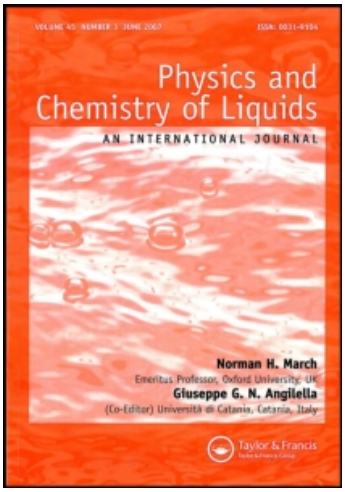

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Rheological, thermodynamic and ultrasonic study of binary mixtures containing 2-methoxyethanol and some alkan-1-ol

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Rheological, thermodynamic and ultrasonic study of binary mixtures containing 2-methoxyethanol and some alkan-1-ol

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Density, ρ, and viscosity, η, of binary mixtures of 2-methoxyethanol with methanol, ethanol, propan-1-ol, butan-1-ol, pentan-1-ol, hexan-1-ol, and heptane-1-ol are determined over the entire range of composition at 298.15, 308.15, and 318.15 K. The speed of sound, u, of the above binary mixtures has been measured at 298.15 K. The experimental values of densities, viscosities, and speeds of sound are used to calculate the excess molar volume V^{E}, viscosity deviation $\Delta\eta$, excess isentropic compressibility K_S^{E}, excess acoustic impedance Z^{E}, and excess intermolecular free length L_f^{E}. The viscosity data have been correlated by Grunberg and Nissan, Tamura–Kurata and Hind correlation equations. The V^{E}, $\Delta\eta$, K_S^{E}, Z^{E}, and L_f^{E} are fitted to the Redlich–Kister equations. The results are discussed in terms of molecular interactions and structural effects.

Keywords: density; viscosity; speed of sound; excess molar volume; viscosity deviation; excess isentropic compressibility; alkan-1-ol; 2-methoxyethanol; excess intermolecular free length; excess acoustic impedance; interaction parameters

1. Introduction

The determination of density, viscosity, and speed of sound is a powerful tool to learn about the liquid state [1] because of the close connection between liquid structure and macroscopic properties.

The various properties, such as excess molar volumes V^{E}, viscosity deviation $\Delta\eta$, excess isentropic compressibility K_S^{E}, excess acoustic impedance Z^{E}, and excess intermolecular free length L_f^{E} are obtained from density, viscosity, and speed of sound. Viscosity data and various acoustical parameters obtained from density and speed of sound, such as specific acoustic impedance Z, intermolecular free length L_f, Van der Wall's constant b, molecular radius r, geometrical volume B, molar surface area Y, available volume V_a, molar speed of sound R, collision factor S, and molecular association M_A, have been used to investigate the molecular packing, molecular motions, and various types of intermolecular interactions and their strength, influenced by the size, shape, and chemical nature of component molecules [2–4].

Systematic investigations of excess molar volumes, viscosity deviations, speeds of sound, isentropic compressibilities, etc., for binary liquid mixtures of an alkanol with

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2-methoxyethanol have been undertaken. In this article, we report the studies on seven binary mixtures of methanol, ethanol, propan-1-ol, butan-1-ol, pentan-1-ol, hexan-1-ol, and heptane-1-ol with 2-methoxyethanol at 298.15, 308.15 and 318.15 K. The liquids were selected on the basis of their industrial use [5–7].

2-methoxyethanol and the monoalcohols have both a proton donor and a proton acceptor group. It is expected that there will be a significant degree of H-bonding leading to self-association in pure state, in addition to mutual association in their binaries [2].

To the best of our knowledge, the properties of mixtures of this liquid have not been reported before.

2. Experiments

2.1. *Source and purity of samples*

2-Methoxyethanol, methanol, ethanol, propan-1-ol, butan-1-ol, pentan-1-ol, hexan-1-ol, and heptane-1-ol were obtained from Merck and were A.R. grade. These were further purified by standard methods [2–10]. The purity of the liquids was checked by GLC and also by comparing experimental values of densities and viscosities with those reported in the literature [11–27], as listed in Table 1. The purity of the solvents was $>99.5\%$. Triply distilled water was used in this experiment.

2.2. *Method*

Densities, ρ, at 298.15, 308.15, 318.15 K were measured with an Ostwald–Sprengel-type pycnometer having a bulb volume of 25 cm^3 and an internal diameter of the capillary of $\sim$1 mm. The pycnometer was calibrated at 298.15 K with triply distilled water and benzene. The measurements were done in a thermostatic water-bath maintained at ± 0.01 K of the desired temperature, and the temperature was determined with a calibrated thermometer and a muller bridge [28]. The viscosities at 298.15, 308.15, 318.15 K have been measured by means of a suspended Ubbelohde-type viscometer [29], which was calibrated at the desired temperatures with water and methanol. The speeds of sound u at 298.15 K in pure liquids and in binary mixtures were determined with a multi-frequency ultrasonic interferometer supplied by Mittal Enterprise, New Delhi. In the present work, a steel cell fitted with a quartz crystal of 2 MHz [30] frequency was used. The solutions were prepared by mixing known volumes of pure liquids in air-tight, narrow-mouth, ground-glass stoppered bottles, taking precautions to minimise the evaporation losses. The masses were determined by using a Mettler electronic analytical balance (AG285, Switzerland) which is accurate to 0.01 mg. The uncertainties of the liquid composition, density, viscosity, and speeds of sound measurements are $\pm 1 \times 10^{-4}$, $\pm 3 \times 10^{-4}$ g cm^{-3}, $\pm 2 \times 10^{-4}$ mPa s, and ± 0.3 m s^{-1}, respectively.

3. Results and discussion

The experimentally measured densities and viscosities at 298.15, 308.15, 318.15 K of the pure components, along with the reference values [11–27], are recorded in Table 1. The comparison of the experimentally determined speeds of sound at 298.15 K of pure liquid along with their literature values [11–27] is also presented in Table 1.

Table 1. Comparison of experimental densities, ρ, viscosities, η, and ultrasonic speeds, u, of pure liquids with literature values.

		$\rho \times 10^{-3}$ (kg m^{-3})		η (mPa s)		u (m s^{-1})	
Liquids	T (K)	Expt.	Lit.	Expt.	Lit.	Expt.	Lit.
2-Methoxyethanol	298.15	0.958914	0.95979 [11]	1.54312	1.543 [11]	1338.62	1339.31 [11]
	308.15	0.95161	0.95251 [11]	1.25748	1.257 [11]	–	–
	318.15	0.94583	0.94623 [11]	1.02686	1.050 [11]	–	–
Methanol	298.15	0.786266	0.78656 [12]	0.541816	0.5422 [12]	1100.76	1103.0 [20]
	308.15	0.7792	0.77728 [13]	0.47411	0.4742 [13]	–	–
	318.15	0.76714	0.76775 [13]	0.41722	0.4174 [13]	–	–
Ethanol	298.15	0.78668	0.7851 [15]	1.08812	1.088 [15]	1145.34	1145.00 [22]
	308.15	0.77691	0.77658 [13]	0.90532	0.904 [13]	–	–
	318.15	0.77788	0.76781 [13]	0.76154	0.763 [13]	–	–
Propanol	298.15	0.8001	0.79954 [18]	2.00411	2.004 [26]	1207.81	1206.5 [18]
	308.15	0.79106	0.79166 [13]	1.55873	1.560 [13]	–	–
	318.15	0.78409	0.78456 [13]	1.22668	1.2253 [14]	–	–
Butan-1-ol	298.15	0.80873	0.8058 [21]	2.56052	2.5600 [26]	1239.25	1240.00 [23]
	308.15	0.79805	0.7981 [14]	1.97944	1.982 [14]	–	–
	318.15	0.79006	0.7902 [14]	1.57482	1.575 [14]	–	–
Pentan-1-ol	298.15	0.81385	0.81108 [21]	3.50027	3.510 [21]	1278.93	1280.00 [23]
	308.15	0.80264	0.8036 [16]	2.65281	2.668 [17]	–	–
	318.15	0.79615	0.7962 [16]	2.03854	2.0419 [16]	–	–
Hexan-1-ol	298.15	0.81987	0.81515 [21]	4.59113	4.590 [21]	1328.24	1328.00 [21]
	308.15	0.80761	0.80800 [19]	3.39722	3.398 [23]	–	–
	318.15	0.80231	–	2.39695	–	–	–
Heptan-1-ol	298.15	0.82133	0.82162 [11]	5.93618	5.937 [25]	1331.7	1330.00 [23]
	308.15	0.80813	0.80793 [17]	4.26474	4.263 [17]	–	–
	318.15	0.80669	–	2.982816	–	–	–

3.1. *Excess molar volume*

The excess molar volumes, V^E, are calculated using the following equation:

$$V^E = \sum_{i=1}^{2} x_i M_i (1/\rho - 1/\rho_i), \tag{1}$$

where M_i, ρ_i, and ρ are the molar mass, density of the ith component and density of the mixture, respectively.

According to Quin *et al.* [8], relative change of volume in mixing, ΔV, is also a relevant quantity. Dependence of ΔV on composition for similar pair of solvents follows a similar pattern, while the corresponding dependence for V^E often does not [8]. Therefore, we have used the following equation to calculate ΔV for the present mixtures:

$$\Delta V = \frac{V^E}{\sum_{i=1}^{2} x_i V_i}. \tag{2}$$

The volume fraction, ϕ_i, of the ith components was calculated as

$$\phi_i = \frac{x_i V_i}{\sum_{i=1}^{2} x_i V_i}. \tag{3}$$

In Table 2, the experimentally determined densities, viscosities, calculated excess molar volumes and viscosity deviations of the binary mixtures are represented along with the mole fraction of 2-methoxyethanol (x_1) at 298.15, 308.15 and, 318.15 K. Experimental results for V^E, $\Delta\eta$, and $\Delta V/\phi_1\phi_2$ plotted against mole fraction (x_1) for all systems studied at 298.15 K are depicted in Figures 1–3. Similar plots are obtained at other temperatures.

