associated DMSO and 1-alkanols can be, therefore, quite interesting.

2. Experimental

2.1. *Materials*

All the chemicals used in the present investigation are of analytical grade. DMSO (S.D. Fine Chemicals) was refluxed over NaOH for 3 h at 90°C and then was distilled at reduced pressure [9]. The middle fraction was corrected and stored over molecular sieves. All the 1-alkanols were purified by the standard method described by Riddick et al. [10]. 1,2-dcb is purified as described in the literature [11]. The purities of all the liquid samples were ascertained by measuring the densities and viscosities, and these were given in Table 1, which agree with values obtained from literature [10].

2.2. *Apparatus and procedure*

The densities of pure components were measured by using a single stem pycnometer (made of Pyrex glass) of bulb capacity $8 \times 10^{-6}\,\mathrm{m}^3$ having a graduated stem with $5 \times 10^{-8}\,\mathrm{m}^3$ divisions. The marks on the stem were calibrated using known densities of triple-distilled water. The uncertainty in density measurements was found to be $\pm 0.0001\,\mathrm{g\,cm^{-3}}$. The ultrasonic velocities were measured using a single crystal variable path interferometer at 3 MHz, described in the literature [12]. The impression in ultrasonic velocity was of the order of $\pm 0.5\,\mathrm{m s^{-1}}$. Viscosities of pure components were obtained from the measured flow using two different suspended type Ubbelohde viscometers to cover all the mixtures [13]. The calibration of viscosities was done with triple distilled water and

Table 1. Viscosities (η) and densities (ρ) of pure components at 303.15 K.

	Viscosities (η/m(Pa s))		Density (ρ/g cm^{-3})	
Component	Present work	Ref. [10]	Present work	Ref. [10]
Dimethyl sulphoxide	1.802	1.803	1.09135	1.09130
1,2-Dichlorobenzene	1.301	1.302	1.29920	1.29922
1-Propanol	1.723	1.725	0.79603	0.79600
1-Butanol	1.296	1.297	0.80203	0.80206
1-Pentanol	2.983	2.984	0.80762	0.80764
1-Hexanol	3.905	3.904	0.81204	0.81201
1-Heptanol	5.026	5.027	0.81573	0.81574
1-Octanol	5.227	5.228	0.82190	0.82192

double distilled cyclohexane or toluene. The estimated error in viscosity is ±0.001 mPa S. All the measurements were made using a thermostatic bath maintained at 303.15 ± 0.01 K.

3. Results and discussion

The isentropic compressibility of ternary mixtures (k_{s123}) was calculated from the expression

$$k_{s123} = u_{123}^{-2}\rho_{123}^{-1}, \tag{1}$$

where u_{123} and ρ_{123} denotes ultrasonic velocity and density of ternary mixtures, respectively.

The density of ternary mixture was computed using the relation

$$\rho_{123} = x_1M_1 + x_2M_2 + x_3M_3/V + V_{123}^E, \tag{2}$$

where x_1, x_2 and x_3 denote the mole fractions and M_1, M_2 and M_3 are the molar masses, V is the molar volume and V_{123}^E is the ternary excess volume for the systems DMSO (1) + 1,2-dcb (2) + 1-alkanols (3) at 303.15 K have already been communicated in our earlier paper [14].

The deviation in isentropic compressibility (k'_{s123}) was estimated using the relation:

$$k'_{s123} = k_{s123} - \Phi_1k_{s1} - \Phi_2k_{s2} - \Phi_3k_{s3}, \tag{3}$$

where Φ_1, Φ_2, Φ_3 and k_{s1}, k_{s2}, k_{s3} are the volume fractions and isentropic compressibilities of the three pure components. The quantity Δk_{s123}, the difference between measured value of k'_{s123} and that of computed from binary data $k'_{s123(\mathrm{b})}$ has been calculated using the relation

$$\Delta k_{s123} = k'_{s123} - k'_{s123(\mathrm{b})}. \tag{4}$$

The latter quantity $k'_{s123(\mathrm{b})}$ was computed using Redlich–Kister relation [15]

$$k'_{s123(b)} = k'_{s12} + k'_{s13} + k'_{s23}, \tag{5}$$

where k'_{s12}, k'_{s13} and k'_{s23} denote the deviation in isentropic compressibilities for the three binary mixtures and these are estimated using the smoothing equation

$$k'_{sij} = \Phi_1\Phi_2\big[a_0 + a_1(\Phi_1 - \Phi_2) + a_2[(\Phi_1 - \Phi_2)^2\big], \tag{6}$$

where b_0, b_1 and b_2 are the constants obtained by the method of least squares. Further, the binary parameters for the mixtures of DMSO with 1-alkanols [16], 1,2-dcb with 1-alkanols [17,18] and DMSO with 1,2-dcb [19] were taken from the literature. Since binary deviation in isentropic compressibility data for the system DMSO with 1-octanol, which is not available in the literature is measured in the present investigation and is given in Table 2. The binary parameters of all the above binary systems are presented in Table 3.

