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Thermochimica Acta 426 (2005) 199–206

thermochimica acta

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Densities, speeds of sound, isentropic compressibilities, refractive indexes, and viscosities of tetrahydrofuran with haloalkane or alkyl ethanoate at $T = 303.15$ K

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Received 23 May 2004; received in revised form 30 July 2004; accepted 2 August 2004
Available online 11 September 2004

Abstract

Isentropic compressibilities κ_S, excess isentropic compressibilities κ_S^E, excess molar volumes V^E, viscosity deviations $\Delta\eta$, and excess Gibbs energy of activation of viscous flow ΔG^{*E} for nine binary mixtures of C_4H_8O with CCl_4, $CHCl_3$, $CHCl_2CHCl_2$, 1-$C_6H_{13}Cl$, 1-$C_6H_{13}Br$, $CH_3CO_2CH_3$, $CH_3CO_2C_2H_5$, $CH_3CO_2C_4H_9$, and $CH_3CO_2C_5H_{11}$ at 303.15 K have been derived from experimental densities ρ, speeds of sound u, refractive indexes n_D and viscosities η. The limiting values of excess partial molar volumes of C_4H_8O at infinite dilution $V_1^{E,\infty}$ in different solvents have been estimated. The results obtained for dynamic viscosity of binary mixtures were used to test the semi-empirical relations of Grunberg–Nissan, Tamura–Kurata, Hind–McLaughlin–Ubbelohde, Katti–Chaudhri, McAllister, Heric, and Auslaender. Finally, the experimental refractive indexes were compared with the predicted results for Lorentz–Lorenz, Dale–Gladstone, Eykman, Arago–Boit, Newton, Oster, Heller, and Wiener equations.

Keywords: Isentropic compressibility; Excess molar volume; Refractive index; Speed of sound; Tetrahydrofuran; Viscosity

1. Introduction

As a part of our systematic studies on the thermodynamic, transport, and acoustic properties of liquid mixtures containing cyclic ethers, in previous papers [1–6] measurements of speeds sound, densities, and viscosities, and related excess functions for binary mixtures of *p*-dioxane and tetrahydrofuran with variety of solvents have been reported. As an extension of our studies in this paper we report densities ρ, speeds of sound u, isentropic compressibilities κ_S, refractive indexes n_D, viscosities η, and related excess properties for binary mixtures of tetrahydrofuran (C_4H_8O) with tetrachloromethane (CCl_4), trichloromethane ($CHCl_3$), 1,1,2,2-tetrachloroethane ($CHCl_2CHCl_2$), 1-chlorohexane (1-$C_6H_{13}Cl$), 1-bromohexane (1-$C_6H_{13}Br$), methyl ethanoate ($CH_3CO_2CH_3$), ethyl ethanoate ($CH_3CO_2C_2H_5$), *n*-butyl ethanoate ($CH_3CO_2C_4H_9$) and *n*-amyl ethanoate ($CH_3CO_2C_5H_{11}$). The results obtained for dynamic viscosity of binary mixtures were used to test the semi-empirical relations of Grunberg–Nissan [7], Tamura–Kurata [8], Hind–McLaughlin–Ubbelohde [9], Katti–Chaudhri [10], McAllister [11], Heric [12], and Auslaender [13]. Finally, the experimental refractive indexes were compared with the predicted results for Lorentz–Lorenz [14,15], Dale–Gladstone [14], Heller [14], Arago–Boit [15], Wiener [15]. Eykman [16], Newton [16], and Oster [16] equations.

2. Experimental

CCl_4, $CHCl_3$, $CH_3CO_2CH_3$, $CH_3CO_2C_2H_5$, CH_3CO_2-C_4H_9 and $CH_3CO_2C_5H_{11}$ from BDH of AR grade and $CHCl_2CHCl_2$ from Riedel Dehaenat Seeze-Hannover, 1-

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doi:10.1016/j.tca.2004.08.001

Table 1
Densities, refractive indexes, speeds of sound, isentropic compressibilities, thermal expansion coefficients and heat capacities for pure liquids at 303.15 K

Liquids	ρ (kg m^{-3})	n_D	u (m s^{-1})	η (mPa s)	α° (kK^{-1})	C°_P (J mol^{-1} K^{-1})
C_4H_8O	876.70	1.4028	1255	0.4383		
	876.7[a]	1.4028[c]	1254[b]	0.438[c]	1.243[b]	125.9[b]
CCl_4	1574.82	1.4555	905	0.8441		
	1574.80[c]	1.4547[c]	905[d]	0.845[c]	1.245[c]	131.3[e]
$CHCl_3$	1470.59	1.4410	967	0.5100		
	1470.60[c]	1.4400[c]	967.5[d]	0.514[c]	1.265[c]	117.0[e]
$CHCl_2CHCl_2$	1578.60	1.4881	1135	1.4570		
	1578.60[c]	1.4886[c]	1134.7[f]		0.964[g]	169.8[c]
1-$C_6H_{13}Cl$	868.78	1.4168	1184	0.6544		
	873.47[n]	1.4197[n]				
	873.33[n,h]	1.4179[n,i]			1.131[g]	213.7[j]
1-$C_6H_{13}Br$	1162.67	1.4441	1075	0.9030		
	1169.62[n]	1.4464[n]				
	1174.40[n,h]	1.4478[n,i]			1.254[g]	220.0[j]
$CH_3CO_2CH_3$	920.83	1.3567	1136	0.3430		
	920.8[k]	1.3564[c]	1136[l]		1.516[m]	144.9[m]
$CH_3CO_2C_2H_5$	888.55	1.3664	1117	0.4043		
	888.51[k]	1.36717[c]	1119[l]	0.400[c]	1.392[m]	168.9[m]
$CH_3CO_2C_4H_9$	870.80	1.3896	1172	0.6453		
	871.29[c]	1.3894[c]	1170[l]	0.6444[c]	1.243[m]	229.9[m]
$CH_3CO_2C_5H_{11}$	867.20	1.3961	1197	0.7573		
	867.2[c]	1.3974[c]	1197[l]		1.156[m]	261.7[m]