Table 2. Values of density (ρ), viscosity (η), excess molar volume (V^E), viscosity deviation ($\Delta\eta$), and Grunberg–Nissan interaction parameter (d_{12}) for binary mixtures of 2-methoxyethanol + methanol, ethanol, propanol, butanol, pentanol, hexanol and heptanol.

x_1	$\rho \times 10^{-3}$ (kg m^{-3})	η (mPa s)	$V^E \times 10^6$ (m^3 mol^{-1})	$\Delta\eta$ (mPa s)	d_{12}	T_{12}	H_{12}
2-Methoxyethanol + methanol							
(298.15 K)							
0	0.78627	0.54182	0	0	–	–	–
0.04469	0.80181	0.60452	−0.06	0.01795	1.341	0.004	0.002
0.09523	0.81914	0.67145	−0.19	0.03427	1.091	0.013	0.009
0.15286	0.83639	0.74668	−0.292	0.05181	0.891	0.027	0.021
0.21917	0.85792	0.85083	−0.61	0.08957	0.791	0.045	0.038
0.29628	0.87704	0.9698	−0.773	0.13131	0.646	0.063	0.059
0.38708	0.89514	1.0854	−0.849	0.156	0.459	0.074	0.077
0.49556	0.91219	1.18999	−0.823	0.15197	0.273	0.07	0.084
0.62744	0.92758	1.29887	−0.631	0.1288	0.129	0.052	0.072
0.7912	0.94238	1.41902	−0.308	0.08498	0.036	0.022	0.035
1	0.95891	1.54312	0	0	–	–	–
(308.15 K)							
0	0.7792	0.47411	0	0	–	–	–
0.04469	0.7948	0.50876	−0.06587	−0.00036	0.576	0.003	0.002
0.09523	0.81247	0.53601	−0.21947	−0.0127	0.283	0.009	0.006
0.15286	0.8301	0.50436	−0.34654	−0.0895	−0.484	0.012	0.009
0.21917	0.85008	0.62489	−0.58393	−0.02091	0.222	0.028	0.024
0.29628	0.86931	0.69907	−0.75646	−0.00714	0.236	0.04	0.037
0.38708	0.88777	0.75938	−0.85623	−0.01796	0.148	0.044	0.047
0.49556	0.90569	0.84072	−0.88778	−0.02159	0.091	0.041	0.051
0.62744	0.92255	0.93212	−0.80028	−0.03351	0.038	0.029	0.043
0.7912	0.9388	1.05826	−0.59599	−0.03565	0.008	0.011	0.021
1	0.95161	1.25748	0	0	–	–	–
(318.15 K)							
0	0.76714	0.41722	0	0	–	–	–
0.04469	0.7928	0.4575	−0.59755	0.01303	1.11	0.003	0.002
0.09523	0.81035	0.46903	−0.73404	−0.00625	0.297	0.008	0.005
0.15286	0.82774	0.49551	−0.83562	−0.0149	0.19	0.015	0.011
0.21917	0.84618	0.53828	−0.96984	−0.01256	0.204	0.024	0.02
0.29628	0.86459	0.60165	−1.07261	0.00381	0.236	0.034	0.032
0.38708	0.88303	0.64841	−1.14481	−0.00479	0.146	0.038	0.04
0.49556	0.90067	0.76486	−1.12426	0.04553	0.163	0.043	0.051
0.62744	0.91825	0.84357	−1.04473	0.04384	0.082	0.032	0.045
0.7912	0.93496	0.9667	−0.82487	0.06713	0.034	0.016	0.025
1	0.94583	1.02686	0	0	–	–	–

(*continued*)

Table 2. Continued.

x_1	$\rho \times 10^{-3}$ (kg m^{-3})	η (mPa s)	$V^E \times 10^6$ (m^3 mol^{-1})	$\Delta\eta$ (mPa s)	d_{12}	T_{12}	H_{12}
2-Methoxyethanol + ethanol							
(298.15 K)							
0	0.78668	1.08812	0	0	–	–	–
0.06304	0.80154	1.05054	−0.035	−0.06627	−0.85	0.004	0.003
0.133	0.81725	1.02429	−0.073	−0.126	−0.703	0.013	0.01
0.20604	0.83345	1.01887	−0.148	−0.163	−0.531	0.026	0.022
0.28759	0.85074	1.03097	−0.24	−0.188	−0.383	0.04	0.036
0.37715	0.86879	1.05272	−0.343	−0.207	−0.272	0.05	0.048
0.47597	0.88679	1.08369	−0.393	−0.221	−0.188	0.053	0.054
0.58556	0.9039	1.17255	−0.32	−0.182	−0.092	0.05	0.055
0.70778	0.92076	1.28616	−0.165	−0.124	−0.033	0.036	0.043
0.84495	0.93867	1.41457	−0.024	−0.058	−0.006	0.014	0.019
1	0.95891	1.54312	0	0	–	–	–
(308.15 K)							
0	0.77691	0.90532	0	0	–	–	–
0.06304	0.79548	0.83419	−0.30816	−0.09333	−1.524	0.002	0.001
0.133	0.80955	0.8445	−0.23202	−0.10712	−0.745	0.01	0.008
0.20604	0.82822	0.8576	−0.46296	−0.12028	−0.47	0.023	0.019
0.28759	0.84522	0.88125	−0.51999	−0.12535	−0.301	0.036	0.033
0.37715	0.86348	0.90628	−0.62511	−0.13185	−0.203	0.046	0.044
0.47597	0.88221	0.94089	−0.71536	−0.13205	−0.13	0.049	0.051
0.58556	0.89976	1.00281	−0.65774	−0.10872	−0.064	0.046	0.05
0.70778	0.91633	1.06956	−0.45828	−0.08501	−0.027	0.031	0.037
0.84495	0.93514	1.1049	−0.366	−0.09797	−0.014	0.009	0.012
1	0.95161	1.25748	0	0	–	–	–
(318.15 K)							
0	0.77788	0.76154	0	0	–	–	–
0.06304	0.79186	0.76221	0.006834	−0.01606	−0.267	0.003	0.003
0.133	0.806	0.77043	0.040827	−0.02599	−0.183	0.013	0.01
0.20604	0.82333	0.77301	−0.1294	−0.04319	−0.18	0.024	0.02
0.28759	0.84115	0.80024	−0.29431	−0.0376	−0.09	0.037	0.034
0.37715	0.85905	0.89703	−0.42043	0.03542	0.084	0.056	0.054
0.47597	0.87757	0.86803	−0.54742	−0.01979	−0.013	0.052	0.053
0.58556	0.89548	0.91098	−0.57507	−0.00592	0.003	0.048	0.052
0.70778	0.91331	0.92299	−0.53938	−0.02634	−0.008	0.03	0.036
0.84495	0.93136	0.96331	−0.45755	−0.02241	−0.003	0.011	0.014
1	0.94583	1.02686	0	0	–	–	–
2-Methoxyethanol + propanol							
(298.15 K)							
0	0.8001	2.00411	0	0	–	–	–
0.08067	0.81331	1.90066	0.024	−0.06627	−0.364	0.008	0.007
0.16488	0.82666	1.77609	0.078	−0.15201	−0.393	0.024	0.023
0.25288	0.84003	1.69154	0.172	−0.196	−0.306	0.047	0.045
0.34491	0.85381	1.65011	0.274	−0.195	−0.198	0.07	0.069
0.44126	0.86859	1.62369	0.332	−0.177	−0.12	0.087	0.086
0.54226	0.8847	1.60114	0.322	−0.153	−0.07	0.09	0.09
0.64823	0.9018	1.59028	0.278	−0.115	−0.034	0.078	0.079
0.75956	0.91973	1.57996	0.219	−0.074	−0.012	0.051	0.052
0.87666	0.9389	1.57113	0.113	−0.02885	−0.002	0.018	0.019
1	0.95891	1.54312	0	0	–	–	–

(*continued*)

Table 2. Continued.

x_1	$\rho \times 10^{-3}$ (kg m^{-3})	η (mPa s)	$V^E \times 10^6$ (m^3 mol^{-1})	$\Delta\eta$ (mPa s)	d_{12}	T_{12}	H_{12}
(308.15 K)							
0	0.79106	1.55873	0	0	–	–	–
0.08067	0.81075	1.34044	−0.57538	−0.19399	−1.522	0.001	0.001
0.16488	0.82416	1.26406	−0.50891	−0.245	−0.882	0.011	0.01
0.25288	0.8379	1.24851	−0.42916	−0.23404	−0.495	0.029	0.028
0.34491	0.85221	1.22738	−0.35454	−0.22744	−0.313	0.047	0.046
0.44126	0.86706	1.20649	−0.28001	−0.21931	−0.204	0.059	0.059
0.54226	0.88281	1.17901	−0.23449	−0.21636	−0.137	0.06	0.06
0.64823	0.8997	1.15371	−0.23591	−0.20974	−0.088	0.049	0.049
0.75956	0.91742	1.13097	−0.25219	−0.19894	−0.05	0.028	0.029
0.87666	0.93618	1.12481	−0.29724	−0.16982	−0.019	0.007	0.007
1	0.95161	1.25748	0	0	–	–	–
(318.15 K)							
0	0.78409	1.22668	0	0	–	–	–
0.08067	0.80572	1.09905	−0.76338	−0.11151	−1.089	0.002	0.002
0.16488	0.81901	1.05824	−0.67517	−0.13549	−0.6	0.013	0.012
0.25288	0.83282	1.00274	−0.58961	−0.17341	−0.463	0.025	0.024
0.34491	0.8471	0.97638	−0.50074	−0.18138	−0.317	0.038	0.037
0.44126	0.86192	0.97939	−0.41047	−0.15912	−0.186	0.049	0.049
0.54226	0.87786	0.97005	−0.36976	−0.14827	−0.117	0.051	0.051
0.64823	0.89506	0.9645	−0.38429	−0.13265	−0.068	0.043	0.043
0.75956	0.91301	0.95894	−0.40516	−0.11596	−0.035	0.026	0.027
0.87666	0.93203	0.95521	−0.45615	−0.0963	−0.013	0.008	0.008
1	0.94583	1.02686	0	0	–	–	–
2-Methoxyethanol + butanol							
(298.15 K)							
0	0.80873	2.56052	0	0	–	–	–
0.09765	0.82094	2.21231	0.073	−0.24886	−0.894	0.004	0.005
0.19582	0.83321	2.06132	0.179	−0.29997	−0.483	0.023	0.027
0.29449	0.84583	1.94753	0.289	−0.31338	−0.298	0.05	0.056
0.39369	0.85883	1.87998	0.4	−0.28	−0.169	0.078	0.083
0.49341	0.87352	1.81318	0.385	−0.24535	−0.098	0.095	0.098
0.59366	0.88891	1.76655	0.351	−0.18999	−0.048	0.097	0.096
0.69443	0.90519	1.72298	0.287	−0.13103	−0.02	0.082	0.078
0.79575	0.92235	1.67393	0.198	−0.077	−0.006	0.051	0.048
0.8976	0.94028	1.6223	0.099	−0.025	0	0.018	0.016
1	0.95891	1.54312	0	0	–	–	–
(308.15 K)							
0	0.79805	1.97944	0	0	–	–	–
0.09765	0.82202	1.68753	−1.21278	−0.22141	−1.065	0.002	0.003
0.19582	0.83433	1.58323	−1.04704	−0.25484	−0.552	0.017	0.02
0.29449	0.84701	1.48965	−0.87913	−0.27718	−0.361	0.037	0.041
0.39369	0.86045	1.35505	−0.7487	−0.34016	−0.309	0.048	0.052
0.49341	0.87467	1.30389	−0.65074	−0.31933	−0.199	0.059	0.061
0.59366	0.88964	1.24819	−0.57826	−0.30265	−0.131	0.058	0.058
0.69443	0.90542	1.21874	−0.53224	−0.25935	−0.075	0.048	0.045
0.79575	0.92171	1.19051	−0.48069	−0.21443	−0.038	0.028	0.025
0.8976	0.93856	1.17895	−0.42559	−0.15246	−0.013	0.008	0.007
1	0.95161	1.25748	0	0	–	–	–