The ultrasonic sound velocity (u), density (ρ), isentropic compressibility (k_{s123}) and deviation isentropic compressibility (k'_{s123}) for the ternary mixtures are given in column 5 and 6 of Table 4. The quantity Δk_{s123}, the difference between measured value of k'_{s123} and that of computed from the constituent binary data $k'_{s123(\mathrm{b})}$ is also included in column 8 of Table 4 and their related data for six ternary mixtures are presented in Table 4.

Table 2. Volume fraction of dimethyl sulphoxide (DMSO) (Φ_1), and deviation in isentropic compressibilities (Δk_s) for the binary mixture DMSO (1) with 1-octanol (2) at 303.15 K.

Volume fraction of DMSO (Φ_1)	Δk_s (T Pa^{-1})
0.0401	0.4
0.0516	0.5
0.1075	1.0
0.1765	1.7
0.2719	2.6
0.3379	3.0
0.4257	3.5
0.5162	4.0
0.5779	4.0
0.7044	3.2

Table 3. Values of binary constants and the standard deviation σ (Δk_s) at 303.15 K.

	T Pa^{-1}			
System	a_0	a_1	a_2	σ (Δk_s)
DMSO (1) + 1,2-dcb (2)[a]	2.3	−102.9	30.5	1
DMSO (1) + 1-propanol (2)[b]	−299.0	78.0	−91.0	2
DMSO (1) + 1-butanol (2)[b]	−223.0	54.0	−56.0	1
DMSO (1) + 1-pentanol (2)[b]	−73.0	12.0	−59.0	2
DMSO (1) + 1-hexanol (2)[b]	−54.0	2.0	16.0	1
DMSO (1) + 1-heptanol (2)[b]	0.0	0.0	0.0	0
DMSO (1) + 1-octanol (2)[c]	0.0	0.0	0.0	0
1,2-dcb (1) + 1-propanol (2)[d]	−131.0	92.0	12.6	0
1,2-dcb (1) + 1-butanol (2)[e]	−141.9	97.2	−19.3	1
1,2-dcb (1) + 1-pentanol (2)[e]	−87.0	16.0	−99.1	1
1,2-dcb (1) + 1-hexanol (2)[e]	−70.2	33.2	−39.5	1
1,2-dcb (1) + 1-heptanol (2)[e]	0.0	0.0	0.0	0
1,2-dcb (1) + 1-octanol (2)[e]	0.0	0.0	0.0	0

It is well known that dipole interactions lead to association in pure DMSO. Infrared studies [20,21] have also shown that sulphoxides have strong hydrogen bonds with lower alkanols. The mixing of alkanols, which are known to be self-associated through hydrogen bonding when these are mixed with DMSO, can be expected to bring about changes in hydrogen bonding equilibria [9] and electrostatic interactions with different resultant contributions to thermodynamic properties of the liquid mixtures. The description of alkanol multimers through breaking of hydrogen bonds as well as the weakening of interactions between DMSO molecules will result in an increase in compressibility. On the other hand, a decrease in volume might arise from interaction between the unlike molecules and from interstitial accommodation.

Table 4. The values of density (ρ), sound velocities (u), isentropic compressibilities (k_{s123}) and its related properties for the ternary mixtures of dimethylsulphoxide (DMSO) (1) + 1,2-dcb (2) + 1-alkanols (3) at 303.15 K.