[a] Ref. [20].
[b] Ref. [21].
[c] Ref. [17].
[d] Ref. [22].
[e] Ref. [23].
[f] Ref. [24].
[g] Ref. [25].
[h] Ref. [26].
[i] Ref. [27].
[j] Values calculated using Missenard group contribution method [28].
[k] Ref. [29].
[l] Ref. [30].
[m] Ref. [31].
[n] At 298.15 K.

$C_6H_{13}Cl$ and 1-$C_6H_{13}Br$ from Merck, Bombay were used after further purification by standard procedures [17]. C_4H_8O (Merck, AR) was refluxed for several hours over sodium metal pieces till free from peroxide and finally fractionally distilled over sodium [17]. Immediately before use all liquid samples were dried over molecular sieve 0.4 nm (Fluka) and fractionally distilled twice. The purity of liquid samples tested by gas–liquid chromatography was better than 99.8 mol% for all samples.

The speeds of sound in pure liquids and in binary mixtures were measured with 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 frequencies was employed. The refractive indexes were measured using research refractometer RL_3 made in Poland. The viscosities were measured with a modified suspended-level Ubbelohde viscometer. A water-circulating thermostat with an accuracy of ±0.02 K was used for controlling the temperature for the speed of sound, refractive index and viscosity measurements. The densities were measured with an Anton Paar vibrating tube digital densimeter (model DMA 60/602) with a thermostated bath controlled to ±0.01 K. The details of the apparatus and procedure have been described in previous publications [18,19].

Mixtures were prepared by in all cases by mass using an electronic Mettler (AE 163, Switzerland) balance accurate to 0.1 mg. The possible error in the mole fraction is estimated to be $\pm 1 \times 10^{-4}$. The errors in values of ρ, u, n_D, and η were estimated to be <0.02 kg m^{-3}, 1 m s^{-1}, 0.0002 units, and 0.002 mPa s, respectively. The isentropic compressibilities determined from the relation $\kappa_S = 1/(u^2\rho)$ are believed to be reliable to ±1 TPa^{-1}. The experimentally measured physical properties ρ, n_D, u, and η of the pure components agree with the literature data, as shown in Table 1.

3. Results and discussion

The experimental densities ρ, speeds of sound u, isentropic compressibilities κ_S, refractive indexes n_D, and viscosities η for binary mixtures at 303.15 K are given in Table 2. No published work on the speeds of sound, isentropic

Table 2
Densities, speeds of sound, isentropic compressibilities, refractive indexes, and viscosities for tetrahydrofuran binary mixtures at 303.15 K