(*continued*)

Table 2. Continued.

x_1	$\rho \times 10^{-3}$ (kg m^{-3})	η (mPa s)	$V^E \times 10^6$ (m^3 mol^{-1})	$\Delta\eta$ (mPa s)	d_{12}	T_{12}	H_{12}
(318.15 K)							
0	0.79006	1.57482	0	0	–	–	–
0.09765	0.81423	1.26599	−1.24303	−0.25532	−1.631	−0.002	−0.001
0.19582	0.82704	1.21228	−1.11071	−0.25524	−0.731	0.01	0.012
0.29449	0.84022	1.17169	−0.97295	−0.24176	−0.407	0.027	0.031
0.39369	0.85386	1.11741	−0.83876	−0.24169	−0.269	0.042	0.045
0.49341	0.86827	1.06264	−0.73511	−0.24181	−0.187	0.049	0.051
0.59366	0.88375	1.04611	−0.68602	−0.20341	−0.106	0.052	0.051
0.69443	0.90006	1.03559	−0.66248	−0.15871	−0.054	0.044	0.042
0.79575	0.91678	0.99597	−0.61949	−0.14281	−0.03	0.025	0.023
0.8976	0.93398	0.9925	−0.56404	−0.09047	−0.009	0.008	0.007
1	0.94583	1.02686	0	0	–	–	–
2-Methoxyethanol + pentanol							
(298.15 K)							
0	0.81385	3.50027	0	0	–	–	–
0.11403	0.82541	2.93903	0.12	−0.33807	−0.632	0.004	0.009
0.22456	0.83732	2.56854	0.234	−0.49223	−0.434	0.021	0.034
0.33174	0.84956	2.34629	0.347	−0.50471	−0.258	0.051	0.068
0.43574	0.86233	2.15536	0.437	−0.49211	−0.166	0.078	0.092
0.53668	0.87627	2.00665	0.442	−0.44325	−0.101	0.093	0.101
0.63471	0.89128	1.89403	0.385	−0.36403	−0.054	0.094	0.093
0.72993	0.90729	1.80026	0.284	−0.27142	−0.025	0.077	0.071
0.82249	0.9237	1.7202	0.202	−0.17034	−0.008	0.048	0.041
0.91247	0.94085	1.68617	0.111	−0.02825	0.002	0.018	0.015
1	0.95891	1.54312	0	0	–	–	–
(308.15 K)							
0	0.80264	2.65281	0	0	–	–	–
0.11403	0.82013	2.12044	−0.61272	−0.37326	−1.079	−0.002	0.001
0.22456	0.83179	1.89417	−0.39815	−0.44531	−0.584	0.012	0.021
0.33174	0.8441	1.72416	−0.22571	−0.46576	−0.369	0.032	0.044
0.43574	0.85743	1.54288	−0.13268	−0.50193	−0.281	0.046	0.056
0.53668	0.87178	1.44226	−0.10501	−0.46171	−0.18	0.058	0.063
0.63471	0.88712	1.4134	−0.13063	−0.35378	−0.09	0.065	0.064
0.72993	0.90314	1.30573	−0.16748	−0.32858	−0.061	0.048	0.044
0.82249	0.91991	1.25368	−0.21852	−0.25149	−0.029	0.028	0.023
0.91247	0.93743	1.24854	−0.27879	−0.13106	−0.007	0.009	0.007
1	0.95161	1.25748	0	0	–	–	–
(318.15 K)							
0	0.79615	2.03854	0	0	–	–	–
0.11403	0.81551	1.65852	−0.86319	−0.26466	−0.995	0	0.002
0.22456	0.82652	1.52527	−0.54718	−0.28609	−0.47	0.014	0.022
0.33174	0.83875	1.42702	−0.34992	−0.2759	−0.26	0.035	0.045
0.43574	0.85185	1.27896	−0.21683	−0.31875	−0.217	0.045	0.053
0.53668	0.86626	1.23417	−0.18583	−0.26142	−0.116	0.058	0.062
0.63471	0.88156	1.22216	−0.19582	−0.17426	−0.044	0.063	0.062
0.72993	0.8975	1.20769	−0.21373	−0.09239	−0.009	0.055	0.05
0.82249	0.91433	1.03535	−0.26046	−0.17109	−0.024	0.024	0.02
0.91247	0.93217	1.03577	−0.33795	−0.07964	−0.005	0.008	0.007
1	0.94583	1.02686	0	0	–	–	–

(*continued*)

Table 2. Continued.

x_1	$\rho \times 10^{-3}$ (kg m^{-3})	η (mPa s)	$V^E \times 10^6$ (m^3 mol^{-1})	$\Delta\eta$ (mPa s)	d_{12}	T_{12}	H_{12}
2-Methoxyethanol + hexanol							
(298.15 K)							
0	0.81987	4.59113	0	0	–	–	–
0.12982	0.83085	3.76543	0.155	−0.43	−0.38	0.005	0.015
0.25132	0.84212	3.22512	0.301	−0.6	−0.236	0.027	0.052
0.36526	0.85386	2.81082	0.417	−0.667	−0.161	0.056	0.088
0.47233	0.8663	2.45845	0.483	−0.693	−0.122	0.078	0.104
0.57314	0.8799	2.25018	0.455	−0.594	−0.066	0.097	0.111
0.66822	0.8944	2.07566	0.38	−0.47873	−0.032	0.097	0.098
0.75804	0.90955	1.93977	0.292	−0.34083	−0.011	0.08	0.072
0.84303	0.92552	1.81547	0.181	−0.20608	−0.002	0.049	0.04
0.92357	0.94221	1.70746	0.063	−0.06861	0.001	0.017	0.013
1	0.95891	1.54312	0	0	–	–	–
(308.15 K)							
0	0.80761	3.39722	0	0	–	–	–
0.12982	0.82514	2.61182	−0.74838	−0.50762	−0.897	−0.005	0.001
0.25132	0.83574	2.23316	−0.40173	−0.62631	−0.506	0.007	0.023
0.36526	0.84722	2.02709	−0.15551	−0.58857	−0.266	0.034	0.057
0.47233	0.8601	1.81494	−0.05531	−0.57161	−0.176	0.055	0.073
0.57314	0.87426	1.66657	−0.06215	−0.50427	−0.106	0.068	0.078
0.66822	0.8894	1.4874	−0.12202	−0.48	−0.08	0.061	0.061
0.75804	0.90514	1.35588	−0.18639	−0.41932	−0.053	0.045	0.04
0.84303	0.92138	1.30324	−0.23988	−0.29011	−0.022	0.028	0.022
0.92357	0.93863	1.27271	−0.32816	−0.14831	−0.005	0.009	0.006
1	0.95161	1.25748	0	0	–	–	–
(318.15 K)							
0	0.80231	2.39695	0	0	–	–	–
0.12982	0.8195	2.1926	−0.71408	−0.02648	0.14	0.013	0.02
0.25132	0.83007	1.90827	−0.36917	−0.14436	−0.045	0.032	0.047
0.36526	0.8413	1.64814	−0.09448	−0.24837	−0.113	0.046	0.063
0.47233	0.8538	1.47674	0.043047	−0.27307	−0.094	0.059	0.072
0.57314	0.86802	1.35617	0.017861	−0.25553	−0.062	0.066	0.071
0.66822	0.88306	1.27774	−0.04264	−0.20368	−0.031	0.064	0.062
0.75804	0.89915	1.21079	−0.15208	−0.14757	−0.013	0.05	0.044
0.84303	0.91566	1.12899	−0.24017	−0.11293	−0.007	0.029	0.023
0.92357	0.93375	1.08271	−0.40841	−0.04886	−0.001	0.009	0.007
1	0.94583	1.02686	0	0	–	–	–
2-Methoxyethanol + heptanol							
298.15 K							
0	0.82133	5.93618	0	0	–	–	–
0.14505	0.83209	4.91995	0.191	−0.37901	0.045	0.013	0.034
0.27627	0.8432	3.9625	0.353	−0.76	−0.084	0.03	0.074
0.39555	0.8549	3.3355	0.461	−0.863	−0.067	0.059	0.111
0.50445	0.86728	2.88904	0.515	−0.83106	−0.04	0.088	0.13
0.60426	0.8808	2.55061	0.473	−0.731	−0.02	0.104	0.126
0.69609	0.89523	2.25247	0.381	−0.62576	−0.014	0.098	0.101
0.78084	0.9102	2.0545	0.289	−0.45141	−0.003	0.08	0.071
0.85931	0.92617	1.85186	0.158	−0.30933	−0.001	0.046	0.036
0.93217	0.94241	1.78999	0.063	−0.05112	0.004	0.019	0.013
1	0.95891	1.54312	0	0	–	–	–