				$\mathrm{T\,Pa^{-1}}$			
Φ_1	Φ_2	ρ (g cm^{-3})	u (m s^{-1})	Δk_{s123}	k'_{s123}	$k'_{s123(b)}$	Δk_{s123}
DMSO + 1,2-dcb + 1-propanol							
0.1048	0.1321	0.78034	1321	734	−52	−57	5
0.0814	0.2342	0.80325	1360	673	−83	−87	4
0.1051	0.3023	0.87075	1347	632	−85	−91	6
0.0679	0.4067	0.93975	1337	595	−97	−104	7
0.0825	0.5272	1.07467	1289	560	−77	−90	13
0.0951	0.6210	1.16380	1255	545	−48	−69	21
0.0585	0.7136	1.19615	1264	523	−50	−61	11
0.0675	0.7498	1.21467	1259	519	−35	−48	13
0.0779	0.8003	1.23671	1255	513	−15	−29	14
0.0705	0.8388	1.24463	1262	504	−12	−21	9
0.0861	0.8784	1.28074	1254	496	−3	−3	6
0.0480	0.9150	1.26691	1266	492	−4	−6	2
DMSO + 1,2-dcb + 1-butanol							
0.0708	0.1081	0.83160	1286	726	−39	−45	6
0.0783	0.1413	0.83996	1300	704	−47	−55	8
0.0626	0.2424	0.84900	1345	651	−71	−78	7
0.0809	0.3182	0.89626	1346	615	−73	−82	9
0.0844	0.4058	0.94717	1344	584	−72	−83	11
0.0686	0.4834	0.98870	1337	565	−71	−82	11
0.0835	0.5937	1.09887	1292	545	−46	−65	19
0.0702	0.6697	1.15633	1274	532	−38	−55	17
0.0654	0.7465	1.22258	1254	520	−25	−41	16
0.0755	0.7777	1.25671	1237	520	−11	−30	19
0.0613	0.8486	1.29140	1238	505	−7	−17	10
0.0679	0.8957	1.30929	1240	496	−3	−3	6
DMSO + 1,2-dcb + 1-pentanol							
0.0508	0.1027	0.85464	1280	714	−19	−23	4
0.0709	0.1093	0.88642	1251	720	−16	−23	7
0.0657	0.2064	0.88400	1282	688	−25	−34	9
0.0783	0.2285	0.91018	1258	694	−22	−34	12
0.0566	0.3435	0.91388	1312	635	−33	−39	6
0.0614	0.4419	0.98188	1300	602	−34	−37	3
0.0790	0.5443	1.08633	1286	556	−35	−32	−3
0.0714	0.6552	1.13496	1319	506	−35	−27	−8
0.0551	0.7317	1.21249	1293	493	−30	−24	−6
0.0709	0.8081	1.27792	1295	466	−22	−13	−9
0.0604	0.8461	1.28938	1280	473	−16	−10	−6
0.0672	0.8970	1.30795	1263	476	−5	−1	−4
DMSO + 1,2-dcb + 1-hexanol							
0.0487	0.0867	0.86558	1293	691	−16	−12	−4
0.0611	0.0963	0.88859	1285	681	−19	−13	−6
0.0558	0.1929	0.87553	1328	647	−30	−21	−9
0.0490	0.2477	0.87206	1346	632	−33	−24	−9
0.0688	0.3149	0.93671	1330	603	−38	−25	−13

(*continued*)

Table 4. Continued.

				TPa^{-1}			
Φ_1	Φ_2	ρ (g cm^{-3})	u (m s^{-1})	Δk_{s123}	k'_{s123}	$k'_{s123(b)}$	Δk_{s123}
0.0575	0.4004	0.96573	1330	585	−37	−26	−11
0.0636	0.4997	1.05114	1305	558	−36	−24	−12
0.0819	0.6125	1.16232	1277	527	−32	−18	−14
0.0647	0.6807	1.19441	1267	521	−26	−16	−10
0.0592	0.7116	1.20879	1266	516	−24	−15	−9
0.0701	0.8259	1.28366	1254	495	−12	−5	−7
0.0533	0.8969	1.30023	1251	491	−3	0	−3
DMSO + 1,2-dcb + 1-heptanol							
0.0384	0.0725	0.90240	1278	678	−3	0.02	−4
0.0495	0.0885	0.92719	1269	669	−5	0.03	−6
0.0578	0.1902	0.91769	1307	637	−12	0.2	−13
0.0543	0.2178	0.92002	1310	633	−11	0.2	−12
0.0587	0.2993	0.94267	1318	611	−14	0.5	−15
0.0667	0.3765	0.99319	1307	589	−16	0.9	−17
0.0573	0.4865	1.04975	1293	569	−13	1.4	−15
0.0640	0.5803	1.14296	1266	545	−14	2.3	−17
0.0618	0.6482	1.19817	1252	532	−14	2.9	−17
0.0578	0.6889	1.22576	1246	525	−11	3.1	−15
0.0693	0.8335	1.31284	1240	495	−7	5.7	−13
0.0555	0.8807	1.31587	1240	494	−1	5.2	−6
DMSO + 1,2-dcb + 1-octanol							
0.0442	0.0744	0.96236	1263	651	−7	1.9	−9
0.0410	0.0796	0.95199	1270	651	−7	2.0	−9
0.0519	0.1761	0.98397	1281	619	−17	3.8	−21
0.0504	0.2132	0.98527	1290	609	−19	4.4	−24
0.0551	0.2660	1.01277	1291	592	−25	5.0	−30
0.0433	0.3422	1.02097	1294	585	−20	5.8	−26
0.0532	0.1648	1.12713	1245	572	−5	7	−12
0.0608	0.5575	1.20741	1246	533	−24	5.8	−30
0.0589	0.6508	1.26446	1224	523	−15	5.2	−21
0.0660	0.7145	1.30275	1222	513	−10	4.3	−15
0.0725	0.7824	1.32589	1221	505	−3	3.1	−7
0.0575	0.8183	1.32701	1226	501	−4	2.8	−7

The addition of more non-polar hydrocarbon part of higher alkanols to the solution tends to dilute both the strong polar interactions between DMSO molecules and the hydrogen bonding between DMSO and alkanol, resulting decrease in compressibility. The experimental values of deviation in isentropic compressibility (k'_{s123}) support this.