x_1	ρ (kg m^{-3})	u (m s^{-1})	κ_S TPa^{-1}	n_D	η (mPa s)
$C_4H_8O + CCl_4$					
0.1068	1513.72	932	761	1.4519	0.8152
0.2017	1457.18	955	753	1.4486	0.7880
0.3004	1395.97	982	743	1.4451	0.7580
0.3960	1334.07	1008	738	1.4409	0.7210
0.5030	1261.58	1042	730	1.4357	0.6782
0.6000	1192.83	1074	727	1.4304	0.6359
0.6923	1124.71	1109	723	1.4247	0.5916
0.7949	1045.62	1152	721	1.4182	0.5453
0.8889	969.98	1196	721	1.4116	0.4962
$C_4H_8O + CHCl_3$					
0.1023	1410.89	986	729	1.4380	0.5307
0.2085	1349.01	1006	733	1.4346	0.5467
0.3045	1292.84	1024	738	1.4315	0.5566
0.4278	1220.11	1051	742	1.4273	0.5590
0.5003	1176.98	1070	742	1.4251	0.5580
0.6047	1114.67	1102	739	1.4210	0.5445
0.6976	1058.96	1133	736	1.4168	0.5245
0.8077	992.59	1174	731	1.4121	0.4955
0.8921	941.69	1208	728	1.4079	0.4676
$C_4H_8O + CHCl_2CHCl_2$					
0.1023	1523.21	1138	507	1.4830	1.3889
0.2128	1460.02	1143	524	1.4760	1.3071
0.3093	1401.59	1149	540	1.4701	1.2270
0.4056	1340.18	1157	557	1.4639	1.1362
0.5093	1270.31	1168	577	1.4556	1.0289
0.6032	1203.28	1180	597	1.4472	0.9116
0.7046	1126.91	1195	621	1.4368	0.7860
0.8008	1050.12	1212	648	1.4268	0.6647
0.8973	968.58	1231	681	1.4160	0.5519
C_4H_8O + 1-$C_6H_{13}Cl$					
0.1039	869.11	1195	806	1.4161	0.6407
0.3050	870.03	1216	777	1.4142	0.6046
0.5025	871.36	1233	755	1.4122	0.5698
0.7336	873.79	1247	736	1.4088	0.5114
0.9013	875.66	1252	729	1.4053	0.4711
C_4H_8O + 1-$C_6H_{13}Br$					
0.0976	1146.32	1087	738	1.4420	0.8602
0.3008	1107.30	1119	721	1.4368	0.7753
0.4975	1061.20	1154	708	1.4307	0.6995
0.6960	1002.92	1194	699	1.4223	0.6258
0.9000	924.62	1235	709	1.4105	0.5054
$C_4H_8O + CH_3CO_2CH_3$					
0.1028	915.90	1151	824	1.3649	0.3512
0.3022	906.64	1178	795	1.3748	0.3672
0.5035	897.56	1204	769	1.3847	0.3841
0.6930	889.35	1226	748	1.3927	0.4035
0.8918	881.07	1246	731	1.4008	0.4251
$C_4H_8O + CH_3CO_2C_2H_5$					
0.0995	887.39	1129	884	1.3707	0.4078
0.2035	886.11	1141	867	1.3750	0.4082
0.3016	884.98	1153	850	1.3785	0.4085
0.3923	883.95	1165	834	1.3821	0.4091
0.4868	882.82	1177	818	1.3858	0.4111
0.5955	881.45	1192	799	1.3892	0.4147
0.6973	880.21	1206	781	1.3921	0.4184
0.8120	878.89	1224	760	1.3964	0.4236
0.9000	877.84	1238	743	1.3995	0.4287
$C_4H_8O + CH_3CO_2C_4H_9$					
0.1033	871.17	1177	829	1.3911	0.6261
0.1989	871.58	1182	821	1.3924	0.6085
0.3041	872.04	1188	812	1.3941	0.5892
0.3995	872.51	1194	804	1.3954	0.5762
0.4967	873.01	1201	794	1.3970	0.5573
0.6013	873.59	1210	782	1.3979	0.5346
0.6979	874.18	1219	770	1.3991	0.5107
0.7978	874.96	1229	757	1.4005	0.4893
0.8999	875.79	1241	741	1.4018	0.4644
$C_4H_8O + CH_3CO_2C_5H_{11}$					
0.1067	867.69	1198	803	1.3967	0.7426
0.2980	868.75	1203	795	1.3978	0.7005
0.4997	870.25	1212	782	1.3992	0.6373
0.6997	872.25	1224	765	1.4005	0.5686
0.9027	875.00	1242	741	1.4021	0.4829

compressibilities and refractive indexes was found for the present mixtures with which to compare our results.

The values of u and κ_S were fitted to a polynomial equation of the form

$$u \text{ or } \kappa_S = \sum_{i=1}^{m} A_i X_1^{i-1} \tag{1}$$

The values of coefficients A_i of Eq. (1) and the corresponding standard deviations σ obtained by the method of least squares are given in Table 3.

Table 4 compares the experimental refractive indexes for binary mixtures with the predicted results for Lorentz–Lorenz [14,15], Dale–Gladstone [14], Eykman [16], Arago–Boit [15], Newton [16], Oster [16], Heller [14], and Wiener [15] equations. In Table 4, the root-mean-square deviations of the calculated values are presented. The Lorentz–Lorenz relationship is most suitable for $C_4H_8O + CCl_4$ and $C_4H_8O + CHCl_3$. For the remaining mixtures, similar deviations are obtained by using all the equations except Arago–Boit. Highest deviations for the calculated refractive indexes are obtained by using Arago–Boit equation.

Tables 5 and 6 show parameters calculated and the standard deviations between experimental values obtained for viscosities and the predicted results using semi-empirical relations of Grunberg–Nissan [7], Tamura–Kurata [8], Hind–McLaughlin–Ubbelohde [9], Katti–Chaudhri [10], McAllister [11], Heric [12], and Auslaender [13]. As observed, the best accuracy is given for the three-parameter Auslaender equation.