(*continued*)

Table 2. Continued.

x_1	$\rho \times 10^{-3}$ (kg m^{-3})	η (mPa s)	$V^E \times 10^6$ (m^3 mol^{-1})	$\Delta\eta$ (mPa s)	d_{12}	T_{12}	H_{12}
(308.15 K)							
0	0.80813	4.26474	0	0	–	–	–
0.14505	0.82755	3.11579	−1.1457	−0.71275	−0.806	−0.011	−0.002
0.27627	0.83799	2.56088	−0.71179	−0.87304	−0.452	−0.004	0.023
0.39555	0.84945	2.22992	−0.42289	−0.84529	−0.253	0.022	0.057
0.50445	0.86175	1.93621	−0.22717	−0.81152	−0.171	0.043	0.071
0.60426	0.87477	1.75273	−0.08993	−0.69484	−0.099	0.06	0.075
0.69609	0.88904	1.59169	−0.05941	−0.57974	−0.059	0.061	0.062
0.78084	0.90413	1.48939	−0.067	−0.42717	−0.028	0.051	0.044
0.85931	0.92047	1.34072	−0.14411	−0.33986	−0.018	0.027	0.02
0.93217	0.93734	1.24719	−0.20951	−0.21428	−0.007	0.007	0.004
1	0.95161	1.25748	0	0	–	–	–
(318.15 K)							
0	0.80669	2.98282	0	0	–	–	–
0.14505	0.82239	2.49608	−0.31553	−0.20303	−0.138	0.009	0.018
0.27627	0.83268	2.20338	0.159474	−0.23906	−0.022	0.036	0.056
0.39555	0.84329	1.90572	0.54727	−0.30342	−0.04	0.057	0.078
0.50445	0.85888	1.61051	0.294662	−0.38562	−0.077	0.062	0.077
0.60426	0.86806	1.48709	0.812041	−0.31381	−0.034	0.071	0.077
0.69609	0.88493	1.45526	0.450254	−0.16604	0.011	0.075	0.072
0.78084	0.89931	1.46527	0.390614	0.00974	0.034	0.068	0.06
0.85931	0.91683	1.1416	0.045617	−0.16044	−0.007	0.025	0.02
0.93217	0.93138	1.09497	0.013016	−0.06456	−0.001	0.008	0.006
1	0.94583	1.02686	0	0	–	–	–

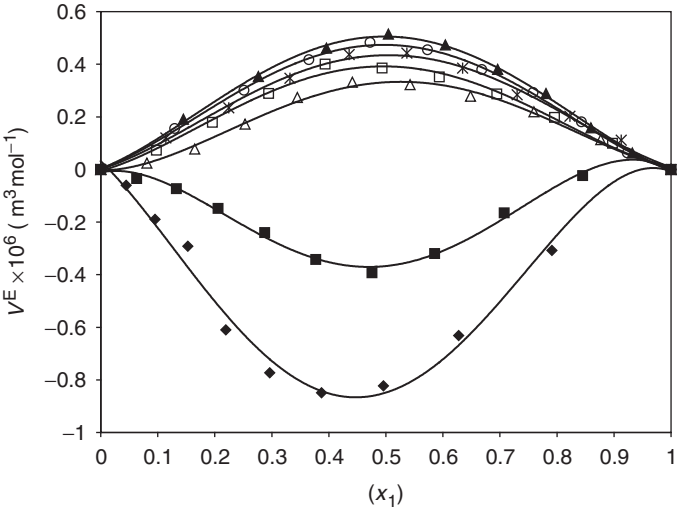

Figure 1. The plots of excess molar volumes (V^E) *vs.* mole fraction (x_1) of 2-methoxyethanol for binary mixtures of 2-methoxyethanol with methanol (◆), ethanol (■), 1-propanol (△), 1-butanol (□), 1-pentanol (∗), 1-hexanol (○) and 1-heptanol (▲) at 298.15 K.

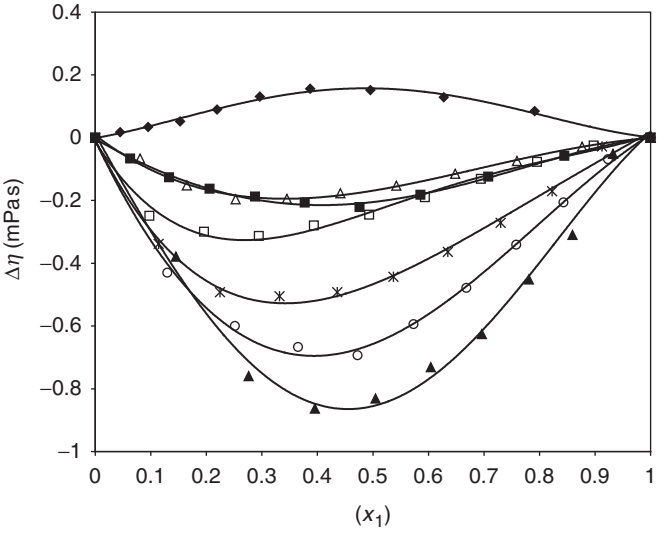

Figure 2. The plots of viscosity deviations ($\Delta\eta$) *vs.* mole fraction (x_1) of 2-methoxyethanol for binary mixtures of 2-methoxyethanol with methanol (◆), ethanol (■), 1-propanol (△), 1-butanol (□), 1-pentanol (∗), 1-hexanol (○) and 1-heptanol (▲) at 298.15 K.

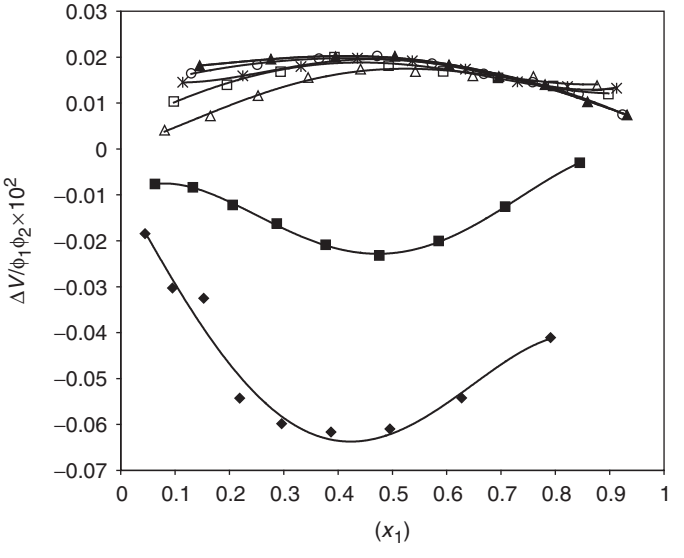

Figure 3. The plots of $\Delta V/\phi_1\phi_2$ *vs.* mole fraction (x_1) of 2-methoxyethanol for binary mixtures of 2-methoxyethanol with methanol (◆), ethanol (■), 1-propanol (△), 1-butanol (□), 1-pentanol (∗), 1-hexanol (○) and 1-heptanol (▲) at 298.15 K.

From Figure 1, we observe that V^E values gradually change from highly negative to less negative and finally turn positive with the increase of chain length along the alcohol homologous series. It has the highest negative value for methanol and ultimately turns positive for the higher alkanols. V^E values are negative for methanol, ethanol, and then

they turn gradually more and more positive from propane-1-ol to heptane-1-ol. Positive V^E values for higher alkanols and negative V^E values for lower alkanols were also reported by some other workers [31–33]. The observed trend of negative values of V^E in 1-alkanol + 2-methoxyethanol mixture is:

$$CH_3OH > C_2H_5OH > C_3H_7OH > C_4H_9OH > C_5H_{11}OH > C_6H_{13}OH > C_7H_{15}OH.$$

Such behaviour is the result of contribution from several contraction and expansion processes which proceed simultaneously when 2-methoxyethanol–alkan-1-ol molecules are formed. The following effects are considered: (1) contraction due to free volume difference of unlike molecules; (2) disruption of liquid order on mixing and unfavourable interactions between unlike molecules producing a positive contribution of V^E; and (3) possible association through hydrogen bond formation between unlike molecules producing a negative contribution to V^E. The large positive V^E observed in the case of $ROH + C_6H_{12}$ [34] and $R_2NH + C_6H_{12}$ [35] mixtures, as a result of disruption of the self-association of alkan-1-ol and amine by the addition of inert hydrocarbon molecules. Thus, the observed negative values of V^E can be accounted considering only the predominance of an energetically favoured [36,37] cross bonding –OH $\cdots$ O– bond over the rupture of –OH $\cdots$ OH– bonds present in pure alkan-1-ol.

From Figure 3 it can be seen that the value of $\Delta V/\phi_1\phi_2$ increases regularly with the number of carbon atoms in alkan-1-ol. This clearly suggests specific interaction between the components and the free volume effect when a mixture is formed [36].

3.2. *Viscosity deviations*

Viscosity deviations from linear dependence on mole fraction were calculated by

$$\Delta\eta = \eta - \sum_{i=1}^{2} x_i\eta_i, \tag{4}$$

where η is the viscosity of the mixture, and x_i and η_i are the mole fraction and viscosity of pure component i, respectively.

The values of $\Delta\eta$ (Figure 2) are positive for methanol and the value decreases regularly as the size of the alkan-1-ol is increased. The observed trend of positive values of $\Delta\eta$ in 1-alkanol + 2-methoxyethanol mixture is:

$$CH_3OH > C_2H_5OH > C_3H_7OH > C_4H_9OH > C_5H_{11}OH > C_6H_{13}OH > C_7H_{15}OH.$$

The positive $\Delta\eta$ values indicate the predominance of H-bonding interactions between the unlike molecules over the dissociation effects of the mixing components [38,39]. This results in a liquid structure where the flow is rather difficult than would be expected on the basis of the viscosities of the pure components.