The molar volumes of the alkanols increase with chain lengths, but the free volumes follow the reverse order. The geometrical factor, arising from interstitial accommodation due to differences in molar volume and free volume between DMSO, alkanols and 1,2-dcb are playing a significant role towards the magnitude of deviation in isentropic compressibility.

A close examination of results included in Table 4 shows that k'_{s123} values are negative at all volume fraction compositions studied in all six ternary mixtures. The results indicate that there is a much strong interaction in these liquid mixtures. Due to the polar nature of

DMSO, 1,2-dcb and alkanols the dipole–dipole interactions prevail in these mixtures. Further, the negative k'_{s123} values in all the ternary systems indicate that structure making effect [22,23] is predominant in all the systems. The pronounced increase or decrease in sound velocity with the composition of the mixtures indicates the presence of interaction between the component molecules in the ternary mixtures. The negative values of deviation in isentropic compressibility also indicate the decrease in free spaces between the molecules in the mixtures due to increased molecular interaction, which would in turn provide a negative deviation in compressibility.

Since DMSO is highly polar (dipole movement $\mu = 3.96\,\mathrm{D}$) [24] than 1,2-dcb and 1-alkanols, mixing of these two with DMSO tends to break DMSO–DMSO dipolar association releasing several DMSO dipoles resulting the free dipoles of DMSO would induce movements in the neighbouring 1,2-dcb/alkanol molecules causing dipole-induced dipole interaction leading to reduction in compressibility of the systems.

The data in Table 4 suggests that k'_{s123} values in general decreases with increasing in chain length of 1-alkanols. This can be interpreted in terms of solvent polarity, the number of alkanol carbon atoms and molecular size [25].

Another important factor is that large negative values of deviation in isentropic compressibility in the lower chain alkanols correspond to strong self-association of the pure alkanols, which reflects the existence of different types of association. The higher negative values in deviation isentropic compressibility for the system DMSO + 1,2-dcb with 1-propanol may be due to high dipole moment ($\mu = 3.09\,\mathrm{D}$) and high dielectric constant (€ = 20.45) at 298.15 K for 1-propanol are noticeably higher compared to the other alkanols ($\mu = 1.76\,\mathrm{D}$, € = 10.34) at 298.15 K for 1-octanol [10] leading to an increase in alkanol polarity resulting in stronger hetero association. Therefore, the chain of the alkanol, as the polarity of –OH decreases, the weaker the corresponding dipole–dipole interactions. Moreover, increasing the alkanol chain length results the concentration of OH groups in higher alkanols causing in weaker interactions between component liquids. The degree of association in alkanols decreases [26] as the carbon chain length in the molecule increases leading to decrease in strength of interactions. The experimental results in the present study support this contention.

Further, the specific interactions through dipole–dipole interaction taking place through hydrogen bond formation the S=O group of DMSO and the OH group of alkanol decreases with increase of chain length, probably due to less proton donating tendency of long chain alkanols.

Theoretical evaluation of ultrasonic sound speeds in liquid mixtures offers a simple and convenient method for the study of the nature of molecular interactions in these ternary liquid mixtures. The theoretical values of ultrasonic speeds in the systems: DMSO + 1, 2-dcb + 1-alkanols were evaluated by using the following relations:

$$\text{(FLT) [7]} = U_{(\mathrm{FLT})} = K/(L_f \rho^{1/2}). \tag{7}$$

$$\text{Collision factor theory CFT [8]} = U_{\mathrm{CFT}} = U_0[x_1 s_1 + x_2 s_2 + x_3 s_3][x_1 s_1 + x_2 s_2 + x_3 s_3]/V. \tag{8}$$

The details of derivations and terms used in these relations are given in the literature [27,28]. The deviations in the experimental and the calculated values for all the six ternary mixtures as a function of composition are listed in Table 5. A close perusal of Table 5 shows that the values predicted by FLT showed maximum deviations for all the systems studied. This is in good agreement with the conclusion arrived by Pandey et al. [29], Kaulgud [30] and Ali *et al.* [31] that large deviations from FLT are noticed for the systems containing polar components.