V^E for each mixture was calculated from equation

$$V^E = \frac{\sum(x_i M_i)}{\rho} - \frac{\sum(x_i M_i)}{\rho_i} \tag{2}$$

Table 3
Coefficients A_i of Eq. (1), and standard deviations σ

Property	A_1	A_2	A_3	A_4	A_5	σ
$C_4H_8O + CCl_4$						
u (m s^{-1})	905.1	247.5	−10.0	112.3		0.5
κ_S (TPa^{-1})	774.9	−154.8	224.1	−247.8	127.6	0.7
$C_4H_8O + CHCl_3$						
u (m s^{-1})	967.0	197.5	−141.3	406.6	−175.0	0.6
κ_S (TPa^{-1})	727.1	−8.7	277.9	−548.7	276.8	0.9
$C_4H_8O + CHCl_2CHCl_2$						
u (m s^{-1})	1135.0	20.0	74.7	25.1	0.2	
κ_S (TPa^{-1})	490.9	142.6	74.8	−112.4	128.1	0.3
$C_4H_8O + 1\text{-}C_6H_{13}Cl$						
u (m s^{-1})	1183.7	117.0	−31.5	−14.7	0.7	
κ_S (TPa^{-1})	821.5	−170.4	73.0		0.7	
$C_4H_8O + 1\text{-}C_6H_{13}Br$						
u (m s^{-1})	1074.9	115.8	112.4	−48.2		0.4
κ_S (TPa^{-1})	743.8	−45.8	−145.1	170.8		0.7
$C_4H_8O + CH_3CO_2CH_3$						
u (m s^{-1})	1135.7	151.7	−31.9			0.5
κ_S (TPa^{-1})	841.1	−173.2	55.9			0.1
$C_4H_8O + CH_3CO_2C_2H_5$						
u (m s^{-1})	1117.0	117.3	3.7	16.9		0.3
κ_S (TPa^{-1})	902.0	−181.7	25.4	−21.8		0.4
$C_4H_8O + CH_3CO_2C_4H_9$						
u (m s^{-1})	1172.0	46.7	12.6	23.6		0.2
κ_S (TPa^{-1})	836.0	−68.2	−23.6	−198		0.4
$C_4H_8O + CH_3CO_2C_5H_{11}$						
u (m s^{-1})	1196.6	15.5	13.4	28.9		0.8
κ_S (TPa^{-1})	804.5	−18.0	−40.4	−21.7		0.9

${\kappa_S}^E$ was calculated from the relation recommended by Benson and Kiyohara [32]

$$\kappa_S^E = \kappa_S - \sum \phi_i \left\{ \frac{\kappa_{S,i}^o + TV(\alpha_i^o)^2}{C_{P,i^o}} \right\} - \frac{T(\sum X_i V_i^o)(\sum \phi_i \alpha_i^o)^2}{\sum X_i C_{P,i}^o} \quad (3)$$

in which the ${V_i}^o$, ${\alpha_i}^o$ and ${C_{P,i}}^o$ are respectively, the molar volume, isobaric thermal expansion coefficient and molar isobaric heat capacity of pure component i and $\phi_i = x_i V_i / \Sigma x_j V_j$ is the volume fraction of i in the mixture, stated in terms of the unmixed components.

The viscosity deviations from a linear dependence on mole fraction $\Delta\eta$ are calculated from

$$\Delta\eta = \eta - \sum_i x_i \eta_i \quad (4)$$

where η and η_i represents the viscosities of the mixture and of the pure component i. On the basis of the theory of absolute reaction rates [33], the excess Gibbs energy of activation ΔG^{*E} of viscous flow may be calculated from

$$\frac{\Delta G^{*H}}{RT} = \ln \frac{\eta V}{\eta_2 V_2} - X_1 \ln \frac{\eta_1 V_1}{\eta_2 V_2} \quad (5)$$

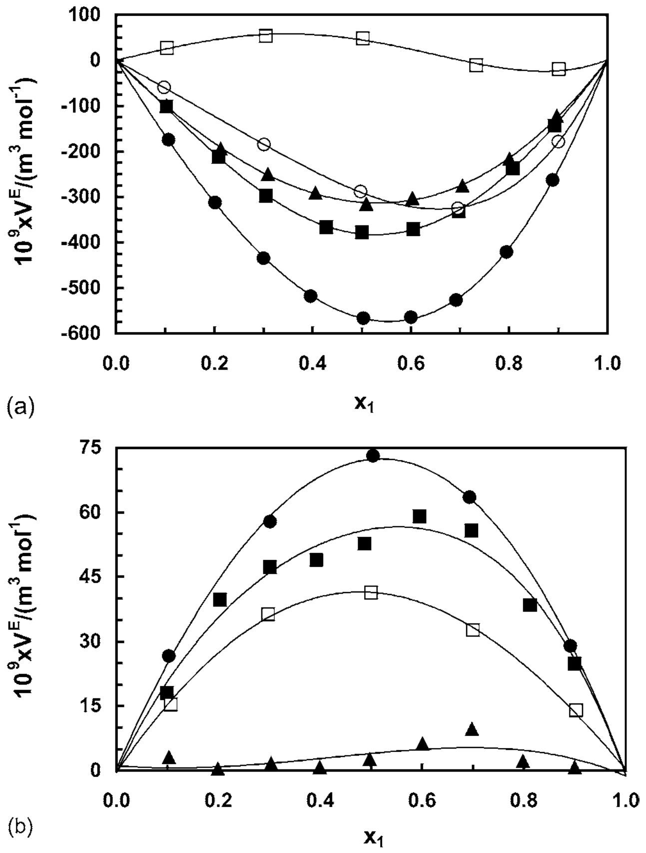

Fig. 1. (a) Excess molar volumes for terahydrofuran + haloalkane at 303.15 K. Experimental points: CCl_4 (●), $CHCl_3$ (■), $CHCl_2CHCl_2$ (▲), $1\text{-}C_6H_{13}Cl$ (□), $1\text{-}C_6H_{13}Br$ (○). (b) Excess molar volumes for terahydrofuran + alkyl ethanoate at 303.15 K. Experimental points: $CH_3CO_2CH_3$ (●), $CH_3CO_2C_2H_5$ (■), $CH_3CO_2C_4H_9$ (▲), $CH_3CO_2C_5H_{11}$ (□).

where V is the molar volume of the mixture and V_i the molar volume of the pure component i. The estimated accuracy in the values of V^E, ${\kappa_S}^E$, $\Delta\eta$, and ΔG^{*E} is within 5×10^{-9} m^3 mol^{-1}, 1 TPa^{-1}, 0.002 mPa s, and 15 J mol^{-1}.