It is known that the strength of the molecular hydrogen bonding is not only the factor influencing the viscosity deviations in liquid mixtures [36,37]. The molecular shape and size of the components and average degree of association of the mixture are equally important factors. The negative values of $\Delta\eta$ for higher alkanols indicate that the average degree of cross-association of mixtures gradually decreases as the chain length of alkan-1-ol is increased [35,36]. Thus, larger the chain length of alkan-1-ol, the greater is the decrease in the average degree of association; as a result, more negative deviations in viscosity *versus*

mole fraction curve are observed. These conclusions are supported by the conclusions from V^E values.

3.3. *Correlating equations*

The several models (equations) have been put forward to correlate the viscosity of binary liquid mixtures in terms of pure components data. Some of them are discussed below:

(i) The viscosity values were further used to determine the Grunberg and Nissan parameter [40] d_{12} as

$$\eta = \exp(x_1 \ln \eta_1 + x_2 \ln \eta_2 + x_1 x_2 d_{12}), \tag{5}$$

where d_{12} is a constant, regarded as a measure of the strength of molecular interactions between the mixing components.

(ii) Tamura and Kurata [41] put forward the following equation for the viscosity of binary liquid mixtures:

$$\eta = x_1\phi_1\eta_1 + x_2\phi_2\eta_2 + 2(x_1x_2\phi_1\phi_2)^{1/2}T_{12}, \tag{6}$$

where ϕ_1 and ϕ_2 are the volume fractions of components 1 and 2, and T_{12} is an adjustable parameter.

(iii) Molecular interactions may also be interpreted using the following viscosity model of Hind *et al.* [42]

$$\eta = x_1^2\eta_1 + x_2^2\eta_2 + 2x_1x_2\eta_1\eta_2H_{12}. \tag{7}$$

The interaction parameters have their merits in ascertaining the strength of molecular interactions in binary mixtures. Among the three parameters, the Grunberg–Nissan parameter provides the best measure to ascertain the strength of interaction. Table 2 represents the calculated results, showing that all the models (equations) are in good agreement with the experimental data.

3.4. *Isentropic compressibility*

Isentropic compressibility K_S and excess isentropic compressibility K_S^E were determined from experimental densities, ρ, and speeds of sound, u, using the equations shown below:

$$K_S = \frac{1}{u^2 \cdot \rho}, \tag{8}$$

$$K_S^E = K_S - \sum_{i=1}^{2} x_i K_{S,i}, \tag{9}$$

where $K_{S,i}$ gives the isentropic compressibility for the ith component of the mixture.

The deviations in speed of sound, Δu, have been determined as shown in the literature [43–45] using following equation

$$\Delta u = u - \sum_{i=1}^{2} x_1 u_1^0. \tag{10}$$

The ultrasonic speeds are represented in Table 3, together with the deviations of speed of sound Δu, isentropic compressibility K_S and excess isentropic compressibility K_S^E for alkan-1-ol + 2-methoxyethanol at 298.15 K.

Experimental results for K_S^E and Δu are plotted against mole fraction of 2-methoxyethanol in Figures 4 and 5.

Table 3. Speed of sound, isentropic compressibility, and excess isentropic compressibility, deviation of speed of sound, excess intermolecular free length and excess acoustic impedance of alkan-1-ol + 2-methoxyethanol at 298.15 K.

x_1	u ($m\,s^{-1}$)	$K_S \times 10^{10}$ (Pa^{-1})	$K_S^E \times 10^{10}$ (Pa^{-1})	Δu ($m\,s^{-1}$)	$L_f^E \times 10^{11}$ (m)	$Z^E \times 10^{-3}$ ($kg\,m^2\,s^{-1}$)
2-Methoxyethanol (1) + methanol (2)						
0	1100.76	10.4965	0	0	0	0
0.04469	1119.598	9.9495	−3.38	8.208	−0.3159	13.5335
0.095232	1141.47	9.3694	−6.82	18.0578	−0.6508	29.7132
0.152858	1156.981	8.9317	−8.5	19.862	−0.8112	38.2882
0.219167	1184.581	8.3066	−11.65	31.6901	−1.1468	59.1455
0.296283	1208.204	7.8109	−13	36.9701	−1.2997	70.2684
0.387081	1230.66	7.3762	−13.1	37.8286	−1.3241	74.2672
0.495559	1261.487	6.8889	−12.9	42.853	−1.3339	78.0129
0.627436	1288.633	6.4922	−10.7	38.6311	−1.123	67.4722
0.791198	1320.706	6.0836	−7.13	31.7516	−0.7718	48.2942
1	1338.62	5.8198	0	0	0	0
2-Methoxyethanol (1) + ethanol (2)						
0	1145.34	9.6902	0	0	0	0
0.063039	1154.222	9.3648	−0.81	−3.3019	−0.0556	0.0165
0.131477	1170.559	8.9302	−2.51	−2.2322	−0.2111	5.3135
0.206039	1195.565	8.3941	−4.99	10.4017	−0.4637	16.5911
0.287587	1224.502	7.8394	−7.38	23.5774	−0.7254	30.6814
0.377148	1252.088	7.342	−8.88	33.8525	−0.9045	42.4824
0.475967	1280.159	6.881	−9.67	42.824	−1.0166	52.1073
0.585557	1297.983	6.5666	−8.57	39.4664	−0.9116	48.1954
0.70778	1314.145	6.2888	−6.62	32.0053	−0.7111	38.1956
0.844953	1324.487	6.0729	−3.47	15.8344	−0.3688	18.9504
1	1338.62	5.8198	0	0	0	0
2-Methoxyethanol (1) + propan-1-ol (2)						
0	1207.81	8.5676	0	0	0	0
0.080671	1219.326	8.2699	−0.76	0.9634	−0.0637	−0.2651
0.164883	1232.879	7.9585	−1.56	3.5007	−0.1373	0.4929
0.252875	1253.07	7.5815	−2.91	12.1815	−0.2826	6.029
0.344907	1271.553	7.2439	−3.76	18.6262	−0.3778	9.8737

(*continued*)

Table 3. Continued.

x_1	u ($m\,s^{-1}$)	$K_S \times 10^{10}$ (Pa^{-1})	$K_S^E \times 10^{10}$ (Pa^{-1})	Δu ($m\,s^{-1}$)	$L_f^E \times 10^{11}$ (m)	$Z^E \times 10^{-3}$ ($kg\,m^2\,s^{-1}$)
0.441263	1287.426	6.9461	−4.09	21.8941	−0.4189	11.8868
0.542256	1299.312	6.6954	−3.82	20.5695	−0.393	11.0996
0.648228	1309.221	6.4694	−3.17	16.6167	−0.3248	8.6378
0.759558	1315.229	6.2855	−1.95	8.0615	−0.1891	2.3137
0.876661	1324.229	6.0737	−0.85	1.7431	−0.0742	−1.1667
1	1338.62	5.8198	0	0	0	0
2-Methoxyethanol (1) + butan-1-ol (2)						
0	1239.25	8.0515	0	0	0	0
0.097652	1250.272	7.7926	−0.41	1.3182	−0.0292	−3.3058
0.195815	1264.371	7.5075	−1.07	5.6626	−0.0929	−3.8344
0.294493	1282.469	7.1883	−2.06	13.955	−0.2031	−0.3448
0.39369	1297.923	6.9119	−2.61	19.5522	−0.2673	1.6839
0.49341	1311.663	6.654	−2.96	23.3826	−0.3136	4.6889
0.593657	1319.982	6.4566	−2.7	21.7402	−0.2872	4.0715
0.694435	1322.364	6.3177	−1.84	14.1084	−0.1873	−0.6491
0.795749	1328.656	6.1416	−1.34	10.3322	−0.1367	−0.6665
0.897602	1330.444	6.0083	−0.4	1.999	−0.0309	−3.821
1	1338.62	5.8198	0	0	0	0
2-Methoxyethanol (1) + pentan-1-ol (2)						
0	1278.93	7.5121	0	0	0	0
0.114029	1289.753	7.2831	−0.36	4.0165	−0.0302	−3.967
0.224557	1302.28	7.0421	−0.9	9.946	−0.087	−4.9495
0.331744	1319.791	6.7577	−1.93	21.0593	−0.2102	−0.157
0.435739	1330.615	6.5497	−2.25	25.6757	−0.2502	0.7931
0.536682	1340.682	6.349	−2.55	29.7174	−0.2916	3.6584
0.634705	1343.934	6.212	−2.26	27.1188	−0.2601	2.8821
0.729934	1341.253	6.1268	−1.5	18.7537	−0.1682	−1.1595
0.822487	1337.454	6.0522	−0.68	9.4299	−0.0689	−5.1228
0.912473	1338.692	5.9309	−0.37	5.2964	−0.0378	−2.8699
1	1338.62	5.8198	0	0	0	0
2-Methoxyethanol (1) + hexan-1-ol (2)						
0	1328.24	6.9136	0	0	0	0
0.129822	1327.039	6.8346	0.63	−2.5488	0.0852	−11.6839
0.251316	1321.021	6.8047	1.66	−9.8276	0.2194	−25.4435
0.365259	1314.867	6.774	2.6	−17.164	0.3418	−37.361
0.472334	1313.087	6.6949	2.98	−20.0562	0.3938	−43.3934
0.573143	1312.267	6.5997	3.13	−21.9218	0.4158	−45.8744
0.668222	1316.333	6.4527	2.7	−18.8435	0.3629	−41.7233
0.758044	1320.475	6.3054	2.21	−15.6332	0.3	−35.4925
0.843035	1327.906	6.1275	1.36	−9.0848	0.1879	−24.0685
0.923573	1332.627	5.9764	0.73	−5.1999	0.1018	−13.137
1	1338.62	5.8198	0	0	0	0
2-Methoxyethanol (1) + heptan-1-ol (2)						
0	1331.7	6.8654	0	0	0	0
0.145051	1325.934	6.8358	1.22	−6.9363	−0.2127	6.6553
0.276272	1317.958	6.8275	2.51	−16.0432	0.0119	−13.9627
0.395552	1309.553	6.8208	3.69	−25.4176	0.2166	−31.7602
0.50445	1304.952	6.771	4.33	−30.6807	0.3484	−43.1727

(*continued*)

Table 3. Continued.