The viscosities of the mixtures [32] were calculated using the equation

$$\eta = K_v \rho\, t, \tag{9}$$

where K_v is the viscometer constant ρ and t are the density and flow time, respectively. The densities of the mixtures were calculated from Equation (2). Deviation in viscosities ($\Delta \ln \eta_{123}$) of the ternary mixtures was obtained by means of the following relation

$$\Delta \ln \eta_{123}/m\,\mathrm{Pa\,s} = \ln \eta_{\mathrm{mix}} - x_1 \ln \eta_1 - x_2 \ln \eta_2 - x_3 \ln \eta_3 \tag{10}$$

where η_{mix} is the viscosity of the mixture, η_1, η_2 and η_3 are the viscosities of the DMSO, 1,2-dcb and 1-alkanols, respectively.

An examination of positive $\Delta \ln \eta_{123}$ values in all the six ternary mixtures indicate that specific interactions are occurring between component molecules. The viscosity deviations depend on molecular interactions as well as size, shape and packing of molecules between unlike molecules for which the molecular interactions decreases.

The experimental viscosities were used to estimate the dynamic viscosity η of liquid mixtures using several empirical relations. Grunberg–Nissan [33] suggested a logarithmic relation between the viscosity of a binary liquid mixture and pure components of the form

$$\ln \eta_{\mathrm{mix}} = x_1 \ln \eta_1 + x_2 \ln \eta_2 + x_1 x_2 d. \tag{11}$$

On applying to a ternary liquid mixture this equation takes up the following form:

$$\ln \eta_{\mathrm{mix}} = x_1 \ln \eta_1 + x_2 \ln \eta_2\, x_3 \ln \eta_3 + x_1 x_2 d_{12} + x_1 x_3 d_{13} + x_2 x_3 d_{23} + x_1 x_2 x_3 d_{123}, \tag{12}$$

where d is a constant regarded as a measure of the strength of molecular interactions between the mixing components.

Tamura–Kurata [34] proposed the relation between the viscosities of a binary liquid mixture and pure components and this equation has been extended to a ternary liquid mixture and it is represented as follows:

$$\eta = x_1 \Phi_1 \eta_1 + x_2 \Phi_2 \eta_2 + x_3 \Phi_3 \eta_3 + x_1 x_2 T_{12} + x_1 x_3 T_{13} + x_2 x_3 T_{23} + x_1 x_2 x_3 T_{123}. \tag{13}$$

Table 5. Standard deviation of the sound velocities predicted by FLT and CFT theories for the ternary mixtures of DMSO (1) + 1,2-dcb (2) + 1-alkanols (3) at 303.15 K.

	Standard deviation (σ)	
Systems	u_{FLT}	u_{CFT}
DMSO (1) + 1,2-dcb (2) + 1-propanol (3)	7.292	3.175
DMSO (1) + 1,2-dcb (2) + 1-butanol (3)	7.242	3.402
DMSO (1) + 1,2-dcb (2) + 1-pentanol (3)	9.590	1.730
DMSO (1) + 1,2-dcb (2) + 1-hexanol (3)	6.744	2.540
DMSO (1) + 1,2-dcb (2) + 1-heptanol (3)	6.123	2.249
DMSO (1) + 1,2-dcb (2) + 1-octanol (3)	5.204	2.483

Hind *et al.* [35] derived an expression for the viscosity of a binary mixture and it is adopted to a ternary mixture which can be written as follows:

$$\eta = x_1^2\eta_1 + x_2^2\eta_2 + x_3^2\eta_3 + x_1x_2H_{12} + x_1x_3H_{13} + x_2x_3H_{23} + x_1x_2x_3H_{123}, \tag{14}$$

where H_{123} is attributed to unlike pair interactions.

The theoretically evaluated values of viscosity using empirical Equations (12–14) are given in Table 6.

Table 6. Viscosities (η), deviation in viscosities ($\Delta\ln\eta$), and interaction parameters d_{123}, T_{123} and H_{123} calculated using Equations (13–15) for the ternary mixtures DMSD (1) + 1,2- dcb (2) + 1- alkanols (3) at 303.15 K.