The values of V^E, ${\kappa_S}^E$, and ΔG^{*E} for the mixture were smoothed to a Redlich–Kister polynomial regression of the type

$$\psi^E = x_1(1 - x_1) \sum_{i=1}^{m} B(1 - 2x_1)^{i-1} \quad (6)$$

where $\psi^E = V^E$, ${\kappa_S}^E$, and ΔG^{*E}

The values of coefficients B_i of Eq. (6) and the corresponding standard deviations σ are given in Table 7. The limiting values of excess partial molar volumes of cyclic ethers $V_1^{E,\infty}$ at infinite dilution in different solvents provide additional information regarding molecular interactions [34]. The values of $V_1^{E,\infty}$ were evaluated from coefficients B_i of Eq. (6) as to the V^E results, as $\sum_{i=1}^{m} Bi$. The values of $V_1^{E,\infty}$ of tetrahydrofuran are also compared with p-dioxane at infinite dilution in various solvents in Table 8.

Fig. 1 shows that the values of V^E for the mixtures $C_4H_8O + CH_3CO_2CH_3$, $C_4H_8O + CH_3CO_2C_2H_5$ and C_4H_8O +

Table 4
Standard deviations of the experimental refractive index results from predicted for the Lorentz–Lorenz (L–L), Dale–Gladstone (G–D), Eykman (Eyk), Arago–Boit (A–B), Newton (Nw), Oster (Os), Heller (He), and Wiener (Wi) equations

L–L	G–D	Eyk	A–B	Nw	Os	He	Wi
$C_4H_8O + CCl_4$							
0.0037	0.0035	0.0036	0.0035	0.0033	0.0034	0.0037	0.0036
0.0011[a]	0.0013[a]	0.0012[a]	0.0037[a]	0.0014[a]	0.0013[a]		
$C_4H_8O + CHCl_3$							
0.0025	0.0024	0.0024	0.0024	0.0023	0.0024	0.0025	0.0024
0.0008[a]	0.0009[a]	0.0008[a]	0.0027[a]	0.0010[a]	0.0009[a]		
$C_4H_8O + CHCl_2CHCl_2$							
0.0046	0.0041	0.0042	0.0041	0.0036	0.0038	0.0046	0.0043
0.0031[a]	0.0028[a]	0.0029[a]	0.0040[a]	0.0025[a]	0.0026[a]		
C_4H_8O + 1-$C_6H_{13}Cl$							
0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005
0.0006[a]	0.0005[a]	0.0005[a]	0.0008[a]	0.0005[a]	0.0005[a]		
C_4H_8O + 1-$C_6H_{13}Br$							
0.0014	0.0013	0.0013	0.0013	0.0012	0.0012	0.0014	0.0013
0.0003[a]	0.0003[a]	0.0003[a]	0.0019[a]	0.0004[a]	0.0003[a]		
$C_4H_8O + CH_3CO_2CH_3$							
0.0029	0.0030	0.0030	0.0037	0.0030	0.0030	0.0029	0.0030
0.0029[a]	0.0029[a]	0.0028[a]	0.0029[a]	0.0029[a]	0.0029[a]		
$C_4H_8O + CH_3CO_2C_2H_5$							
0.0024	0.0023	0.0023	0.0023	0.0022	0.0023	0.0024	0.0023
0.0026[a]	0.0025[a]	0.0025[a]	0.0030[a]	0.0024[a]	0.0024[a]		
$C_4H_8O + CH_3CO_2C_4H_9$							
0.0017	0.0016	0.0016	0.0016	0.0016	0.0016	0.0017	0.0016
0.0017[a]	0.0017[a]	0.0017[a]	0.0017[a]	0.0016[a]	0.0016[a]		
$C_4H_8O + CH_3CO_2C_5H_{11}$							
0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005
0.0006[a]	0.0006[a]	0.0006[a]	0.0009[a]	0.0006[a]	0.0006[a]		

[a] Non additivity on mixing.

Table 5
Values of parameters in Grunberg–Nissan (G_{12}), Tamura–Kurata (C), Hind–McLaughlin-Ubbelohde (η_{12}), Katti–Chaudhri (W_{vis}/RT) equations, and standard percentage deviations σ(%) in correlating viscosity of binary mixtures at 303.15 K

Mixture	G_{12}	σ (%)	C	σ (%)	η_{12}	σ (%)	W_{vis}/RT	σ (%)
$C_4H_8O + CCl_4$	0.45	0.66	0.70	0.51	0.72	0.36	0.44	0.60
$CHCl_3$	0.62	0.72	0.63	0.97	0.63	0.98	0.60	0.71
$CHCl_2CHCl_2$	1.01	1.62	1.04	2.59	1.10	2.20	1.03	1.62
1-$C_6H_{13}Cl$	0.26	0.81	0.59	0.38	0.60	0.49	0.40	0.96
1-$C_6H_{13}Br$	0.46	2.65	0.69	1.34	0.73	1.63	0.60	2.78
$CH_3CO_2CH_3$	−0.03	0.15	0.38	0.18	0.38	0.17	−0.03	0.14
$CH_3CO_2C_2H_5$	−0.09	0.46	0.41	0.42	0.40	0.49	−0.07	0.45
$CH_3CO_2C_4H_9$	0.17	0.54	0.56	0.30	0.57	0.38	0.28	0.68
$CH_3CO_2C_5H_{11}$	0.43	0.62	0.67	1.13	0.68	0.44	0.62	0.88
Average $\langle\sigma$ (%)$\rangle$		0.92		0.87		0.79		0.98