x_1	u (m s^{-1})	$K_S \times 10^{10}$ (Pa^{-1})	$K_S^E \times 10^{10}$ (Pa^{-1})	Δu (m s^{-1})	$L_f^E \times 10^{11}$ (m)	$Z^E \times 10^{-3}$ (kg m^2 s^{-1})
0.604264	1302.754	6.6896	4.56	−33.3905	0.4238	−49.103
0.696086	1305.555	6.5536	4.16	−30.9613	0.415	−47.6686
0.780839	1315.469	6.3489	3	−21.3525	0.3035	−37.4579
0.859309	1323.941	6.1599	1.93	−13.3505	0.1979	−25.8455
0.932169	1330.891	5.9907	1	−7.0113	0.1059	−14.0415
1	1338.62	5.8198	0	0	0	0

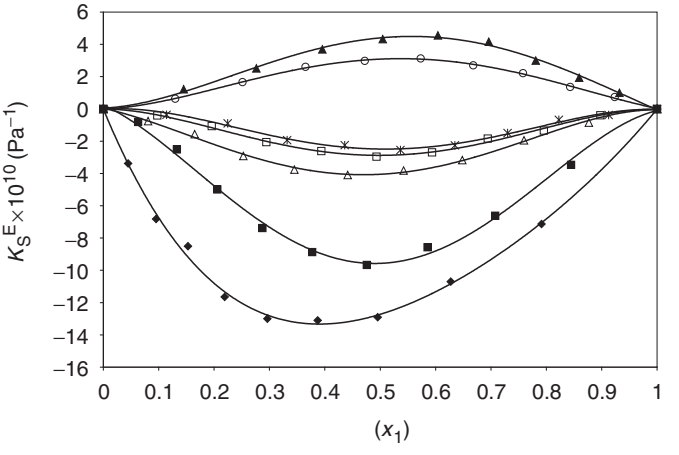

Figure 4. The plots of K_S^E *vs.* mole fraction (x_1) of 2-methoxyethanol for binary mixtures of 2-methoxyethanol with methanol (◆), ethanol (■), 1-propanol (△), 1-butanol (□), 1-pentanol (⁎), 1-hexanol (○) and 1-heptanol (▲) at 298.15 K.

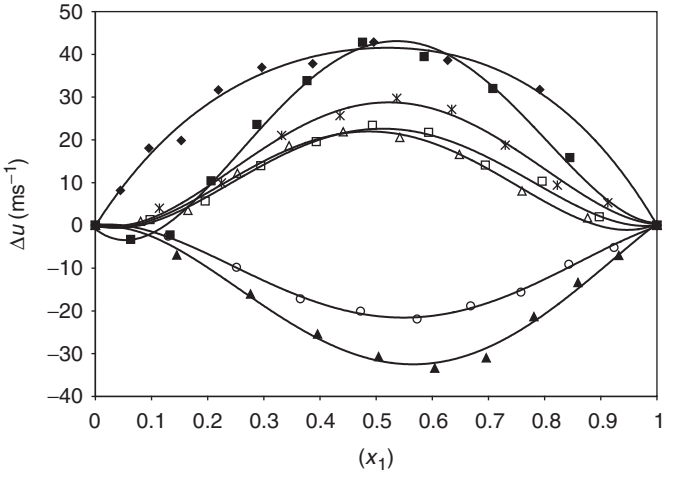

Figure 5. The plots of Δu *vs.* mole fraction (x_1) of 2-methoxyethanol for binary mixtures of 2-methoxyethanol with methanol (◆), ethanol (■), 1-propanol (△), 1-butanol (□), 1-pentanol (⁎), 1-hexanol (○) and 1-heptanol (▲) at 298.15 K.

From the experimental data of speed of sound and density, various acoustical parameters such as specific impedance Z [46], intermolecular free length L_f [47], Van der Waal's constant b, molecular radius r [47], geometrical volume B, molar surface area Y, available volume V_a [48], molar speed of sound R [49], collision factor S [50] and molecular association M_A [51] have been calculated by the following relations:

$$Z = u\rho, \tag{11}$$

$$b = \left(\frac{M}{\rho}\right) - \left(\frac{RT}{\rho u^2}\right)\{[1 + (Mu^2/3RT)]^{1/2} - 1\}, \tag{12}$$

$$r = \left(\frac{3\mathrm{b}}{16\pi N}\right)^{1/3}, \tag{13}$$

$$L_f = \frac{K}{(u\rho^{1/2})}, \tag{14}$$

$$B = \left(\frac{4}{3}\right)\pi r^3 N, \tag{15}$$

$$Y = (36\pi N B^2)^{1/3}, \tag{16}$$

$$V_a = V - V_0, \tag{17}$$

$$R = \frac{Mu^{1/3}}{\rho}, \tag{18}$$

$$S = \frac{uV}{u_\infty B}, \tag{19}$$

$$M_A = \left[\left(\frac{u_{mix}}{\Sigma x_i u_i}\right)^2 - 1\right], \tag{20}$$

where K is a temperature-dependent constant [$=(93.875 + 0.375\,T) \times 10^{-8}$] [47], V_0 is volume at absolute zero, u_∞ is taken as $1600\,\mathrm{ms}^{-1}$. These parameters are listed in Table 4 for the pure components and in Table 5 for the binary mixtures.

The excess functions of acoustic impedance, Z, and intermolecular free length, L_f, were calculated using the following equations:

$$L_f^E = L_f - \sum_{i=1}^{2} x_i L_{fi}, \tag{21}$$

$$Z^E = Z - \sum_{i=1}^{2} x_i Z_i. \tag{22}$$

The observed values of L_f^E and Z^E with mole fraction of x_1 for all systems studied at 298.15 K are depicted in Figures 6 and 7, respectively.

Table 4. Van der Wall's constant b, molecular radius r, geometrical volume B, collision factor S, molar speed of sound R, available volume V_a, intermolecular free length L_f, molar volume at absolute zero V_0, molar surface area Y and specific acoustic impedance Z of the pure component at 298.15 K.

Component	$b \times 10^6$ (m^3)	$r \times 10^{10}$ (m)	$B \times 10^5$ ($m^3\,mol^{-1}$)	S	$R \times 10^4$ [$m^3\,mol^{-1}(m\,s^{-1})^{1/3}$]	$V_a \times 10^5$ (m^3)	$L_f \times 10^{11}$ (m)	$V_0 \times 10^5$ (m^3)	$Y \times 10^{-4}$ (m)	$Z \times 10^{-3}$ ($kg\,m^2\,s^{-1}$)
2-Methoxyethanol	65.57343	1.8664	16.39336	4.05018	8.7463	1.2965	1.5687	6.6396	26.3508	1283.62
Methanol	32.11293	1.4711	8.02823	3.49201	4.2075	1.2715	2.1067	2.8035	16.3717	865.49
Ethanol	46.16799	1.6604	11.542	3.63285	6.1286	1.6645	2.0241	4.193	20.8546	901.02
Propan-1-ol	59.47325	1.8066	14.86831	3.81372	7.9995	1.8412	1.9033	5.6704	24.6901	966.37
Butan-1-ol	72.76919	1.9323	18.1923	3.90194	9.8442	2.0664	1.8451	7.0985	28.2449	1002.22
Pentan-1-ol	86.14167	2.044	21.53542	4.02021	11.7569	2.1735	1.7822	8.6577	31.607	1040.86
Hexan-1-ol	99.30969	2.1433	24.82742	4.16722	13.6998	2.1168	1.7097	10.3461	34.7512	1088.98
Heptan-1-ol	112.7884	2.2362	28.19736	4.28539	15.5652	2.3724	1.7038	11.7753	37.8284	1093.77

Table 5. Molar surface area Y, available volume V_a, molar speed of sound R, intermolecular free length L_f, specific acoustic impedance Z and molecular association for 2-methoxyethanol + alkan-1-ol at 298.15 K.

X_1	$Y \times 10^{-4}$ (m)	$V_a \times 10^5$ (m^3)	$R \times 10^4$ [$m^3\,mol^{-1}(m\,s^{-1})^{1/3}$]	$L_f \times 10^{11}$ (m)	$Z \times 10^{-3}$ ($kg\,m^2\,s^{-1}$)	M_A
2-Methoxyethanol (1) + methanol (2)						
0.04469	16.8736	1.2735	4.4044	2.051	897.71	0.0148
0.09523	17.4185	1.2677	4.6237	1.9904	935.02	0.0324
0.15286	18.0316	1.2836	4.8662	1.9433	967.69	0.0352
0.21917	18.6885	1.2619	5.1429	1.8741	1016.28	0.0557
0.29628	19.4689	1.259	5.4757	1.8173	1059.64	0.0641
0.38708	20.3896	1.2661	5.8769	1.766	1101.61	0.0644
0.49556	21.4826	1.2496	6.381	1.7067	1150.71	0.0716
0.62744	22.8018	1.2522	7.0014	1.6568	1195.31	0.0628
0.7912	24.4033	1.2392	7.7888	1.6038	1244.61	0.0499
2-Methoxyethanol (1) + ethanol (2)						
0.06304	21.4758	1.6675	6.3891	1.9899	925.15	−0.0057
0.13148	22.0995	1.643	6.6671	1.9431	956.63	−0.0003
0.20604	22.7288	1.5851	6.9683	1.8839	996.44	0.0176
0.28759	23.3509	1.5093	7.2774	1.8206	1041.73	0.0397
0.37715	23.9639	1.4367	7.5838	1.7619	1087.8	0.0563
0.47597	24.568	1.3608	7.8927	1.7057	1135.23	0.0704
0.58556	25.1635	1.3294	8.1833	1.6663	1173.25	0.0637
0.70778	25.707	1.3064	8.4497	1.6307	1210.01	0.0505
0.84495	26.1361	1.3106	8.6484	1.6024	1243.25	0.0243
2-Methoxyethanol (1) + propan-1-ol (2)						
0.08067	24.8407	1.7959	8.0639	1.8699	991.69	0.0016
0.16488	25.0007	1.7414	8.1382	1.8344	1019.17	0.0057
0.25288	25.1711	1.6558	8.233	1.7904	1052.62	0.0197
0.34491	25.3459	1.5777	8.3263	1.7501	1085.66	0.03
0.44126	25.5181	1.5105	8.4114	1.7137	1118.25	0.0349
0.54226	25.6849	1.461	8.4834	1.6825	1149.5	0.0324
0.64823	25.8485	1.4202	8.5487	1.6539	1180.66	0.0259
0.75956	26.0157	1.3982	8.6069	1.6302	1209.65	0.0124
0.87666	26.1821	1.3608	8.6702	1.6025	1243.32	0.0026
2-Methoxyethanol (1) + butan-1-ol (2)						
0.09765	28.0841	1.9786	9.7515	1.8152	1026.4	0.0021
0.19582	27.9271	1.8758	9.6698	1.7817	1053.49	0.009
0.29449	27.7645	1.7528	9.5952	1.7434	1084.75	0.0221
0.39369	27.6009	1.6465	9.5132	1.7095	1114.69	0.0308
0.49341	27.4129	1.5493	9.4112	1.6773	1145.76	0.0366
0.59366	27.2173	1.4824	9.2923	1.6523	1173.35	0.0338
0.69443	27.0098	1.4472	9.1538	1.6344	1196.99	0.0217
0.79575	26.7979	1.3918	9.0228	1.6114	1225.48	0.0157
0.8976	26.5769	1.3599	8.8781	1.5939	1250.99	0.003
2-Methoxyethanol (1) + pentan-1-ol (2)						
0.11403	31.0604	2.0385	11.4442	1.7548	1064.58	0.0063
0.22456	30.5207	1.8988	11.143	1.7255	1090.43	0.0155
0.33174	29.9932	1.7347	10.865	1.6903	1121.24	0.0327
0.43574	29.4722	1.6186	10.5738	1.6641	1147.44	0.0397
0.53668	28.9453	1.5108	10.2782	1.6384	1174.81	0.0459

(*continued*)

Table 5. Continued.