X_1	X_2	η_{mix} (mPa S)	$\Delta\ln\eta$ (mPa S)	d_{123}	T_{123}	H_{123}
0.1141	0.0910	1.705	0.9230	6.5482	22.1959	23.4557
0.0921	0.1675	1.700	0.9241	3.7354	20.7975	20.5028
0.1217	0.2215	1.683	0.8652	4.3872	16.4594	15.9705
0.0820	0.3107	1.646	0.8631	4.3122	20.4950	18.7858
0.1045	0.4224	1.618	0.7890	4.5623	17.6012	15.6413
0.1252	0.5172	1.573	0.7100	3.9447	16.2145	14.0479
0.0804	0.6201	1.505	0.6881	3.4369	22.4537	18.7063
0.0942	0.6619	1.465	0.6340	2.9970	20.5409	17.0085
0.111	0.7226	1.403	0.5542	3.4468	19.8630	16.3043
0.1025	0.7714	1.385	0.5370	2.4499	23.2506	18.8509
0.1274	0.8224	1.353	0.4710	1.09735	34.6073	27.8087
0.0725	0.8741	1.326	0.4991	0.9256	39.1402	31.2059
DMSO + 1,2-dcb + 1-butanol						
0.0905	0.0875	2.282	1.4784	2.8895	36.9135	36.1139
0.1006	0.1148	2.160	1.3936	1.9944	27.0835	26.1394
0.0824	0.2017	2.085	1.3348	2.1742	25.8903	23.6416
0.1075	0.2674	1.973	1.1809	2.2074	19.6730	17.8367
0.1141	0.3468	1.865	1.0958	2.5213	17.8514	15.8972
0.0947	0.4217	1.775	1.0023	3.1569	19.6922	17.0890
0.1174	0.5276	1.658	0.8709	2.5854	17.2320	14.8749
0.1007	0.6074	1.589	0.8068	2.6758	19.6079	16.7029
0.0956	0.6895	1.513	0.7250	2.3728	21.6041	18.1536
0.1107	0.7210	1.477	0.6550	2.0323	20.9305	17.6932
0.0917	0.8029	1.385	0.5712	1.5827	25.7847	21.6915
0.1025	0.8546	1.335	0.4897	0.6170	37.2919	32.0149
DMSO + 1,2-dcb + 1-pentanol						
0.0752	0.0962	2.784	1.9108	1.9545	43.5241	39.6492
0.1040	0.1014	2.656	1.8110	1.2371	31.2956	29.3989
0.0970	0.1927	2.575	1.7161	1.0856	28.2288	25.2113
1.1149	0.2122	2.434	1.6135	1.1333	22.5099	20.3259
0.0844	0.3240	2.358	1.5403	1.3802	27.8030	23.9859
0.0917	0.4176	2.237	1.3978	1.4817	26.3892	22.6401
0.1175	0.5120	2.124	1.2242	1.5323	23.3011	20.1619
0.1071	0.6217	1.975	1.0780	1.2131	26.5379	22.7348
0.0836	0.7024	1.835	0.9689	1.1231	32.7689	27.6769
0.1072	0.7721	1.732	0.8218	2.2485	34.5719	29.7502

(*continued*)

Table 6. Continued.

X_1	X_2	η_{mix} (mPa S)	$\Delta \ln \eta$ (mPa S)	d_{123}	T_{123}	H_{123}
0.0919	0.8141	1.652	0.7654	1.4775	41.3639	35.4295
0.1022	0.8620	1.483	0.6004	0.5550	58.9515	52.0951
DMSO + 1,2-dcb + 1-hexanol						
0.0815	0.0917	3.823	2.4433	2.2632	71.2426	61.0284
0.1011	0.1007	3.605	2.3365	1.2081	50.2199	44.5484
0.0917	0.2005	3.424	2.1937	1.2105	41.8755	35.8773
0.0805	0.2574	3.103	2.0546	1.1433	36.8286	31.4312
0.1107	0.3206	2.897	1.8576	1.2459	28.0991	24.4169
0.0925	0.4075	2.634	1.7025	1.3560	29.4301	25.2273
0.1010	0.5017	2.593	1.5668	1.4760	31.4746	26.9996
0.1271	0.6011	2.167	1.2272	1.9595	25.1266	22.1365
0.1009	0.6715	1.928	1.0842	1.5879	27.7619	24.2165
0.0924	0.7026	1.735	0.9612	2.6307	26.2087	22.8626
0.1075	0.8011	1.563	0.7191	1.7383	31.5547	28.5419
0.0821	0.8740	1.423	0.5948	1.5549	47.0279	43.2538
DMSO + 1,2-dcb + 1-heptanol						
0.0724	0.0864	4.826	2.9125	1.5916	97.3094	79.1610
0.0919	0.1040	4.631	2.8045	0.9307	69.7278	58.6121
0.11041	0.2165	4.325	2.5573	0.8749	50.1612	41.8852
0.0974	0.2470	3.985	2.4490	0.7679	43.1077	36.5155
0.1029	0.3319	3.703	2.2480	0.8905	39.2967	33.4077
0.1142	0.4074	3.275	1.9990	1.1619	32.5614	28.2282
0.0964	0.5179	3.015	1.8063	1.4313	38.1891	32.9102
0.1050	0.6020	2.867	1.6234	1.9935	39.9900	34.9830
0.1001	0.6640	2.593	1.4500	1.1780	41.4428	36.5902
0.0932	0.7019	2.361	1.3203	1.2735	41.9015	37.1243
0.1074	0.8170	1.893	0.9125	1.0281	52.2467	48.9603
0.0862	0.8642	1.557	0.6996	1.0063	53.2644	50.4161
DMSO + 1,2-dcb + 1-octanol						
0.0904	0.0962	5.165	2.9594	3.1817	103.125	79.1319
0.0840	0.1031	4.723	2.8747	1.7672	62.4453	58.7943
0.1014	0.2176	4.435	2.6136	1.2010	52.6890	42.8206
0.0974	0.2604	3.908	2.4366	0.8253	39.7815	33.6948
0.1041	0.3175	3.521	2.2379	0.8251	32.5933	28.2679
0.0807	0.4029	3.116	2.0494	0.8762	34.2905	29.7546
0.0942	0.5205	2.825	1.7576	1.0688	34.0050	29.6450
0.1039	0.6019	2.603	1.5409	1.5801	33.8762	30.0630
0.0980	0.6842	2.340	1.3332	2.0657	37.1305	33.4428
0.1070	0.7324	1.954	1.0657	2.9423	31.4230	29.1365
0.1146	0.7819	1.726	0.8558	1.8711	31.9085	30.5621
0.0911	0.8201	1.535	0.7381	1.5558	31.8372	30.3036