$CH_3CO_2C_5H_{11}$ are small and positive, while for $C_4H_8O + CCl_4$, $C_4H_8O + CHCl_3$, $C_4H_8O + CHCl_2CHCl_2$, and C_4H_8O + 1-$C_6H_{13}Br$ are negative. For C_4H_8O + 1-$C_6H_{13}Cl$, the values of V^E are both small positive and small negative. The V^E for $C_4H_8O + CCl_4$, $C_4H_8O + CHCl_3$, $C_4H_8O + CHCl_2CHCl_2$ and $C_4H_8O + CH_3CO_2C_2H_5$ mixtures have been reported in the literature [35–38]. The present V^E values for $C_4H_8O + CCl_4$, $C_4H_8O + CHCl_3$ and $C_4H_8O + CH_3CO_2C_2H_5$ are in reasonable agreement with literature values. However, equimolar literature V^E –617 × 10^{-9} m^3 mol^{-1} [38] for $C_4H_8O + CHCl_2CHCl_2$ is quite different than the present value –313.2 × 10^{-9} m^3 mol^{-1}. The values of $\kappa_S{}^E$ (Fig. 2) for the mixtures $C_4H_8O + CCl_4$, $C_4H_8O + CHCl_2CHCl_2$, C_4H_8O + 1-$C_6H_{13}Cl$, C_4H_8O + 1-$C_6H_{13}Br$, $C_4H_8O + CH_3CO_2CH_3$ and $C_4H_8O + CH_3CO_2C_2H_5$ are negative, while for $C_4H_8O + CH_3CO_2C_5H_{11}$ $C_4H_8O + CHCl_3$ are positive. For $C_4H_8O + CH_3CO_2C_4H_9$ the values of V^E and $\kappa_S{}^E$ are almost zero. The $\Delta\eta$ and ΔG^{*E} in Figs. 3 and 4 show positive values for the binary mixtures $C_4H_8O + CCl_4$, $C_4H_8O + CHCl_3$, $C_4H_8O + CHCl_2CHCl_2$, C_4H_8O + 1-$C_6H_{13}Cl$, C_4H_8O + 1-$C_6H_{13}Br$,

Table 6
Values of the parameters in McAllister (Z_{12} and Z_{21}), Heric (α_{12} and α_{21}), Auslaender (B_{12}, A_{21}, and B_{21}) equations and standard percentage deviations σ (%) in correlating viscosities of binary mixtures at 303.15 K

Mixture	Z_{12}	Z_{21}	σ (%)	α_{12}	α_{21}	σ (%)	B_{12}	A_{21}	B_{21}	σ (%)
$C_4H_8O + CCl_4$	0.57	0.56	0.22	0.44	0.08	0.22	0.54	0.93	1.44	0.26
$CHCl_3$	0.52	0.47	0.77	0.60	−0.04	0.77	−3.06	1.05	3.85	0.40
$CHCl_2CHCl_2$	0.85	0.92	0.42	1.03	0.20	0.42	2.31	3.76	0.25	0.59
1-$C_6H_{13}Cl$	0.66	0.70	0.55	0.40	0.11	0.55	−0.27	−0.46	−3.47	0.43
1-$C_6H_{13}Br$	0.73	0.68	0.84	0.60	0.34	0.84	1.43	1.46	1.10	0.37
$CH_3CO_2CH_3$	0.45	0.41	0.13	−0.03	−0.01	0.13	−0.02	−0.04	−35.04	0.12
$CH_3CO_2C_2H_5$	0.46	0.47	0.17	−0.07	−0.06	0.17	−0.32	−1.02	−3.32	0.13
$CH_3CO_2C_4H_9$	0.63	0.68	0.19	0.28	0.09	0.19	−0.05	−0.08	−16.45	0.22
$CH_3CO_2C_5H_{11}$	0.73	0.83	0.51	0.62	0.10	0.51	0.14	0.47	3.15	0.29
Average ⟨σ (%)⟩			0.42			0.42				0.31