X_1	$Y \times 10^{-4}$ (m)	$V_a \times 10^5$ (m^3)	$R \times 10^4$ [$m^3\,mol^{-1}(m\,s^{-1})^{1/3}$]	$L_f \times 10^{11}$ (m)	$Z \times 10^{-3}$ ($kg\,m^2\,s^{-1}$)	M_A
0.63471	28.4177	1.4455	9.9672	1.6207	1197.83	0.0416
0.72993	27.8896	1.4144	9.6451	1.6095	1216.9	0.0286
0.82249	27.3733	1.3899	9.3324	1.5997	1235.41	0.0143
0.91247	26.8595	1.3393	9.0374	1.5836	1259.5	0.008
2-Methoxyethanol (1) + hexan-1-ol (2)						
0.12982	33.7537	2.0286	13.0663	1.6999	1102.57	−0.0038
0.25132	32.8078	1.9799	12.4602	1.6962	1112.46	−0.0147
0.36526	31.8992	1.9338	11.8873	1.6924	1122.72	−0.0256
0.47233	31.0274	1.8601	11.3587	1.6825	1137.52	−0.0299
0.57314	30.1784	1.7828	10.8536	1.6705	1154.66	−0.0326
0.66822	29.3567	1.68	10.3848	1.6518	1177.32	−0.028
0.75804	28.5653	1.5829	9.9403	1.6328	1201.04	−0.0233
0.84303	27.7978	1.4735	9.5234	1.6096	1229	−0.0135
0.92357	27.0568	1.385	9.1205	1.5896	1255.61	−0.0078
2-Methoxyethanol (1) + heptan-1-ol (2)						
0.14505	36.3181	2.0265	14.6812	1.6629	1127.96	0.0346
0.27627	34.9217	2.004	13.7539	1.6676	1132.26	0.0138
0.39555	33.6203	1.9799	12.9078	1.672	1137.1	−0.0065
0.50445	32.3998	1.9241	12.144	1.6704	1146.37	−0.02
0.60426	31.2458	1.8515	11.4434	1.6645	1159.39	−0.0291
0.69609	30.1543	1.7496	10.8081	1.6512	1178.25	−0.0302
0.78084	29.1248	1.6123	10.2396	1.6286	1204.56	−0.0204
0.85931	28.1446	1.4938	9.7038	1.6075	1231.07	−0.0126
0.93217	27.2221	1.3931	9.2058	1.5884	1256.7	−0.0069

From Figure 4, it is evident that the K_S^E values are negative for lower alkane-1-ol but the magnitude of negative values decreases and the positive values increases with the increasing chain length of the alcohols. The values of K_S^E, in terms of negativity, are increased by the following order:

$$CH_3OH > C_2H_5OH > C_3H_7OH > C_4H_9OH > C_5H_{11}OH > C_6H_{13}OH > C_7H_{15}OH.$$

The overall behaviour of K_S^E is similar for Δu but with opposite sign. Positive K_S^E values are due to the breaking of interactions and the corresponding disruption of molecular order in the pure components [52]. The donor–acceptor interaction between the 2-methoxyethanol and the alcohols play an important part for the mixtures containing lower alcohols like methanol, ethanol, propan-1-ol where there is strong specific interaction between the component molecules leading to negative value of K_S^E. Interactions between the molecules of 2-methoxyethanol or monoalcohols are broken in the mixing process; the breaking leads to positive K_S^E values for the mixture containing greater chain length of alcohols as compared to the lower alcohols. There is a similarity in the qualitative behaviour of K_S^E and V^E curves.

It is observed that the value of specific acoustic impedance Z increases with increasing x_1 for all the mixtures, while the L_f behaves in an opposite manner (Table 5). The decrease

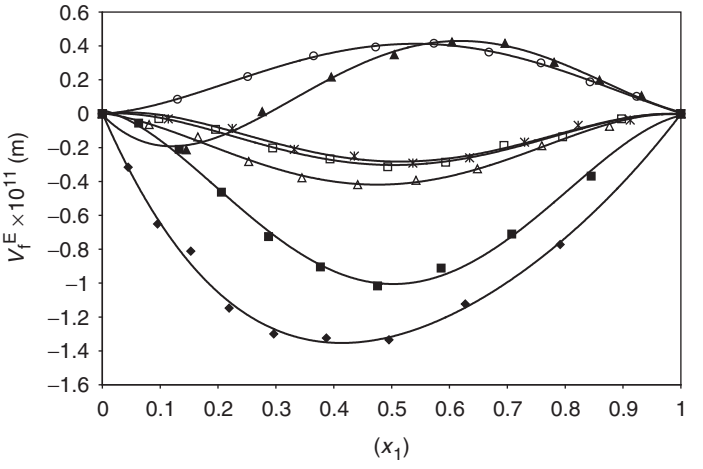

Figure 6. The plots of L_f^E *vs.* mole fraction (x_1) of 2-methoxyethanol for binary mixtures of 2-methoxyethanol with methanol (◆), ethanol (■), 1-propanol (△), 1-butanol (□), 1-pentanol (∗), 1-hexanol (○) and 1-heptanol (▲) at 298.15 K.

in L_f and V_a with increase in x_1 indicates significant interaction between the mixing molecules [37].

These results can be explained in terms of molecular interactions and structural effects. Positive K_S^E values are due to the breaking of interactions and the corresponding disruption of molecular order in the pure components [52]. The donor–acceptor interaction between the 2-methoxyethanol and the alcohols plays an important part for the mixtures containing lower alcohols like methanol, ethanol where there is strong specific interaction between the component molecules leading to negative value of K_S^E. Interactions between the molecules of 2-methoxyethanol or monoalcohols are broken in the mixing process; the breaking leads to positive K_S^E values for the mixture containing greater chain length of alcohols as compared to the lower alcohols. There is a similarity in the qualitative behaviour of K_S^E and V^E curves.

The variations of V_a, Z, L_f, R and M_A for binary mixtures with x_1 are given in Table 5. The values of R increase for C_1–C_3 alkan-1-ol and decrease regularly for C_4–C_7 alkan-1-ol with x_1. The increase in u and the corresponding decrease in K_S and L_f suggest significant interaction between alkan-1-ol and 2-methoxyethanol molecule. The values of R increase for mixture containing C_1, C_2, and C_3 in alkan-1-ol, and decreases for C_4, C_5, C_6, and C_7 alkan-1-ol. Similarly, there are large positive deviations in M_A for alkan-1-ol + 2-Methoxyethanol systems and these deviations decrease from methanol to heptan-1-ol. Thus, it is concluded that the intermolecular hydrogen bonding or average degree of association decreases as the chain length of alkan-1-ol increases in the mixtures.

From Figures 6 and 7 we observe that L_f^E values gradually change from highly negative to less negative and finally turn positive with the increase of chain length along the alcohol homologous series while the Z^E behaves in an opposite manner. Positive and negative deviations in these functions from rectilinear dependence on composition for the present system are indicative of interactions between unlike molecules. Large negative values of L_f^E indicate the predominance formation of –OH $\cdots$ O– bonds over the rupture

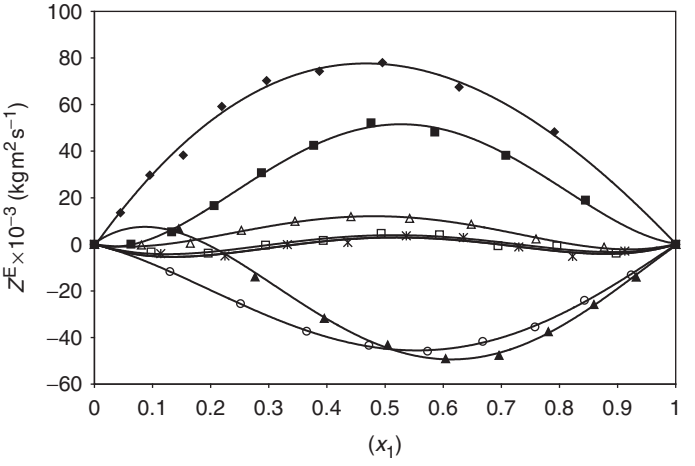

Figure 7. The plots of Z^E *vs.* mole fraction (x_1) of 2-methoxyethanol for binary mixtures of 2-methoxyethanol with methanol (◆), ethanol (■), 1-propanol (△), 1-butanol (□), 1-pentanol (∗), 1-Hexanol (○) and 1-heptanol (▲) at 298.15 K.

of –OH···OH– hydrogen bonds present in pure alkan-1-ol. These conclusions are supported by the conclusions drawn fromthe V^E and K_S^E values.