The interaction parameter is a useful parameter for the study of intermolecular interactions between ternary liquid mixtures. The positive '*d*' values in general, all the ternary systems in the present investigation confirm complex formation between the component molecules as a result of molecular interaction.

Further, if (i) $\Delta \ln \eta > 0$ and $d > 0$ and the magnitude of both is large then strong specific interactions would be present, (ii) $\Delta \ln \eta < 0$ and $d > 0$ then weak specific

Table 7. Values of ternary constants *A*, *B*, *C* and standard deviations σ (A') at 303.15 K.

Property	*A*	*B*	*C*	σ (A')
		DMSO + 1, 2-dcb + 1-propanol		
Δk_{s123} (T Pa^{-1})	615.9	12752.6	147707.2	1.0
$\Delta \ln \eta$ (mPa S)	44.2	−113.4	7452.1	0.003
		DMSO + 1,2-dcb + 1-butanol		
Δk_{s123} (T Pa^{-1})	720.5	13615.1	360408.7	0.0
$\Delta \ln \eta$ (mPa S)	35.2	751.1	21791.2	0.007
		DMSO + 1,2-dcb + 1-pentanol		
Δk_{s123} (T Pa^{-1})	176.2	−25622.0	–140541	.7 0.0
$\Delta \ln \eta$ (mPa S)	62.7	−831.9	23577.0	0.0
		DMSO + 1,2-dcb + 1-hexanol		
Δk_{s123} (T Pa^{-1})	−872.3	1195.7	−155215.9	0.0
$\Delta \ln \eta$ (mPa S)	70.8	−1487.3	32863.8	0.06
		DMSO + 1,2-dcb + 1-heptanol		
Δk_{s123} (T Pa^{-1})	−1201.9	−1687.6	−366834.6	0.0
$\Delta \ln \eta$ (mPa S)	84.0	−2060.5	43718.5	0.7
		DMSO + 1,2-dcb + 1-octanol		
Δk_{s123} (T Pa^{-1})	−2568.5	24447.8	271213.3	0.0
$\Delta \ln \eta$ (mPa S)	80.6	−2196.9	36602.2	0.3

interactions would be present and (iii) if $\Delta \ln < 0$ and $d < 0$ and the magnitude of both is large, the specific interactions would be absent.

The experimental results in the present study, reveals that specific interactions are prevailing in all the six ternary mixtures.

The values of Δk_{s123} and $\Delta \ln \eta$ for all the ternary systems are fitted to an empirical relation [15].

$$A' = z_1 z_2 z_3 \left[A + B z_1 (z_2 - z_3) + C z_1^2 (z_2 - z_3)^2 \right], \tag{15}$$

where z_1, z_2 and z_3 represent the volume fractions with respect to Δk_{s123} and mole fractions in case of $\Delta \ln \eta$, respectively, for components 1, 2 and 3; A' is the corresponding property. The values of parameters *A*, *B* and *C* are obtained by the least square analysis, are included in Table 7 along with standard deviation σ (A'). The values of standard deviation are calculated by the following equation:

$$\sigma(A') = \left[\Sigma \left(A'_{\mathrm{cal}} - A'_{\mathrm{exp}} \right)^2 \Big/ n - p \right]^{1/2}, \tag{16}$$

where *n* is the number of experimental points and *p* is the number of parameters.