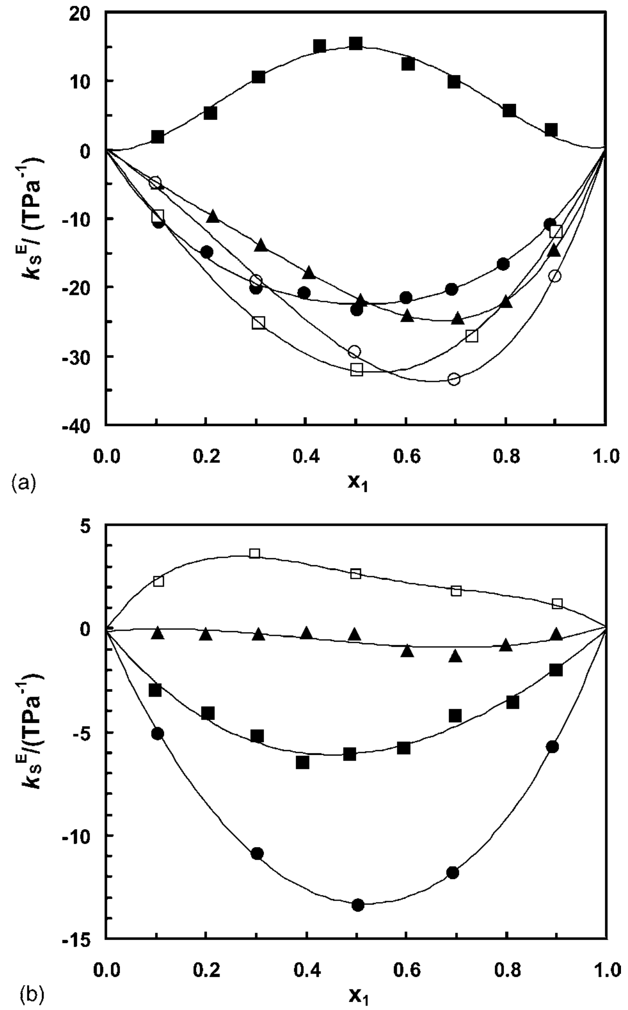

Fig. 2. (a) Excess isentropic compressibility for terahydrofuran + haloalkane at 303.15 K. Experimental points: CCl_4 (●), $CHCl_3$ (■), $CHCl_2CHCl_2$ (▲), 1-$C_6H_{13}Cl$ (□), 1-$C_6H_{13}Br$ (○). (b) Excess isentropic compressibility for terahydrofuran + alkyl ethanoate at 303.15 K. Experimental points: $CH_3CO_2CH_3$ (●), $CH_3CO_2C_2H_5$ (■), $CH_3CO_2C_4H_9$ (▲), $CH_3CO_2C_5H_{11}$ (□).

Table 7
Coefficients B_i of Eq. (6) and standard deviations σ

Mixture	Property	B_1	B_2	B_3	B_4	σ
$C_4H_8O + CCl_4$	$10^9 V^E$ (m^3 mol^{-1})	−2260.4	530.2			2.5
	κ_S^E (TPa^{-1})	−89.1	2.4	−31.9		0.7
	ΔG^{*E} (J mol^{-1})	1090.1	−198.1	47.1		5.4
$CHCl_3$	$10^9 V^E$ (m^3 mol^{-1})	−1529.1	225.9	358.1		3.3
	κ_S^E (TPa^{-1})	58.4	−3.7	−57.5		1.0
	ΔG^{*E} (J mol^{-1})	1611.9	−117.9	−400.5	443.1	4.6
$CHCl_2CHCl_2$	$10^9 V^E$ (m^3 mol^{-1})	−1252.6	163.0	55.8		3.3
	κ_S^E (TPa^{-1})	−86.0	67.3	−30.3		0.1
	ΔG^{*E} (J mol^{-1})	2640.7	−512.9	−207.0		2.8
1-$C_6H_{13}Cl$	$10^9 V^E$ (m^3 mol^{-1})	170.2	326.8	−216.2		6.3
	κ_S^E (TPa^{-1})	−129.5	20.6	16.8		0.6
	ΔG^{*E} (J mol^{-1})	926.6	−267.8	231.7		12.6
1-$C_6H_{13}Br$	$10^9 V^E$ (m^3 mol^{-1})	−1164.4	820.4	−263.2		2.1
	κ_S^E (TPa^{-1})	−120.6	91.4	−13.9		0.8
	ΔG^{*E} (J mol^{-1})	1399.6	−869.4	355.6		0.3
$CH_3CO_2CH_3$	$10^9 V^E$ (m^3 mol^{-1})	290.8	−12.3			1.6
	κ_S^E (TPa^{-1})	−53.0	2.9	−6.6		0.2
	ΔG^{*E} (J mol^{-1})	−82.3	35.2	33.3		2.4
$CH_3CO_2C_2H_5$	$10^9 V^E$ (m^3 mol^{-1})	229.2	−36.1	26.0		3.6
	κ_S^E (TPa^{-1})	−25.0	−5.2			0.4
	ΔG^{*E} (J mol^{-1})	−179.9	149.4			4.5
$CH_3CO_2C_4H_9$	$10^9 V^E$ (m^3 mol^{-1})	16.0	−2.7	3.8		3.2
	κ_S^E (TPa^{-1})	−2.9	2.2			0.3
	ΔG^{*E} (J mol^{-1})	727.6	−213.8	−66.5		3.3
$CH_3CO_2C_5H_{11}$	$10^9 V^E$ (m^3 mol^{-1})	163.1	5.8			1.3
	κ_S^E (TPa^{-1})	10.6	7.6	13.3		0.3
	ΔG^{*E} (J mol^{-1})	1495.8	−239.0	180.3		6.3

Table 8
The limiting values of excess partial molar volumes of C_4H_8O at infinite dilution $V_1^{E,\infty}$ in different solvents at 303.15 K

Solvent	$10^6 \times V_1^{E,\infty}$ (m^3 mol^{-1})	Solvent	$10^6 \times V_1^{E,\infty}$ (m^3 mol^{-1})
CCl_4	−1.73, −1.93[a]	$CH_3CO_2CH_3$	0.28
$CHCl_3$	−0.95	$CH_3CO_2C_2H_5$	0.22
$CHCl_2CHCl_2$	−1.03	$CH_3CO_2C_4H_9$	0.02
1-$C_6H_{13}Cl$	0.28	$CH_3CO_2C_5H_{11}$	0.17
1-$C_6H_{13}Br$	−0.61		

[a] Ref. [35].