3.5. *Redlich–Kister polynomial equation*

The excess properties (V^E, $\Delta\eta$, K_S^E, Δu, L_f^E and Z^E) were fitted to the Redlich–Kister (1948) polynomial regression [53] of the type

$$F(x) = x_1 x_2 \sum_{i=0}^{m} A_i (1 - 2x_1)^i, \tag{23}$$

where $F(x) = V^E$, $\Delta\eta$, K_S^E, Δu, L_f^E or Z^E.

The values of coefficients A_i of Equation (23) and the corresponding standard deviations δ obtained by least square method, assigning equal weights to each point, are given in Table 6. The standard deviations δ have been defined as

$$\delta = [\Sigma(Y_{obs} - Y_{cal})^2/(n - m)]^{1/2}, \tag{24}$$

where n and m represent the number of experimental points and numbers of coefficients used in Equations (23) and (24) and Y refers to excess properties.

4. Conclusions

The investigated mixtures were chosen in order to obtain information about the molecular interactions between their components. In this work, the mixed systems have been studied at different temperatures in terms of excess molar volumes, viscosity deviations, sound speed deviations, excess acoustic impedance, excess intermolecular free length, excess isentropic compressibility and interaction parameters. It may be concluded after a

Table 6. Redlich–Kister coefficients and standard deviations (σ) for the binary mixtures of 2-methoxyethanol + methanol, ethanol, 1-propanol, 1-butanol, 1-pentanol, 1-hexanol and 1-heptanol.

Binary mixture	Excess property	Temperature (K)	A_0	A_1	A_2	A_3	A_4	A_5	A_6	σ
2-Methoxyethanol + methanol	$V^E \times 10^6$ ($m^3 mol^{-1}$)	298.15	1.4765	0.3755	–	–	–	–	–	0.2235
		308.15	1.7070	0.4483	–	–	–	–	–	0.1914
		318.15	1.0711	0.1920	–	–	–	–	–	0.3507
	$\Delta\eta$ (mPa s)	298.15	2.5331	0.5238	−5.1709	−4.9671	–	–	–	0.0407
		308.15	2.5275	1.6461	−2.9553	−9.3074	−5.6318	–	–	0.0395
		318.15	2.4163	−10.9157	−41.906	2.6546	108.8164	77.4651	–	0.0297
	$K_S^E \times 10^{10}$ (Pa^{-1})	298.15	0.8817	−17.2635	−27.283	−4.8082	−0.3275	−0.0098	−0.0001	0.4244
	Δu (ms^{-1})	298.15	−0.099	0.0009	–	–	–	–	–	4.2030
	$L_f^E \times 10^{11}$ (m)	298.15	1.1484	0.2066	–	–	–	–	–	0.2950
	$Z^E \times 10^{-3}$ ($kg m^2 s^{-1}$)	298.15	16.038	−0.6397	0.0089	−0.0004	0.0000	–	–	6.0074
2-Methoxyethanol + ethanol	$V^E \times 10^6$ ($m^3 mol^{-1}$)	298.15	2.7444	1.2627	−3.9676	−4.8977	−1.4884	–	–	0.1065
		308.15	1.7539	0.5017	–	–	–	–	–	0.2621
		318.15	2.7190	1.2040	−3.7058	−4.2438	−1.1608	–	–	0.1135
	$\Delta\eta$ (mPa.)	298.15	2.5221	2.4610	0.5640	−7.0449	−9.5401	−3.3225	–	0.0563
		308.15	2.6128	2.3224	−1.8127	−8.6884	−5.3312	–	–	0.0190
		318.15	–	–	–	–	–	–	–	
	$K_S^E \times 10^{10}$ (Pa^{-1})	298.15	2.9722	−2.7603	−11.236	−3.6634	−0.4251	−0.0208	−0.0003	0.2598
	Δu (ms^{-1})	298.15	−1.159	0.0476	−0.0006	0.0000	–	–	–	1.5337
	$L_f^E \times 10^{11}$ (m)	298.15	1.7001	0.4345	–	–	–	–	–	0.2486
	$Z^E \times 10^{-3}$ ($kg m^2 s^{-1}$)	298.15	2.0789	−0.4097	0.0138	−0.0002	0.0000	–	–	0.1634
2-Methoxyethanol + 1-propanol	$V^E \times 10^6$ ($m^3 mol^{-1}$)	298.15	2.7282	3.3017	−2.9796	−7.5458	–	–	–	0.0778
		308.15	1.7541	0.5924	–	–	–	–	–	0.3372
		318.15	1.5979	0.4652	–	–	–	–	–	0.4017
	$\Delta\eta$ (mPa s)	298.15	2.4854	2.8845	2.6021	−5.5956	−10.4435	−4.0957	–	0.0537
		308.15	–	–	–	–	–	–	–	–
		318.15	2.4850	2.9849	2.6088	−6.4008	−10.9584	−4.0569	–	0.0333
	$K_S^E \times 10^{10}$ (Pa^{-1})	298.15	2.7266	0.7691	0.0552	–	–	–	–	0.7931
	Δu (ms^{-1})	298.15	−0.161	0.0028	–	–	–	–	–	4.7717
	$L_f^E \times 10^{11}$ (m)	298.15	2.2148	0.8620	–	–	–	–	–	0.1783
	$Z^E \times 10^{-3}$ ($kg m^2 s^{-1}$)	298.15	7.9300	−2.81409	0.22066	−0.0049	–	–	–	2.12157
2-Methoxyethanol + 1-butanol	$V^E \times 10^6$ ($m^3 mol^{-1}$)	298.15	2.2379	1.4875	–	–	–	–	–	0.1499
		308.15	1.3048	0.2991	–	–	–	–	–	0.5614
		318.15	1.2722	0.2767	–	–	–	–	–	0.5723
	$\Delta\eta$ (mPa s)	298.15	2.2450	0.9553	–	–	–	–	–	0.2242

(*continued*)

Talbe 6. Continued.

Binary mixture	Excess property	Temperature (K)	A_0	A_1	A_2	A_3	A_4	A_5	A_6	σ
		308.15	2.2777	0.9673	–	–	–	–	–	0.2132
		318.15	2.4317	3.5755	4.6716	−6.9728	−14.3204	−5.5531	–	0.0320
	$K_S^E \times 10^{10}$ (Pa^{-1})	298.15	0.7952	0.0880	–	–	–	–	–	0.7033
	Δu (ms^{-1})	298.15	−0.156	0.0027	–	–	–	–	–	5.5013
	$L_f^E \times 10^{11}$ (m)	298.15	2.4320	1.1190	–	–	–	–	–	0.1620
	$Z^E \times 10^{-3}$ (kg m^2 s^{-1})	298.15	0.0308	0.0011	–	–	–	–	–	2.6414
2-Methoxyethanol + 1-pentanol	$V^E \times 10^6$ (m^3 mol^{-1})	298.15	2.3405	1.8760	–	–	–	–	–	0.1449
		308.15	2.2195	0.9592	–	–	–	–	–	0.3453
		318.15	2.0619	0.7743	–	–	–	–	–	0.4325
	$\Delta\eta$ (mPa s)	298.15	2.2904	0.8632	–	–	–	–		0.2638
		308.15	2.2904	0.8653	–	–	–	–	–	0.2693
		318.15	2.3923	1.1104	–	–	–	–	–	0.2292
	$K_S^E \times 10^{10}$ (Pa^{-1})	298.15	1.5377	0.2291	–	–	–	–	–	0.5154
	Δu (ms^{-1})	298.15	6.9397	−0.6607	0.0175	−0.0001	–	–	–	1.7541
	$L_f^E \times 10^{11}$ (m)	298.15	2.5928	1.2213	–	–	–	–	-	0.1553
	$Z^E \times 10^{-3}$ (kg m^2 s^{-1})	298.15	0.1553	0.0093	—	–	–	–	–	2.2009
2-Methoxyethanol + 1-hexanol	$V^E \times 10^6$ (m^3 mol^{-1})	298.15	2.4002	2.2491	–	–	–	–	–	0.1430
		308.15	2.3361	1.0603	–	–	–	–	–	0.3929
		318.15	2.3612	1.0973	–	–	–	–	–	0.3897
	$\Delta\eta$ (mPa s)	298.15	2.2735	0.7623	–	–	–	–		0.3048
		308.15	2.2807	0.8020	–	–	–	–	–	0.3200
		318.15	2.6999	1.3269	–	–	–	–	–	0.1539
	$K_S^E \times 10^{10}$ (Pa^{-1})	298.15	−1.367	0.1761	–	–	–	–		0.9437
	Δu (ms^{-1})	298.15	1.5310	0.5093	0.0416	0.0012	0.0009	–	–	1.3790
	$L_f^E \times 10^{11}$ (m)	298.15	2.4717	2.0671	–	–	–	–	–	0.1460
	$Z^E \times 10^{-3}$ (kg m^2 s^{-1})	298.15	0.0622	0.0004	–	–	–	–		7.9222
2-Methoxyethanol + 1-heptanol	$V^E \times 10^6$ (m^3 mol^{-1})	298.15	2.2313	2.5728	1.8137	–	–	–	–	0.1372
		308.15	2.1647	0.7556	–	–	–	–	–	0.5339
		318.15	2.7422	0.0043	–	–	–	–		0.2939
	$\Delta\eta$ (mPa s)	298.15	2.3974	1.7720	0.4057	–	–	–	–	0.3108
		308.15	1.9731	0.5678	–	–	–	–	–	0.4103
		318.15	2.6541	1.2346	–	–	–	–	–	0.2227
	$K_S^E \times 10^{10}$ (Pa^{-1})	298.15	−1.180	0.1196	–	–	–	–	–	1.0305
	Δu (ms^{-1})	298.15	−0.037	0.0126	0.0008	0.0009	–	–	–	3.1520
	$L_f^E \times 10^{11}$ (m)	298.15	2.3594	1.9006	–	–	–	–	–	0.2406
	$Z^E \times 10^{-3}$ (kg m^2 s^{-1})	298.15	0.0666	0.0005	–	–	–	–	–	10.1801

thorough study of the behaviour of alkan-1-ols and 2-methoxyethanol mixtures that the lower alkan-1-ols were found to associate more strongly with the 2-methoxyethanol molecules as compared with the higher ones and self-association in an alkan-1-ol was found to increase with the increasing chain length of the alkan-1-ols. The measured data and calculated values of all systems are in good accordance, and are theoretically and statistically satisfying.

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