References

[1] K. Prasad, K. Siva Kumar, G. Prabhakar, and P. Venkateswarlu, J. Mol. Liq. **123**, 51 (2006).
[2] V. Syamala, K. Siva Kumar, G. Prabhakar, and P. Venkateswarlu, Phys. Chem. Liq. **2**, 127 (2006).

[3] V. Syamala, K. Siva Kumar, and P. Venkateswarlu, J. Chem. Eng. Data. **51**, 928 (2006).

[4] T.S. Rao, N. Veeraiah, and C. Rambabu, Indian J. Chem. A **41**, 2268 (2002).

[5] R.T. Lagemann and W.S. Dunbar, J. Phys. Chem. **49**, 428 (1945).

[6] A. Ali and H. Soghra, Indian J. Phys. B **76**, 23 (2002).

[7] J. Jacobson, J. Chem. Phys. **20**, 927 (1952).

[8] W. Schaaff's, *Molekularakustik* (Springer-Verlag Berlin, Gottingen, Heidelberg, 1963).

[9] R.K. Dewan, S.P. Gupta, and S.K. Mehta, J. Soln. Chem. **18**, 13 (1989).

[10] J.A. Riddick, W.B. Bunger, and T.K. Sakano, *Organic solvents* (Wiley Interscience, New York, 1986).

[11] T.S. Vijayalakshmi and P.R. Naidu, J. Chem. Eng. Data. **34**, 413 (1989).

[12] N. Prasad, R. Singh, O. Prakash, and S. Prakash, Indian J. Pure Appl. Phys. **14**, 676 (1976).

[13] J. Jeorge, N.V. Sastri, S.R. Patel, and K.V. Mahendra, J. Chem. Eng. Data **47**, 262 (2002).

[14] Syamala, K. Siva Kumar, P. Venkateswarlu, J. Mol. Liq. **136**, 29 (2007).

[15] O. Redlich and A.P. Kister, Ind. Eng.Chem. **40**, 345 (1948).

[16] G. Narayanaswamy, G. Dharmaraju, and G.K. Raman, Acoustics Lett. **4**, 210 (1981).

[17] V. Chandrakumar, B. Sreenivasulu, and P.R. Naidu, J. Chem. Eng. Data. **37**, 71 (1992).

[18] T.S. Vijayalakshmi and P.R. Naidu, Indian J. Pure Appl. Phys. **28**, 215 (1990).

[19] V. Syamala, K. Siva Kumar, P. Venkateswarlu, J. Chem. Thermodyn. **38**, 1553 (2006).

[20] A. Allerhand and P.R. Schleyervon, J. Am. Chem. Soc. **85**, 371 (1963).

[21] M. Taemres and S. Searles Jr, J.Am. Chem. Soc. **81**, 2100 (1959).

[22] A. Ali, K. Tiwari, A.K. Nain, and V. Chakravarthy, Indian. J. Phys. **74B**, 351 (2000).

[23] V. Rajendran and A.N. Kannappan, Indian J. Phys. **68**, 131 (1994).

[24] Y. Marcus, *Introduction to Liquid State Chemistry* (New York, Wiley Interscience, 1977).

[25] R.J. Fort and W.R. Moor, Trans. Faraday. Soc. **62**, 1112 (1966).

[26] G.A. Krestov, *Thermodynamics of Solvation* (Ellis Harwood, England, 1991).

[27] A. Ali, Abida, N. Anil Kumar, and S. Hyder., J. Pure & Appl. Ultrason. **23**, 73 (2001).

[28] H. Iloukhani and Z. Rostami, J.Soln.Chem. **32**, 451 (2003).

[29] J.D. Pandey, R Dey, and D.K. Dwivedi, Pramana. J. Phys. **52**, 187 (1999).

[30] M.V. Kaulgud, Acustica **10**, 316 (1980).

[31] A. Ali, A.K. Nain, V.K. Sharma, and S. Ahmad, Acoustics Lett. **24**, 9 (2000).

[32] K.V.N. Suresh Reddy, P. Srrinivasa Rao, and A. Krishnaiah, Phys. Chem. Liq. **42**, 561 (2004).

[33] L. Grunberg and A.H. Nissan, Nature **164**, 799 (1949).

[34] M. Tamura and M. Kurata, Bull. Chem. Soc. Jpn **25**, 32 (1952).

[35] R.K. Hind, E. Mc Laughlin, and A.R. Ubbelohde, Trans. Faraday. Soc. **56**, 328 (1960).