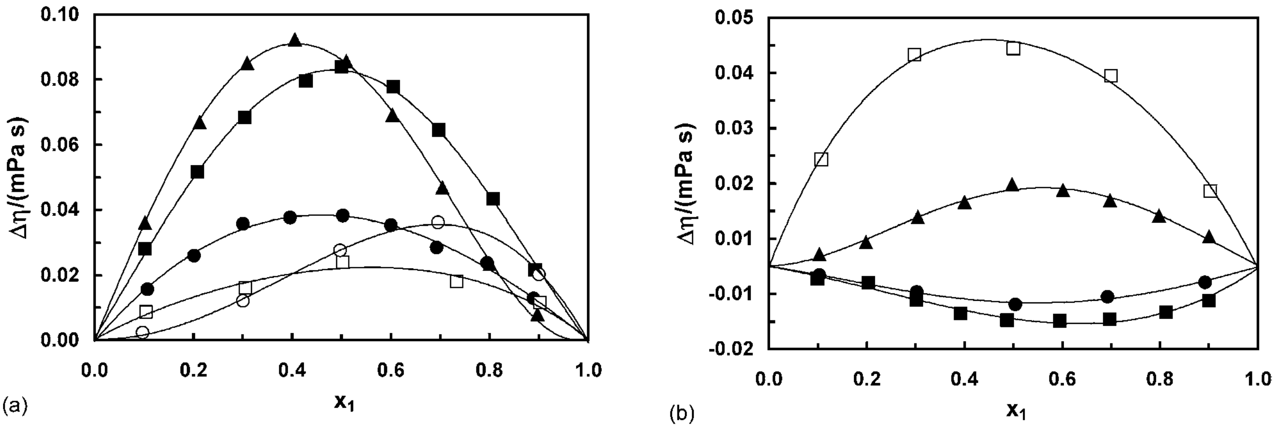

Fig. 3. (a) Viscosity deviations in for terahydrofuran + haloalkane at 303.15 K. Experimental points: CCl_4 (●), $CHCl_3$ (■), $CHCl_2CHCl_2$ (▲), 1-$C_6H_{13}Cl$ (□), 1-$C_6H_{13}Br$ (○). (b) Viscosity deviations in for terahydrofuran + alkyl ethanoate at 303.15 K. Experimental points: $CH_3CO_2CH_3$ (●), $CH_3CO_2C_2H_5$ (■), $CH_3CO_2C_4H_9$ (▲), $CH_3CO_2C_5H_{11}$ (□).

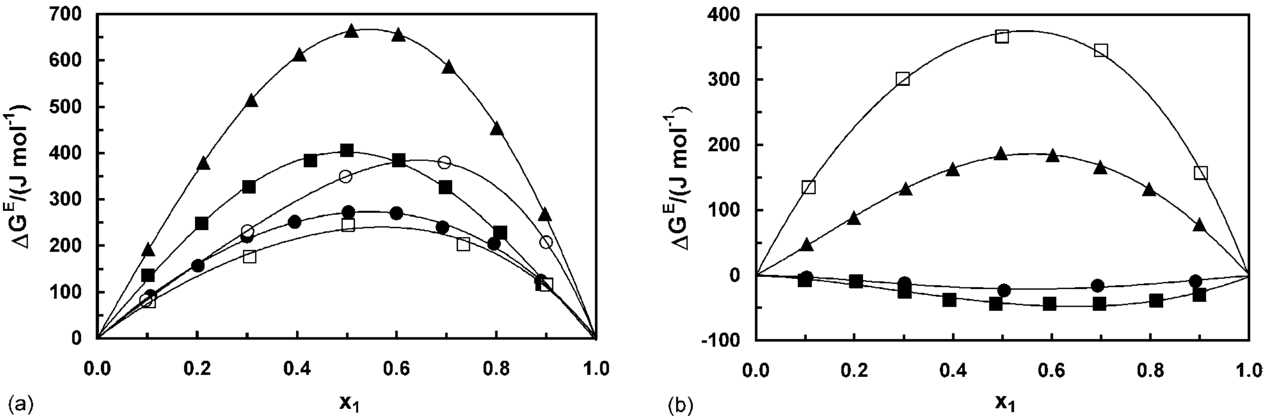

Fig. 4. (a) Excess Gibbs energy of activation of viscous flow for terahydrofuran + haloalkane at 303.15 K. Experimental points: CCl_4 (●), $CHCl_3$ (■), $CHCl_2CHCl_2$ (▲), 1-$C_6H_{13}Cl$ (□), 1-$C_6H_{13}Br$ (○). (b) Excess Gibbs energy of activation of viscous flow for terahydrofuran + alkyl ethanoate at 303.15 K. Experimental points: $CH_3CO_2CH_3$ (●), $CH_3CO_2C_2H_5$ (■), $CH_3CO_2C_4H_9$ (▲), $CH_3CO_2C_5H_{11}$ (□).

$C_4H_8O + CH_3CO_2C_4H_9$, $C_4H_8O + CH_3CO_2C_5H_{11}$ while negative values for $C_4H_8O + CH_3CO_2CH_3$ and $C_4H_8O + CH_3CO_2C_2H_5$.

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